Power Scaling Of Large Mode Area Thulium Fiber Lasers In Various Spectral And Temporal Regimes

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ABSTRACT

High power thulium fiber lasers are interesting for a myriad of applications due to their potential for high average output power, excellent beam quality, compactness, portability, high operating efficiency and broad, eye-safe spectral range from 1.8-2.1 μm. Currently, the majority of thulium laser research effort is being invested into scaling average output powers; however, such output powers are being scaled with no degree of control on laser system output spectrum or temporal behavior. Thulium fiber laser technology is not useful for many of its most important applications without implementation of techniques enabling tunable, narrow spectral widths with appropriate pulse durations for particular applications. This work outlines several techniques for spectral control of thulium fiber lasers and investigates scaling of average laser powers while using these techniques to maintain a desired spectral output. In addition, an examination of operation in both nanosecond and picosecond pulsed regimes and scaling of average powers and pulse energies in these regimes to useful power levels is conducted. The demonstration of thulium fiber laser systems for applications in frequency conversion and spectral beam combination is also discussed. In addition to the experimental results, theoretical modeling of thulium fiber amplifier operation, simple thermal management analysis, as well as practical fiber and system design considerations for future power scaling are presented. Experimental and theoretical results of this work will enable the successful design of future extremely high power spectrally and temporally controlled thulium fiber laser systems.
To my parents
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<tr>
<td>AO</td>
<td>Acousto-optical</td>
</tr>
<tr>
<td>AOM</td>
<td>Acousto-optic modulator</td>
</tr>
<tr>
<td>AR</td>
<td>Anti-reflective</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified spontaneous emission</td>
</tr>
<tr>
<td>BK7</td>
<td>A borosilicate glass from Schott commonly used in lenses</td>
</tr>
<tr>
<td>CCC</td>
<td>Chirally coupled core fiber</td>
</tr>
<tr>
<td>CNT</td>
<td>Carbon nanotubes</td>
</tr>
<tr>
<td>CPA</td>
<td>Chirped pulse amplification</td>
</tr>
<tr>
<td>CR</td>
<td>Cross relaxation</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous wave lasing</td>
</tr>
<tr>
<td>DFB</td>
<td>Distributed feedback laser</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium doped fiber amplifier</td>
</tr>
<tr>
<td>EH</td>
<td>One of the families of hybrid optical fiber modes</td>
</tr>
<tr>
<td>Er</td>
<td>Erbium</td>
</tr>
<tr>
<td>ETU</td>
<td>Energy transfer upconversion</td>
</tr>
<tr>
<td>FBG</td>
<td>Fiber Bragg grating</td>
</tr>
<tr>
<td>FC/APC</td>
<td>A type of fiber connector with an angle polished facet</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width at half maximum</td>
</tr>
<tr>
<td>FWM</td>
<td>Four wave mixing</td>
</tr>
<tr>
<td>GGIAG</td>
<td>Gain Guiding Index Anti-guiding optical fiber</td>
</tr>
<tr>
<td>GMRF</td>
<td>Guided mode resonance filter</td>
</tr>
<tr>
<td>GVD</td>
<td>Group velocity dispersion</td>
</tr>
<tr>
<td>HE</td>
<td>One of the family of hybrid optical fiber modes</td>
</tr>
<tr>
<td>HHG</td>
<td>High harmonic generation</td>
</tr>
<tr>
<td>Ho</td>
<td>Holmium</td>
</tr>
<tr>
<td>HOM</td>
<td>Higher order modes</td>
</tr>
<tr>
<td>HR</td>
<td>High reflectivity</td>
</tr>
<tr>
<td>HT</td>
<td>High transmission</td>
</tr>
<tr>
<td>HWFZ</td>
<td>Half width at first zero (a width specification for VBGs)</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>LCF</td>
<td>Leakage channel fiber</td>
</tr>
<tr>
<td>LD</td>
<td>Laser diode</td>
</tr>
<tr>
<td>LIBS</td>
<td>Laser induced breakdown spectroscopy</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Light detecting and ranging</td>
</tr>
<tr>
<td>LMA</td>
<td>Large mode area</td>
</tr>
<tr>
<td>LP</td>
<td>Optical fiber mode family containing HE, EH, TE and TM</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength de-multiplexer</td>
</tr>
<tr>
<td>XPM</td>
<td>Cross phase modulation</td>
</tr>
<tr>
<td>YAG</td>
<td>Yttrium aluminum garnet crystal host material</td>
</tr>
<tr>
<td>Yb</td>
<td>Ytterbium</td>
</tr>
<tr>
<td>ZBLAN</td>
<td>A type of fluoride glass</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

High power, eye-safe lasers with either spectral or temporal control are critical for numerous applications in many diverse technological fields. With the rise in popularity and capability of fiber laser systems, solutions based on thulium doped fiber lasers are considered among the top choices for high average power eye-safe applications. This chapter introduces the fiber laser and its inherent advantages, and brings to light the purpose and motivation for the work completed for this dissertation: the development of spectrally and temporally controlled thulium fiber lasers. It also outlines the history of, and reasons for, the use of thulium fiber lasers in applications requiring eye-safe wavelengths.

1.1 Why Fiber Lasers?

Lasers can take an almost infinite number of forms, from nano-lasers formed from molecular scale particles to compact semiconductor based lasers common in every barcode scanner and CD and DVD player, to building sized systems like the National Ignition Facility. Demands by the application for which they are intended dictate the form of the laser selected. The number of applications calling for lasers with high average power, compact and portable size, high reliability and the ability to propagate a beam over long distances is rapidly increasing, especially in the medical, material processing, defense and sensing related fields.
The fiber laser has emerged as a laser design that is an excellent fit for the needs of such highly demanding applications. Fiber lasers are simple in conception and construction, consisting mainly of a length of active optical fiber with a core and cladding. The core of the active is doped with some form of rare earth ion depending upon the operating wavelength desired, and the cladding is typically designed in such a way that pump light is able to propagate down it and excite the laser ions in the core. Feedback mechanisms, either feedback or fiberized, are aligned with or spliced to the active fiber to form a laser resonator. Like any laser, additional components can be added to provide spectral or temporal control; additionally, power scaling is achieved in fiber based systems by simply adding additional stages of active fibers and pumps to create amplifier chains. As is detailed in subsequent sections, the fiber based architecture allows for excellent beam quality, high stability, compact size, efficient operation and excellent average power handling. Fibers also have a great deal of spectral selectivity, as they can be doped with a number of different rare earth laser ions, enabling lasing over a great range of interesting wavelengths and making them appealing for a large number of potential applications that call for specific spectral windows.

1.1.1 Overview of Fiber Laser Advantages Compared to Other Laser Designs

There are several categories in which fiber laser performance can be superior to that of its bulk solid state or gas laser cousins. These areas include relatively compact size, robust and simple construction, enhanced thermal management performance and ease in the achievement of high beam quality that is immune to beam distortions at high average powers. The sum of these beneficial properties is the driving force behind the use of fiber lasers for high power applications.
1.1.1.1 Compact Size and Robust, Simple Construction

One of the most obvious advantages of fiber lasers is the compact size and relative simplicity of fiber laser systems. Even the simplest bulk lasers consist of a pump source, pumping optics, a gain medium and two end mirrors. If the laser is to have any special property, for instance narrow linewidth or pulsed operation, additional components need to be added into the cavity. These components all require careful alignment and must be held with mechanical stability to extremely tight tolerances, withstanding vibration and temperature variations. This stability can only be achieved by well designed mounting fixtures. Even with such fixtures, bulk lasers can have the tendency to misalign due to thermal perturbations or vibrations and can also have difficulty operating in harsh environments where contaminants might spoil mirror surfaces or even cause catastrophic failure. All of these issues can and have been minimized in bulk lasers over years of development. Achieving such stable bulk laser systems requires a large amount of engineering effort, including the use of exotic materials and designs with vibration damping and athermal properties in addition to hermetically sealing laser cavity or filling it with purge gasses. All of these remedies tend to be expensive and add significantly to the total cost of the laser as well as to its bulk and weight. Furthermore, bulk laser components are not readily able to be self-aligned, thus requiring skilled technicians to manufacture and maintain these systems.

In comparison, many current fiber laser systems can be made completely monolithic, meaning they are comprised of an unbroken chain of all-fiber glass-based components with no need for alignment and no potential for contamination. The only current limitation of monolithic fiber systems is the commercial availability of components able to handle ever higher powers, as most current components are designed for low power telecommunications applications. Even
though the current, somewhat hindered, state of fiber based component technology forces some very high power fiber lasers use free space optics, such lasers can still perform more highly in terms of efficiency and beam quality than bulk lasers due to the nature of the fiber itself. Because many components are fusion spliced together, lasers based on fibers are far more stable under thermal perturbations and mechanical vibrations. The manufacture of monolithic fiber lasers is a simple process requiring minimal alignment, the bulk of which can be done by splicing machines which often are semi- or fully automated.

Fiber based lasers have small space requirements because optical fibers can be coiled to a few centimeters in diameter and packaged into nearly any tight space required. The real limitation to the size of a fiber laser is the size of the diodes required to provide the desired output power as well as the size of the associated diode power supply and chiller, both of which can be decreased in size with appropriate engineering. In fiber lasers all of these components can be packaged into a single box with minimal impact on laser performance. This is in contrast to bulk lasers, where generally the laser head and its alignment sensitive optics must usually be kept separate from any electrical or cooling systems to avoid the potential for contamination in the laser resonator and avoid vibrations form any cooling pumps that may be required.

1.1.1.2 Thermal Management

Fiber lasers have a distinct advantage over bulk lasers in terms of thermal management, and thus are often the most suitable choice for high average power operation. This advantage is not due to the thermal properties of glass, as the thermal conductivity of crystal or ceramic based bulk lasers is far superior to that of glass based fiber lasers. Fiber lasers have a larger surface area to volume ratio than that of short length bulk laser crystals due to their comparatively long
length [1-4]. Heat load is therefore spread over a much larger area than in a bulk laser [1-4]. Fiber gain media can be as long as 10’s of meters, which allows any heat deposited in the fiber from the pumping process to be distributed over the full length of a fiber while the same amount of heat generated in a bulk laser would have to be dissipated in less than a few centimeters, necessitating more exotic thermal management schemes.

The fiber is superior in terms of thermal performance and in fact, all but the highest power fiber lasers can operate without the need for any active cooling of the fiber. In contrast, running a bulk laser to over a few watts of pump power without temperature control would be extremely difficult. High power fiber lasers can also be readily adapted to air or water cooling techniques, since the simple all-fiber nature of a cavity allows for the entire resonator to be immersed in water, wrapped around a cooled mandrel, or even directly cooled by a fan. Cooler lasers tend to operate more efficiently when the laser ion is based on a three level or quasi-three-level structure, as is nearly always the case in rare earth doped fiber lasers. This improvement in efficiency due to thermal management combined with operation near saturation intensity due to tightly confined modes, which are well overlapped with the pumped gain volume, leads to nearly quantum defect limited laser efficiencies which bulk lasers cannot easily achieve [1-5].

The cooling and attention to thermal issues in fiber lasers cannot be completely ignored and is investigated in studies done in [6-8], however overall, the thermal advantages of fiber lasers are clearly another reason for the fiber based gain medium’s importance when scaling to high power levels especially compared to solid state lasers designed for similar power levels.
1.1.1.3 Beam Quality

Often, high power applications call for the power to be delivered at long distances from the laser output itself. This is true not only of the obvious remote sensing and directed energy applications, but also of many materials processing applications where slag from processing could damage optics near the work piece. In addition, the advantage of using a laser in many laser materials processing applications is the ability to make smaller, cleaner and finer features compared to other techniques. Achievement of such features implies a laser with excellent beam quality. Such long distance and fine focal spot work can only be done if the laser beam is near diffraction limited, meaning it oscillates on the TEM$_{00}$ mode in free space or in the case of fibers, couples to that mode from the LP$_{01}$ fiber mode.

In bulk lasers there are several reasons why it is difficult to maintain beam quality, one of which is the nature of the modes of the laser cavity. In free space, all the modes are allowed to exist, and if given enough gain, they will lase. Modes can be controlled by using intracavity apertures or unstable resonators, but even these techniques have limitations and may also affect laser efficiency [9, 10]. In a fiber, the laser modes can be controlled by simply designing the fiber properly, ensuring that no other modes are allowed to exist in the wave-guiding cavity. Since the modes simply cannot exist, the beam quality can be pushed to near diffraction-limited, independent of the operating power level, assuming thermal or optical damage to the fiber can be avoided [11].

Thermal issues also come into play when considering beam quality. Bulk lasers are often victims of thermal beam distortions due to thermal lensing and birefringence caused by temperature gradients and the temperature sensitive nature of the refractive index in bulk gain media [9]. These gradients can severely distort light passing through a crystal or gas, and as a
result even if the resonator supports only a $\text{TEM}_{00}$ mode, the beam may be distorted due to
temperature effects. Thermal lenses can be so severe in some bulk lasers that the thermal lens
can actually misalign or destabilize the laser resonator at high powers if not properly
compensated. Thermal considerations cannot be ignored in fibers as seen in several analyses of
the thermal properties of fiber lasers [6-8]. In general, however, fiber lasers are mostly immune
to any thermal distortion of their beams (except at the highest operating powers with large core
diameters [12]). This is because they are not only more efficient at removing heat from their
structures, but also the wave guiding nature of the fiber keeps the beam profile uniform until the
beam exits the fiber core, thus maintaining the quality of the beam set by the waveguide, which
is independent of the heat load on the fiber.

Maintaining this beam quality is one of the main limitations for fiber lasers, as increases
in output power necessitate increases in core size, which will eventually allow higher order
modes to exist in the fiber [13]. Understanding how to maintain near-diffraction limited beam
quality while scaling power is the main reason for the push into the regime of large mode area
fibers, later discussed.

1.1.2 Comparison of Fibers to Other Laser Gain Medium Geometries

Compared to other bulk laser geometries fiber lasers are at an advantage in terms of
thermal management and susceptibility to thermal effects. There are several potential geometries
for laser resonators as seen in Figure 1, including the rod, slab and thin disk. Each of these
geometries, though they have some advantages over fiber lasers in terms of energy storage and
damage thresholds due to larger apertures, all suffer from thermal issues in terms of beam quality
or added system complexity.
The laser rod is the standard geometry in most solid state lasers; in terms of thermal performance it is perhaps the most difficult to manage. The surface to volume ratio of rods can be quite poor, meaning that there is a very small surface area compared to volume of gain medium [9]. This leads to difficulties in removing heat and requirement of special water cooling configurations [9]. Even with such cooling configurations these types of lasers tend to suffer from thermal lensing and thermal depolarization or beam distortion as a result of thermally induced birefringence [9]. Symmetric side pumping configurations can improve performance in some aspects, but the pumping schemes and engineering involved still makes such geometries difficult, especially for pure power scaling [9]. Regardless of pump geometry, gain can still be difficult to extract in a fundamental mode which is required for high beam quality. The gain per pass is also quite low compared to a fiber laser, usually on the order of 3 to 7 dB compared to 20 to 30 dB for fiber lasers, thus meaning that multiple passes or multiple rods are required for high gain systems. One main advantage is that rod diameters can be scaled almost arbitrarily, enabling
very high pulse energies in short durations to be achieved without need for concern about non-linear or damage effects.

The slab laser can be an improvement over the rod, as a thin slab enables an improved surface to volume ratio, and side pumping of the slab enables a simpler one dimensional thermal gradient to deal with [9]. Such a gradient can lead to more engineering and beam quality issues, which in some cases can be accounted for by “zigzagging” the beam through the slab. However, even such techniques still cause difficulty with efficiently extracting gain in a low order mode [9]. Through careful engineering and design, slab lasers can produce high powers with good beam quality, though the cost and complexity of such systems can be substantial [14]. In fact, the highest power diode pumped laser yet produced is based on slab geometries [15]. Like the rod, the slab technique also allows for very large apertures, enabling high pulse energies without damage.

Thin disk technology is a new and promising technique that uses a very thin (few hundred micron) disk of doped material with a back surface that acts as a mirror via dielectric coatings to form the laser gain medium [9, 16]. The geometry enables the source of the heat to be essentially in contact with the heat sink. Due to the thinness of the disk the surface to volume ratio is again quite high, enabling efficient heat extraction [9, 16]. Since the thermal profile is along the beam propagation direction rather than radial there is also little concern about thermal lensing and other beam distortion effects, therefore beam quality can be quite high [9, 16]. In terms of optical damage thresholds, such lasers can achieve higher pulse energies than fiber lasers due to somewhat larger mode sizes on thin disks; however disks may still be at a disadvantage compared to slabs or rods in terms of mode size and power scaling potential from a single disk, though multiple disk resonators can be implemented to improve this. Thin disk
technology still suffers from the need for more complex thermal management for achievement of high average powers. The need for careful engineering of disks in terms of avoiding thermal shock and enabling reflectivity is also critical, as is the requirement for complex mounting and pumping schemes, possibly involving multiple disks which increase system cost and complexity [9, 16].

There are disadvantages associated with the use of fibers in terms of the potential for damage at high pulse energies and the nonlinearities associated with long potential interaction lengths. Nevertheless, when thermal mitigation issues are important, as they are in high average power systems, fiber lasers can be advantageous. Pump power can be spread over many meters of gain medium with extremely high surface to volume ratio and heat can be further spread due to the fiber’s ease of implementation as a high gain, highly efficient amplifier [3]. Thermal mitigation is relatively simple; it is usually achieved by passive, or at most, active cooling of the fiber on a metal mandrel even for kilowatt level systems. Because of the double clad waveguide pumping scheme, and the potential for use of “all-fiber” pump combiner techniques which are spliced together, they do not suffer pump misalignment issues or issues associated with engineering pump and thermal management together that plague other solid state lasers [3, 9]. Fiber Bragg gratings also spliced into cavities or spliced pulsed seed lasers (fiber coupled laser diodes) enable “all-glass” configurations with minimal concerns about alignment stability over time. In addition, beam quality is fixed by the fiber core geometry, without concern for any thermal effects, and the same is true for the most part of polarization state, provided polarization maintaining (PM) fiber is used [3]. In a fiber, the saturation intensity is easily reached, due to the confined mode, so efficiency is limited by quantum defect. This is usually not the case in other bulk lasers. Also, the further reduced thermal loading from low quantum defect pumping makes
the laser more attractive for applications where efficiency matters, such as those requiring a high
degree of portability [3]. Higher efficiency and better thermal performance also lead to smaller
power supplies for a given power, smaller laser chillers and thus lighter, cheaper systems. The
overall mechanical complexity of a fiber based system can be significantly lower, and as a
consequence, laser cost, assembly time, size and weight can be lower for fiber based systems in
terms of dollars per watt, watts per cubic meter of system volume or watts per pound of
equipment.

In general, in a situation where average power is the most desired parameter with stability
and modest pulse energies, the fiber laser is often the most logical choice of gain medium.
Though energies beyond the mJ level are not yet achievable, techniques outlined herein, along
with the advantages inherent in thulium (discussed later), will enable fiber lasers to take the next
step in pulse energy and average power scaling to meet and surpass many solid state lasers.

1.2 History and Rapid Growth of Fiber Lasers

Fiber laser technology is nearly as old as the laser itself. The initial concept for the laser
was first suggested in 1958 by Schawlow and Townes [17] and only two years later in 1960, the
first laboratory demonstration of a laser was made in a ruby crystal by Maiman [18, 19]. Soon
after this demonstration, several other laser types were demonstrated including the helium neon,
carbon dioxide, laser diode and Nd:YAG laser [20-23]. In this same time frame, the earliest
forms of fiber lasers were also being investigated. The following sections outline the history of
the fiber laser from initial invention to current configurations for both fiber lasers in general and
the thulium fiber laser in particular.
1.2.1 General History of Fiber Lasers

The history of fiber lasers is outlined by several milestone steps in technological development which allowed fiber lasers to make advances in output power and beam quality. The following sections outline these stages, including the early stages of flashlamp pumping, subsequent diode based core pumping advances, the advent of double clad fibers and finally the development of large mode area (LMA) fibers. These stages each comprise a critical step along the path to current state-of-the-art kilowatt class fiber lasers and amplifier systems.

1.2.1.1 Early Flashlamp Pumped Fiber Lasers

In 1961, the early days of the development of laser technology, the potential of fiber based gain media was recognized and proposed by Snitzer [24]. Soon after this, the first glass laser was produced, based on neodymium doped barium crown glass [25]. Because of manufacturing difficulties with these early glass lasers, related to defects in the glass causing high laser threshold and poor efficiency, the glasses were formed into core/cladding structures with a lower index of refraction soda-lime silica glass as an outer cladding, giving a refractive index step of 0.02 and thus an NA of ~0.25. The relatively large cores of these early “proto-fiber lasers” were on the order of tens to hundreds of microns in size giving highly multimode outputs from the relatively short length (~7.5cm) fibers [24-26]. Later versions of these early fiber lasers were as long as a meter in length with 10 μm core diameters and very large claddings of around a millimeter in diameter, hot formed into coiled structures around a flashlamp to allow more efficient pumping [26].
An additional interesting version was the doped cladding fiber laser where the core was actually undoped and the cladding was doped with the laser medium, allowing gain at the total internal reflection interfaces due to evanescent fields. Better beam quality and efficiency with use of poorer quality doped materials were possible, since the core of the fiber was made from low loss undoped material while the cladding provided gain [27]. Even this novel technique was not enough to overcome the obvious deficiencies in early fiber lasers.

The flashlamp pumping required by these early fiber lasers was their main downfall, as it was difficult for the waveguide fiber laser to compete in terms of output power and efficiency compared to its bulk laser cousins. The physically small fiber cross section made it difficult to effectively absorb and store large amounts of energy [2]. Since flashlamps were the only real source of pump energy for early lasers (aside from direct electrical pumping in gasses and semiconductors), the fiber laser was set aside while its bulk counterparts enjoyed the majority of research and development. There was simply not sufficient interest or technology yet developed to make the high beam quality and high average power handling capabilities of fiber lasers attractive to the laser community as a whole.

1.2.1.2 Directly Core Pumped Lasers

Interest in fiber lasers was reborn with recognition of their potential uses in the field of optical communications. In order for the fiber laser to be feasible for such applications, improved fiber materials and pumping schemes were required. Clearly flashlamp pumping was not a practical way to pump a fiber. A new core pumped scheme for fiber lasers became the design of choice to take advantage of the waveguide nature of the fiber to allow it to efficiently absorb any launched pump power.
The earliest core pumping experiments were done using dye or gas ion lasers as pump sources, due to lack of any other feasible pumping medium which could provide sufficient power to the relatively small core of an optical fiber (diode lasers had not been proven sufficiently high powered practical at this point). The lasers were used to pump the fiber core directly, and because of the beam quality limitations of the pump beam, fiber cores were forced to remain multimode, with diameters in the 10’s of microns. Stone and Burrus demonstrated some of the first end pumped fiber lasers in 1973 [28]. Their lasers were highly doped with neodymium, and were still very short in length, limited to only a few centimeters by losses associated with glass host material quality. The work of Stone and Burrus also pioneered the use of the now “gold-standard” fiber material, fused silica, as their laser medium. Fused silica was higher in optical and thermal damage threshold, mechanically stronger and lower loss than any earlier fiber laser materials [28].

Stone and Burrus also suggested the feasibility of pumping fiber lasers with semiconductor based sources (either laser diodes or LEDs) based on such devices use for pumping of Nd:YAG lasers [29, 30]. Stone and Burris demonstrated the practicality of this suggestion in a fiber laser with a ~30 μm core by using an early 885 nm injection laser diode as a pump source for a fiber laser [31].

From 1975 to 1985 little work was done in the area of fiber laser power scaling, however a great deal of effort was being put into the field of telecommunications devices. In this period, many of the components that would later make monolithic, compact fiber lasers possible, including wavelength multiplexers, couplers, laser diode pump sources, and higher quality fiber were developed to support the development of the telecommunications industry [32].
As interest in fibers for telecommunications increased steadily, materials and techniques for fiber fabrication improved dramatically and allowed for long length and relatively low dopant concentration fiber lasers with single mode cores. In 1985, the first fiber laser resembling most modern fiber laser systems was demonstrated by using a low dopant concentration Nd-doped silica fiber core pumped directly by a laser diode. Lasing with extremely low threshold was achieved due to the four level nature of the Nd ion, however due to the poor coupling efficiency of the only 1.5 mW diode into the core, the total laser output power was extremely low [33].

The direct-core-pumping geometry is a limitation due to its requirement of single transverse mode laser diodes to allow efficient pump power launch into the doped single mode fiber core. In order to achieve higher power these first single mode fiber lasers were also configured to be pumped with an argon ion laser; such lasers, made in both neodymium and erbium doped fibers, achieved multi-mW output powers and were able to utilize the broad emission bandwidths associated with rare earth ions doped into glass to become the first tunable fiber lasers by way of feedback from a Littrow configured diffraction grating [34, 35]. This large range of tunability was seen as an advantage compared to crystal lasers in terms of potential for use in telecommunications where the ability to work on many different wavelengths was critical to increasing the amount of data transferred over a network.

Further work on decreasing the losses of silica fiber by removing excess OH⁻ impurities was driven by the demand for longer distance telecommunications systems. Though not the direct reason for the advances in optical fiber technology, fiber lasers directly benefited from such breakthroughs in fiber loss reduction, further lowering the achievable laser threshold and improving efficiency [36]. In this same period, the erbium doped fiber amplifier (EDFA) also became a widespread area of research for amplification of weak signals in long-haul fiber optic
networks. EDFAs pulled much of the attention away from high power, high efficiency fiber laser systems and directed it towards low-noise fiber based amplifiers useful communications systems that would mark the late 20th century photonics landscape. Such amplifiers were first constructed beginning in 1987 [37, 38].

However, in addition to the EDFA, this time period in the life of the fiber laser also saw the earliest Q-switched, mode locked, and narrow line oscillator and amplifier systems which would serve as the basis for future scaling of fiber laser powers with further advances in fiber laser technology [34, 39-43].

Despite all the major technological advances in this era driven by telecommunications, the output power of fiber lasers and amplifiers was still limited by the availability of single transverse mode pump power that could be launched into single mode fiber cores. A further step in technology was required to move into the modern era of high power fiber lasers.

1.2.1.3 The Advent of Double Clad Fibers

Though the use of direct diode end pumping in fiber lasers was a large step forward for the improvement of performance, there was still a distinct limitation on the maximum output power from such lasers. In order to have a single mode fiber laser, the core size had to be selected such that it would support only one transverse mode, meaning that the core would also only support light from a single mode pump source. It is extremely difficult to couple light from diode sources into small fiber cores due to their elliptical beam output shape. Furthermore, single mode laser diodes at the time when power scaling of fiber lasers was becoming an issue were only capable of <1 W of output power in a single transverse mode [2, 44].
In 1988 a new method that solved the pumping problem was first put into practice, a fiber laser based on a double clad, offset core design was demonstrated [45]. The figure below is a schematic of a double clad fiber. It should be noted that in this figure the outer cladding must have a lower index of refraction than the inner cladding and the core must have higher index than the inner cladding.

![Figure 2: Simple schematic of a double clad fiber. The refractive index profile should have the following index relation: $n_{\text{core}} > n_{\text{inner cladding}} > n_{\text{outer cladding}}$](image)

Often the inner cladding is not round as shown in the schematic, but otherwise shaped to improve pump absorption. This innovation led to a period of extremely rapid increase in fiber laser output power that was largely only limited by power levels of pump diodes, with watt level fiber lasers being produced within a year of Snitzer’s original double clad concept and a 5 W laser based on a square cladding design within five years of the original idea [46-48]. The double clad fiber enabled scaling to 110 W average powers and $\sim$100 $\mu$J peak powers in purely single mode fiber lasers; however, these fibers began experiencing a new set of problems, imposed by unwanted nonlinear effects and fiber damage due to the single mode core design [49, 50]. If power scaling was to continue, further improvement beyond the double clad fiber was required.
1.2.1.4 LMA Fibers Enable Current Power Growth

The first Large Mode Area (LMA) fibers (and in fact the terminology LMA) was introduced in [13, 51, 52]. The desire for larger mode areas was twofold, spurred on by a desire for greater energy storage to improve pulsed laser output energy and also to limit damage to the fiber end facets due to the extremely high, but tightly confined peak powers of Q-switched fiber lasers [50]. These early designs were effective, but rather complicated to manufacture. They involved graded or sectional doping of the fiber core and multi-stepped refractive index profiles to manage the fiber mode and give the lowest order mode preferential gain to allow lasing on a single transverse mode despite the multimode nature of the fiber core [51, 52]. Other designs made the NA so vanishingly small (~0.06) that only the fundamental mode could propagate without large losses with even small bending [13]. Later, simpler LMA designs were enabled by the realization that simply coiling the fiber to a sufficiently tight radius when the core NA is made low enough was sufficient to strip off higher order modes and allow single mode lasing [53]. In addition LMA amplifiers were enabled by using multimode, low NA fiber and properly aligning the input signal light as to only excite the lowest order fiber mode [54]. The combination of these two techniques is the basis for the most common standard LMA fiber applications today, thus enabling CW lasers with 10 kW output power with single mode beam quality and LMA pulsed lasers with 5 MW peak power output [55-57].

1.2.2 History of 2 μm Thulium Doped Fiber Lasers

The thulium fiber laser has roots extending far back into the early history of lasers. Use of thulium as a laser ion dates back nearly to the development of the earliest lasers, the first
reported uses of thulium doped crystals (CaWO₄ and YAG) occurred in the early 1960’s, an era where numerous crystals and dopants were being investigated at an extremely rapid pace [58-61]. Having been proven as a potential laser ion, continued interest in thulium’s emission wavelength in the 1.9 - 2.1 μm range drove further research. The next step towards thulium fiber lasers involved getting thulium into a host which could be used to eventually produce an optical fiber. This step was taken when the first thulium doped silicate glass laser was demonstrated in 1967 [62]. Continued interest in the unique wavelengths thulium could provide sparked continued research into its use in many bulk gain media and laser systems; however, the fiber laser would not be among these laser systems for many years. As outlined in 1.2.1, though the fiber laser had been demonstrated very early on, its attraction as a laser gain medium design did not catch on until the mid 1980s with the production of higher quality fibers, the development of laser diodes capable of being used for pumping and the drive provided by telecommunications. Thus, for more than 20 years from its first demonstration in silicate glass, thulium was never used for fiber lasers, as any fiber work done in the 1970s and early 80s was done mainly in the simpler-to-work-with neodymium ion.

The first thulium fiber laser (and the longest fiber laser wavelengths generated in silica fiber to that point) was reported in 1988, and was pumped with a dye laser at 790 nm, achieving a few 10’s of mW of power [63]. With a resurgence of interest in fiber lasers for applications requiring compact, high power sources with flexible wavelengths, work on thulium fiber lasers began to pick up. Taking advantage of the largest tuning range of any rare earth ion, the first tunable thulium fiber laser was reported in [64] with a tuning range of 1780 nm to 2056 nm. Around the same time, thulium began to also draw attention for the many other emission wavelength bands in both the S-band for telecommunications and in a blue upconversion band
These fibers tend to be implemented in fluoride (ZBLAN) fibers not capable of handling high powers and their spectral emission is outside the 2 μm eye safe regime of concern in this dissertation, so their history will not be discussed further.

The first watt level thulium laser was quickly demonstrated soon after the first thulium fiber laser [68] by simply scaling up pump power at the readily available Nd:YAG pump band of 1064 nm. Though unconventional by current thulium laser standards, this pump scheme did enable the first watt-level lasing, however, the fiber structure was single clad, with direct core pumping. Around this same time the first double clad fiber lasers at other wavelengths were being developed; the subsequent burst in output power in these lasers discussed in 1.2.1.3 coupled with insufficient diode pump powers at 790 nm and the interest in the use of thulium for S-band and blue generation likely left no room for any power scaling aspirations of thulium in the 1990’s. During this time, the first reported mode-locked thulium fiber lasers were also reported [69, 70].

In 1998, when diode pump power began to catch up, the next leap in thulium technology occurred with the demonstration of a 5.4 W double clad laser with direct diode pumping [71]. This laser represents the earliest incarnation of a high power thulium fiber laser scheme that resembles the current state of technology; however, with slope efficiency only in the range of 30-35%, high power operation could still not be achieved. A final advancement was required to bring thulium fiber lasers to the highest power levels they are currently capable of, the implementation of high doping concentrations and the use of the cross relaxation process to enhance operating efficiencies. Cross relaxation in thulium is a long understood process, known to exist in thulium doped crystals [72], (the theory behind this process is covered in 2.3.3.1). The basic idea is that two laser photons can be produced from a single pump photon, thus leading to
twice the potential slope efficiency compared to the quantum defect. This effect is first noticed in thulium fibers in [73] when slope efficiency was found to be around 46% (greater than the quantum defect) in the highly doped thulium fiber used in the experiment which achieved 12 W of output power. The ability to dope thulium in high concentrations was realized by the inclusion of aluminum in the glass doping formula to reduce clustering and enhance the desirable cross relaxation process in thulium fiber lasers, which was further studied by Jackson in [74, 75]. The new understanding brought on by such investigations and the increase in available diode power lead to the rapid advance in output power in thulium fiber lasers from 12 W in the year 2000 to the near kW levels currently achievable [76]. In nearly every case of high reported output powers from thulium in this period, the lasers were based on thulium doped silica fibers with the exception of a 75 W Yb:Tm co-doped fiber laser and a 100 W germinate fiber laser [77, 78].

The increased interest in thulium fiber lasers since the mid 2000s has lead to the development of higher power pump diodes and improvements in fiber composition to better enable cross relaxation. As these advances rapidly became available thulium output powers and efficiencies began the period of extremely rapid increase (discussed in section 1.2.3) where the growth of thulium fiber laser output powers is plotted. In the same period of rapid growth, the greater interest in thulium has also begun to spawn research into applications of lasers beyond simple power scaling with emphasis on pulsed operation and spectral control which are the regimes that are the main theme of this dissertation.

1.2.3 Comparison of Yb and Tm Doped Fiber Laser Growth

From its humble roots as a flashlamp pumped quasi-laser-rod in the early days of laser development, [24-26] through the 1970s and 80s where the technology was largely ignored with
power levels only reaching the watt level in 1988 [45], the explosion in growth in fiber laser output power and efficiency seen in the last decade may not have been expected. As the level of fiber laser technology progresses and achievable output powers, efficiencies, pulse durations, beam qualities and linewidths are optimized, fiber lasers are entering a realm where they can compete directly with gas and bulk lasers in many applications.

Yb based fiber lasers represent the largest and most technologically mature category of fiber lasers currently used. Due to their low quantum defect associated with 1.01 - 1.1 \( \mu \text{m} \) lasing and pump wavelengths in the 915-976 nm range which are readily available, these lasers have been the number one candidate for power scaling of fiber lasers. Components in this range are readily available, which, coupled with the readily available laser diode pump power, made Yb fiber lasers simpler to implement in high power systems than any other fiber dopant family. As a consequence, most of the enabling techniques, including LMA fibers, for overcoming power scaling challenges were developed in Yb first. Chapter 2 details what these power scaling challenges are and the numerous techniques developed to meet each of the challenges. Techniques for overcoming many of these challenges are currently becoming mature and are continuing to be strongly developed for fiber lasers based on ytterbium doping. The power levels ytterbium based lasers are able to achieve makes them increasingly viable as replacements for solid state and gas lasers.

Achievable output powers from a single aperture, single mode ytterbium doped fiber has grown dramatically in the last twelve years from watt level to nearly 10 kW level, shown in Figure 3 [49, 55, 79-91]. In addition, upwards of 50 kW is achievable from fiber lasers with slightly multimode behavior but still reasonable beam quality [92].
Pulsed laser output energies in ytterbium have grown nearly as quickly with energies from a single fiber or combined systems reaching into the multi-mJ regime with hundreds of watts of output power [91, 93, 94].

Despite their high power achievements, Yb fiber lasers cannot be used when eye-safe ($\lambda > 1.4$ $\mu$m) wavelengths are required. As a result, several other wavelength regimes are being investigated. Development of telecommunications technologies have enabled fiber laser technology in the 1.5 $\mu$m wavelength regime to also grow rapidly, however there are limitations to the erbium-ytterbium doping system due to ASE associated with the Yb co-doping required for reaching high powers due to the lack of high power pump sources for direct Er pumping [95]. Consequently, power scaling in the longer wavelength eye-safe regime is leaning towards the use of the thulium ion [1, 3, 96, 97]. The increase in CW output power of thulium based fiber lasers over the last twelve years is shown in Figure 4 [77, 96-104].
Figure 4: Increase in reported maximum output power of CW thulium fiber lasers in the past twelve years for 1550 nm or 790 nm pumping technologies. Note that the highest, near kW power was from slightly multimode beam and was the total of two outputs; the highest reported near diffraction limited beam quality from a single aperture is 608 W [77, 96-104].

Via comparison with Figure 3 (which shows the growth in ytterbium fiber lasers) the growth in thulium fiber lasers, though occurring approximately two years later, is progressing along a similar power scaling trend-line. The reason for this similar trend in thulium is a combination of the contribution from improved and rapidly increasing power from high brightness fiber coupled diodes in the 790 nm pump region [105, 106], as well as the increased interest (and hence funding) for eye-safe lasers in general.

The achievements of ytterbium fiber lasers, serving as proof that fiber lasers are capable of multi kW level operation, have spurred the rapid growth of thulium fiber laser technology. Many problems associated with power scaling were already solved by work with ytterbium fiber lasers, thus leaving an easier path for the rapid increase in thulium fiber laser output powers. This is evidenced in the more rapid growth rate of thulium fiber lasers from 100 W to 1 kW output powers. To make this order of magnitude increase in power took Yb lasers more than five years; the same increase in Tm output powers occurred in less than three years. Thulium fiber lasers do face challenges specific to its operating wavelength and somewhat lower operating efficiency (some of which are addressed by this dissertation); however, with continuing research it is likely
that thulium fiber lasers will continue this rapid growth trend and perhaps catch Yb fiber lasers in terms of output power. It is possible that thulium may pass ytterbium as the high power fiber laser medium of choice due to inherent advantages of thulium associated with its longer wavelength, leading to higher damage and nonlinear thresholds [12].

1.3 Applications of Thulium Fiber Lasers

Many applications for fiber lasers, including most materials processing applications, call for raw power and do not require specific wavelengths or spectral constraints to be effective. These applications fall into the realm of the most efficient, robust and cheapest technology, which, in the current market is the ytterbium fiber laser [92]. This preference stems mainly from the low cost of the 915-976 nm pump diodes required for pumping and the low quantum defect of the ytterbium laser scheme [92]. Thulium lasers simply cannot compete in terms of cost with such systems.

More demanding and complex applications call for laser operation in a specific spectral region which, in many cases, can be most effectively provided by thulium doping. As noted in the previous section, power scaling of thulium fiber lasers continues to increase. This increase in average powers brings thulium fiber lasers to a level where they have the potential to be valuable for a number of applications which can find use for thulium’s over 300 nm potential lasing bandwidth (well below 1.8 μm to beyond 2.1 μm). This dissertation covers the development of such fiber lasers with regards to improvements to temporal and spectral control of thulium lasers at average high powers. In order to best understand the needs of more advanced thulium fiber lasers systems it is critical to understand the applications that will benefit from their implementation.
1.3.1 Eye-safe Atmospheric Applications

Because of defense and other atmospheric propagation based applications, there is a need for high average power sources with so called eye-safe operating wavelengths. This safety is important not only in situations where the laser has the potential to directly shine into a person’s eyes, but also when sufficiently high power radiation scatters off a target [107]. At sufficient power levels even this scattered radiation can cause damage. Eye-safety is defined as any wavelength longer than 1.4 $\mu$m [107]. The reasoning for this definition is that beyond 1.4 $\mu$m, the majority of any laser radiation incident on the eye is absorbed in the aqueous humor, lens or cornea before it can reach the retina [107]. Since retinal damage is the main cause for irreversible vision loss, lasers which operate in a regime where the retina is protected for high powers are considered “eye-safe”. A better term for these lasers might be “retina-safe” since even lasers in the so called eye-safe regime can do significant thermal damage to other parts of the eye. However, to keep with the terminology used in most literature, “eye-safe” will be the term of choice.

Applications such as free space communications, remote sensing, LIDAR, standoff chemical detection and directed energy systems all involve propagation through the atmosphere. In order to maximize range or effect, high power laser light must be used, often with short pulses, meaning high peak powers as well as high average powers. Consequently, use of lasers in such applications pose a risk for human exposure to direct high power beams or, equally as importantly, backscattered and reflected light from a target. In conjunction with high power, these applications often require long distance beam propagation which puts requirements on beam quality, precise spectral control and output power or pulse energy.
1.3.1.1 Atmospheric Propagation for Directed Energy

There is a great interest in high power lasers for propagation through the atmosphere in directed energy applications. Interest is especially high in the defense field for such tasks as missile and other ordinance defense systems and stand-off improvised explosive device detonation [108-111]. In order to meet demands, these lasers must be in the kilowatt to hundred kilowatt class. Currently many these technologies are based on 1 μm lasers. However in order to make them safer for eventual application, they will need to be developed at eye-safe wavelengths to protect those around them from scattered power, as at the kilowatt level even stray light can have damaging power levels. Thulium fiber lasers may have a niche here as they are eye-safe and also have advantages in power scaling compared to other fiber lasers as is further discussed herein and as has been discussed in [12].

Propagation of high power laser radiation through the atmosphere can lead to many linear and nonlinear problems with achieving a sufficient amount of laser energy on target [112-117]. Nevertheless, the use of thulium lasers may give advantages in terms of being sufficiently tunable to avoid the worst atmospheric absorption regions and thus mitigate some of the loss effects [118]. This tunability could be extended to active tunability where the laser could be adjusted to account for day-to-day or location-to-location variations in atmospheric transmission. In addition, reducing atmospheric and particulate absorption in the atmosphere may help to mitigate thermal blooming effects that can limit the propagation of high quality atmospheric beams [112-117]. Some of the nonlinear effects that might occur in this propagation may also be mitigated by the longer laser wavelength. Power scaling by beam combination, especially spectral beam combination may also be beneficial for thulium fiber lasers due to their large
bandwidth, and therefore ability to pack a large number of channels as discussed later in this dissertation and in [119].

1.3.1.2 Free Space Communication

Free space communication with lasers is of interest due to its direct line of sight and well confined beam. Communication is possible at high speeds associated with conventional “in-fiber” telecommunications without the need for the fibers and without concern for radio interference [118]. Strategically, the direct line of sight may seem like a disadvantage compared to radio where line of sight is not necessary; however, in defense applications there are inherent advantages in knowing exactly where the information is being beamed and enabling the only potential receiver to be the target receiver [118, 120]. It is extremely difficult to tap direct line-of-sight laser communications without the receiver knowing that information is being tapped, thus resulting in a more secure channel. In addition, the use of thulium wavelengths may be an advantage, as it lies outside of traditional communications wavelengths in the 1.5 μm regime, thus making detection more difficult for outsiders [118, 120]. There are atmospheric windows readily available for transmission of these types of communications through the atmosphere around thulium wavelengths and again, the tunability of thulium enables optimization of transmission in different environmental conditions [118, 120].

1.3.1.3 Remote Sensing

Remote sensing applications such as laser radar (LIDAR) in the 2 μm spectral region are of interest due to the eye-safety of the wavelength region, the ability of the light to be propagated
through the atmosphere and also its ability to hit the absorption resonances of several gasses in the atmosphere including water vapor and carbon dioxide [121, 122]. One application of particular interest is wind sensing LIDAR which benefits particularly from the thulium laser wavelengths [121, 122]. The tuning range of thulium within atmospheric transmission windows enables differential absorption studies or optimization of laser signal based on selecting optimal transmission wavelengths [121, 122]. Though based on thulium, most of the work done in this field is done in thulium bulk lasers based on Tm:YAG because of the need for higher pulse energies than current fiber lasers can provide [121, 122]. However, with the development of ever larger mode area fiber lasers with extremely high beam quality, compact size and portability, these lasers may find their way into the remote sensing field as replacements for current Tm:YAG systems. In addition, even for current applications which are beyond the reach of thulium fiber in terms of pulse energy, thulium fiber lasers may be used as low quantum defect pump sources for Tm or Ho:YAG lasers used for atmospheric measurement, as such fiber laser pumped systems may exhibit better efficiency and lower thermal beam distortion, enabling improved LIDAR performance.

1.3.1.4 Laser Induced Breakdown Spectroscopy

Laser induced breakdown spectroscopy (LIBS) is a technique for detection and identification of chemical species by hitting the desired target with intense laser radiation, causing a plasma to form [123]. Depending on the properties of the materials that are forming the plasma, the light emitted from the plasma will have a distinctive spectrum based on the ionized species within the small amount of material ablated from the sample [123]. Detection of the plasma emission with appropriate optics and spectrometers and subsequent analysis of the
spectra enables identification of the chemical constituents of the target [123]. The small laser plasma formed when doing the analysis does not do significant damage to the material, therefore the technique is minimally destructive. Almost any material can be analyzed using LIBS if the laser source has sufficient power and the detection can be done either close to the sample or from a long distance by use of appropriate telescopes. The “stand-off” methods have numerous applications where long distance detection of hazardous materials such as biological agents or explosives may be desired.

Typically lasers in the 1 μm regime are used for this technology, as sufficient laser pulse energies are readily available. However, there are potentially benefits to choosing the spectrum of the laser used to match the materials desired to be detected [124]. Use of thulium fiber lasers with their longer wavelength which is readily absorbed by water and other organic materials, may enable enhanced LIBS detection with either lower laser power or enhanced sensitivity for medical applications such as “in vivo” analysis of tissues or other biological material identification [124]. In addition, the fiber laser platform provides a system which can be compact, robust and portable for field applications such as detection and identification of potentially dangerous biological agents [124]. The high beam quality of the fiber laser platform and the ability of thulium to hit atmospheric transmission windows, while remaining at eye safe wavelengths also makes the laser an attractive source for “stand-off” LIBS [124]. Development of thulium fiber lasers with sufficient pulse energy and capability is only recently coming online and the first thulium fiber laser based LIBS measurements have only recently been demonstrated [124]. With further improvement of thulium fiber laser pulse energies, the potential for their use in LIBS will increase.
1.3.2 Medical Applications

In addition to applications which generally fall into the eye-safe regime, there are also applications which specifically call for wavelengths around 2 µm. Medical applications where particular biological absorption resonances must be hit (or avoided) to optimize a particular procedure are one large area requiring spectrally controlled thulium fiber lasers. The 1.94 µm wavelength regime is a useful wavelength for enabling large amounts light absorption in tissue and hence cleaner, faster cuts with reduction of bleeding [125, 126]. A large amount of research is currently being conducted in the field of urology where Ho:YAG lasers are the current laser source of choice for applications such as tissue cutting and prostate ablation [125, 126]. Studies are being conducted to prove the usefulness of the thulium fiber laser to allow the beginning of clinical trials. The thulium fiber laser is a useful replacement for older Ho:YAG technology because it can be run CW as well as pulsed, which is critical for some applications. In addition, the beam quality and laser efficiency are significantly higher in more compact packages and have superior beam quality [125, 126]. Other urological applications including laser lithotripsy, or fragmentation of urinary and kidney stones, are becoming interesting for similar reasons; thulium fiber lasers have superior beam quality compared to Ho:YAG lasers, and thus can be launched into smaller fibers, enabling less invasive surgery and more flexible delivery fibers and have the potential to operate in the 19xx nm regime where water absorption enables more effective ablation [127, 128].

There are still improvements required for such lasers in terms of the length of pulses (hundreds of microseconds) that are required at relatively low repetition rates, but these challenges can be overcome. Other medical applications are also on the horizon, as many laser scalpel applications for CW thulium YAG lasers have been reported [129, 130] and thulium fiber
lasers operating at similar or higher powers in a broader potential range of wavelengths should be superior to Tm:YAG in terms of cost and reliability. Highly tunable thulium lasers have also been used for laser welding of urinary tissues with success [131]. The ability to scan to different wavelengths is another potential advantage of the thulium laser over the limited tunability Ho:YAG based counterparts.

As thulium lasers prove themselves for medical applications over conventional surgical alternatives [132] or over Ho:YAG lasers, numerous new medical applications requiring power scaled thulium lasers in the hundreds of watt range will continue to arise. Such applications will have steep demands on spectral control to target particular molecules within the thulium bandwidth such as hemoglobin, melanin or water. Tuning of the amount of absorption in tissue for cutting or welding by actively changing the spectrum of a single laser unit may be required. Applications will also demand compact, portable, cost effective systems with minimal requirements for infrastructure such as external water cooling [133].

1.3.3 Materials Processing

Laser processing of materials is a well known application for all types of lasers from kilowatt class cutting and welding lasers to watt level marking and printing lasers. Lasers with pulse durations from CW down to femtoseconds can be used to do such diverse things as cut inch thick steel plate for shipbuilding to inducing small refractive index changes in a non-destructive manner in glasses to form waveguides. Depending on the particular application, the laser wavelength may or may not matter.

Some materials are more effectively processed in the 2 μm wavelength band due to the presence of absorption resonances which enable more efficient processing with lower laser
powers. Materials that are advantageous for thulium laser processing may include biological or other organic materials with significant water content, as well as plastics and glasses that are not transparent in thulium’s spectral region. Properly selecting the wavelength of a thulium fiber laser to take advantage of these resonances will give the system an advantage over a laser at a shorter wavelength.

On the opposite end of the processing spectrum, there are applications where material absorptions need to be avoided, for instance laser writing of waveguides in the volume of a material via nonlinear processes [134]. Some materials, such as many semiconductors and some mid-IR glasses, which are of interest for waveguide writing and other “inside-material” processing, may not be transparent at wavelengths of other traditional laser wavelengths used for such applications such as the 800 nm Ti:sapphire laser. As a consequence, development of ultrashort pulse thulium fiber laser systems may enable processing of materials that could not be processed before. This regime requires both the spectral control to be sure the material is transparent and the temporal control to produce pulses of sufficiently short duration to allow high peak powers without thermal effects associated with long pulses. The USP laser systems discussed later in this dissertation will help to fill the needs of these materials processing applications without the need for use of more complicated and expensive OPO based laser systems driven by Ti:sapphire lasers currently used to produce pulses in this wavelength region.

1.3.4 Frequency Conversion

Frequency conversion via nonlinear processes represents an additional potential application regime for thulium. Short wavelengths not achievable by frequency conversion or direct lasing in other types of fiber lasers, for instance those from 900 -1000 nm (difficult to
achieve in Yb or Nd lasers at high powers), are accessible by frequency doubling of Tm lasers. Such wavelengths are of interest, requiring high power and high beam quality, for applications in the medical and defense fields [135]. Further utility via short wavelength conversion can be achieved by tripling or quadrupling Tm laser output to reach red and blue wavelengths, respectively, which may not be accessible in other laser types. Such wavelengths are also of interest for medical applications and blue is especially interesting for defense related underwater communications applications due to the low absorption of water in the blue region of the spectrum. All of these nonlinear processes can be achieved in standard, readily available nonlinear optical materials such as periodically polled lithium niobate (PPLN) or beta barium borate (BBO) among many others well known for 1 \( \mu \text{m} \) uses.

Thulium is also suitable for conversion to longer wavelengths in the mid-IR (especially 3-5 \( \mu \text{m} \) which is useful for communications and countermeasures applications [118, 136]) and potentially for THz generation. The longer wavelength gives it an advantage in efficiency over systems pumped by Yb based lasers and the greater than 300 nm lasing allows for a large potential tuning range. Generation of supercontinuum in materials such as ZBLAN fibers with transmission out to 4.5 microns or chalchogenide fibers with even larger transmission ranges may be done more efficiently with a larger amount of mid-IR based on thulium fibers, as they are easier to power scale to desired levels (10’s to 100’s of watts) than Er:Yb fiber lasers currently used to produce such supercontinua [137, 138].

In the opposite direction of mid-IR generation is high harmonic generation (HHG) where high energy ultrashort pulses are used to produce extremely short wavelengths and ultrashort pulses in the attosecond regime. In many cases, lasers around 2 \( \mu \text{m} \) wavelength may be advantageous for such applications, as they enable shorter wavelengths to be created. The energy
of photons achievable in HHG processes scales up with the square of the wavelength [139, 140]. Thulium based fiber lasers, though not necessarily achieving the pulse durations or power levels required for direct HHG generation can play a role in the pre-amplification and perhaps even to some extent power amplification of the 2 µm pulses used to achieve HHG, as thulium fiber amplifiers can have sufficient bandwidth (>300 nm) to support the short pulse durations required for HHG and bring pulse energies up at very high average powers.

1.3.5 Other Potential Applications

Thulium fiber lasers can also achieve critical pump wavelengths for Ho:YAG bulk crystal systems and other Ho based lasers with pump bands around 1908 nm or 1940 nm. Such bulk lasers are able to achieve the extremely high (>10 mJ) level pulse energies that are currently not within fiber laser capabilities [141]. The low quantum defect, high spectral brightness, high average power pumping that can be provided by thulium fiber lasers enables efficient scaling of such Ho based amplifiers to ever higher average powers with pulse energies greater than the current capabilities of fiber lasers. These hybrid fiber-pumped bulk crystal systems can bridge gaps between conventional solid state lasers and traditional fiber lasers [3].

As will be discussed in 5.3, thulium fiber lasers also have great potential as ultrashort pulse sources owing to their large bandwidth and hence ability to potentially generate extremely short pulses. Because of the benefits of higher nonlinear thresholds due to longer laser wavelengths, the potential for better energy scaling also exists. Use of more exotic glasses may also help thulium ultrashort pulse fiber lasers, as materials other than silica can have their dispersions be designed to be near zero at thulium wavelengths, thus enhancing pulse generation
capabilities. Such high average power ultrashort pulse lasers may then open other applications further in the areas of defense, materials processing and nonlinear optics.

Ultra-broadband sources in the 2 µm wavelength regime with CW output powers based on thulium amplified spontaneous emission (ASE) sources are of interest for many applications as well, including for use in sensing gasses [142] and in medical applications such as OCT (optical coherence tomography) [143]. The development of such sources with ever higher average output powers and broader bandwidths will also open further channels of uses for thulium fiber ASE systems, including in the defense related fields [144]. Power scaling has reached the 10 W level, but further scaling is still of interest for numerous applications [144].

1.3.6 Applications Summary

As is evidenced from the contents of this section, applications of thulium doped fiber lasers are already widespread, and have the potential to expand with further development of the technology. Thulium lasers have impacts in almost every field that a laser might find an application, as its uniquely broad tuning range enables it to be used for applications where absorption features must be missed or hit and for applications requiring broad spectra. The fiber format also enables the scaling to extremely high average powers, which is the driving factor behind an increasing number of applications.

1.4 Dissertation Theme

Meeting the increasing demands put forth by the applications listed in the previous section requires more than raw laser power. In order to make thulium fiber lasers work at their
maximum potential, this high average power must be delivered with controls tailored to a specific application. Some applications require power to be delivered in a spectrally narrow window which may also need to be tunable to accommodate day to day changes. Others need the laser to operate in extremely short pulses, but not with extreme spectral control; the most demanding systems require both spectral and temporal control.

The vast extent of work done on high power thulium fiber lasers to date has concentrated on scaling average power with other considerations which make the lasers useful for applications as only secondary concerns. The central theme of this dissertation is to move thulium fiber laser technology beyond power scaling and into the realm of lasers that can be useful for applications which demand spectral and temporal control by applying novel laser design concepts to high power thulium fiber laser systems.

1.5 Overview of Dissertation Contents

In the following chapters several main categories are covered. Chapter 2 is a discussion of the limitations and difficulties found with fiber lasers when trying to scale to high average power in any temporal or spectral regime. This includes information on past research that has lead fiber lasers to where they are today and also discusses future technologies in terms of fiber designs leading to improved fiber laser performance. In addition, this chapter covers the reasoning for the selection of thulium as the gain medium of choice for power scaling in the eye-safe regime. Chapter 3 is a discussion of a concept for scaling the mode field diameters of fiber lasers based on the new and novel Gain Guiding Index Anti-guiding (GGIAG) technique which, when mature, will allow scaling of fiber laser mode field diameters to extreme sizes, enabling higher power operation. Work related to high average power spectrally controlled thulium fiber
lasers in the CW operating regime is then discussed in Chapter 4, including results on two
different high power experimental systems using different spectral control concepts. A numerical
model of thulium fiber amplifiers which can be applied to CW systems to predict performance is
also demonstrated in this section. Temporally controlled thulium fiber lasers in both nanosecond
and picosecond pulse regimes and their power scaling are the subject of Chapter 5. Chapter 6
covers the use of spectrally controlled fiber laser systems in demonstrations of potential
applications, including a demonstration of spectral beam combining. The chapter also includes
further pulsed laser application demonstrations in the field of frequency conversion. Finally,
Chapter 7 concludes the dissertation and gives insight into the future directions that high power
thulium fiber laser systems may take and what the full potential of the technology may be.
2 POWER SCALING ISSUES AND FIBER DESIGN SOLUTIONS

The current status of thulium fiber laser technology is such that there is a need for scaling of laser power levels in the CW and pulsed regime beyond the hundred watt level, towards kilowatt powers and beyond, as well as scaling pulse energies towards the mJ level to suit the needs of many applications. This chapter outlines obstacles in the way of achieving power scaling, including nonlinear mechanisms and fiber damage mechanisms. As laid out in [12], there are also limitations in pump coupling in terms of potential available diode brightness. However, this is not considered for this dissertation, as thulium laser pump technology has not reached its potential, and appropriate development can lead to significantly higher potential coupled pump powers than currently available. Subsequently, techniques for limiting such issues are discussed in terms of fiber design and thermal management. Finally, the potential benefits of power scaling thulium fiber lasers when eye-safe wavelengths are required are considered and the specifics of achieving power scaling are discussed.

2.1 Factors Limiting Power Scaling

The limitations to power scaling of fiber lasers in the CW and pulsed regimes lie in two regimes which can both come into play depending on system parameters. Various nonlinear optical limitations and optical damage depend on peak power or intensity levels while thermal damage regimes depends, in most cases, on average power effects. The following sections briefly
outline the origins of and limitations imposed by these effects and comments on the potential advantages of the use of thulium wavelengths in each regime.

2.1.1 Nonlinear Optical Based Limitations

Nonlinear optics can be extremely useful when used in controlled situations to achieve desired effects in terms of applications such as wavelength conversion and spectral broadening leading to pulse length reductions. However, in the context of high power fiber laser and amplifier systems, these nonlinear effects are often unwanted, leading to degradation in pulse quality, shift in wavelength outside the desired band, loss in forward output power and unwanted spectral broadening. As a consequence, much of the effort in power scaling fiber lasers goes towards methods for mitigation of these effects. It is important to understand the effects as potential limiting factors for further power scaling, and to understand potential advantages of working with the thulium ion.

2.1.1.1 Stimulated Raman Scattering

Raman scattering is caused by interaction between a photon incident on a molecular material and the vibrational modes of that material. The incident photon can excite a vibrational state of a molecule, thus losing energy and shifting to a longer wavelength (Stokes process) which is the more favorable process, as typically a molecule has a higher probability of being in a ground state, rather than an excited state. A photon can also take energy from an already excited molecular vibration, resulting in a more energetic and hence shorter wavelength photon (anti-Stokes process). In either case at its simplest, this process is known as spontaneous Raman
scattering and is extremely weak, with only $\sim 10^{-6}$ of any incident power being scattered \[145, 146\]. However, when a material is subjected to high intensity laser radiation, Raman scattering can also take another form, known as stimulated Raman scattering (SRS) which can be a nonlinear process that transfers large portions of the incident laser energy to the Stokes (and anti-Stokes, but at significantly lower efficiencies) \[145, 146\]. As a consequence, this effect can limit the potential output power of a fiber laser, if the laser reaches a critical power level where SRS begins to draw energy away from the desired operating wavelength and put it into Raman shifted bands. Such bands in silica fibers are $\sim 13$ THz shifts in frequency at 1 $\mu$m corresponding to $\sim 40$ nm wavelength shifts (the same 13 THz shift at 2 $\mu$m corresponds to a $\sim 170$ nm spectral shift) \[145\]. As power increases beyond this threshold, what are known as second, third, fourth and beyond Stokes shifts can be excited, cascading the spectrum longer and longer in wavelength. Anti-stokes processes also come into play as power increases. Regardless of shift direction, all of the effects transfer energy away from the desired wavelengths, in most cases even outside of the amplification band of the fiber and especially in the case of thulium, beyond the transparency window of the fiber itself.

Usually fiber laser design attempts to stop these shifts before they occur, by designing the fiber such that the system remains below the critical power for the onset of Raman gain. This expression, which is derived from basic nonlinear optical principles and analysis of the equations for the nonlinear growth with propagation of the Raman signal in the presence of a material with Raman gain and a pump, is derived in \[145\] and altered by \[12\] to account for fiber lasers and amplifiers with gain, rather than in passive fibers. The equation takes the approximate form of

$$p_{SRS}^{\text{max}} \approx \frac{16A_{\text{eff}}}{g_{R}L_{\text{eff}}}$$

(1)
where $g_R$ is the Raman gain coefficient ($\sim 10^{-13}$ in silica glass at 1 $\mu$m, but scaling proportionally to $1/\lambda$), $A_{\text{eff}}$ is the effective mode area based on the mode field diameter of the optical fiber mode, $L_{\text{eff}}$ is an effective length given by

$$L_{\text{eff}} = \frac{1}{g} (e^{aL} - 1)$$

(2)

where $g$ is the gain of the fiber in the saturated regime and $L$ is the length of the fiber. It is also important to note that the factor of 16 in (1) is not “set in stone” as discussed in [12], since it actually is dependent on the input power of the laser. However it is a logarithmically dependent factor and thus only increases to $\sim 25$ for power levels of 1 kW. In addition, there is a factor of two not included which would be included to account for the effects of random polarization [12]. It is also important to note that because $g$ is used in the effective length rather than loss, the dominant direction of SRS is actually counter-propagating with the laser signal, which is the opposite of the case for passive fibers [12]. Since $g$, the saturated gain coefficient, is simply the natural log of $G$, (where $G$ is the actual gain of the fiber amplifier, i.e. how many times larger the signal is) divided by the fiber length, for large gains where $G >> 1$, equation (1) can be approximated by

$$p_{\text{SRS}}^{\text{max}} \approx \frac{16A_{\text{eff}}}{g_R L} \ln (G)$$

(3)

as suggested in [12]. At the CW power levels used in this work, the threshold does not come into play, as it is on the order of a kW of power at 1 $\mu$m and thus even higher at 2 $\mu$m. However this
threshold is also valid for the pulsed regime and thus for the high peak powers which are easily reached even at modest pulse energies in the pulses regime [145].

The presented analysis is valid for CW lasers, and also in the pulsed regime until pulses become shorter than 1 ns, when the effect of walk-off between the laser signal and the Raman pulses becomes significant. Walk-off in fibers is caused by the pulses of two different wavelengths (Stokes and signal) generated traveling at different speeds in the fiber due to dispersion, thus separating spatially over propagation down the fiber; no spatial overlap means no nonlinear effect [145]. This is usually characterized by a walk-off length

\[ L_W = \frac{\tau_{pulse}}{v_{signal}^{-1} - v_{Raman}^{-1}} \]

where \( \tau_{pulse} \) is the pulse duration and \( v \) is the velocity of the pulse in the fiber as determined by dispersion relations at the two different wavelengths [145]. For picosecond duration pulses, the walk-off length can be on the order of one meter or less, a length shorter than most fiber amplifiers, and thus as walk-off occurs, other nonlinear effects will begin to dominate as discussed later. In terms of nonlinear effects, SRS is the limiting factor for fiber lasers operating in the CW and pulsed regime, provided that the pulses are \( \sim 1 \text{ ns} \) in duration [12, 145].

It is also relatively easily seen from (3) that thulium fiber lasers enable an increase in SRS threshold from a number of directions. They can achieve larger effective areas, while still maintaining beam quality. In addition, thulium fiber amplifiers tend to be shorter in length than other gain media (at least a factor of 2 shorter), as high dopant concentrations are critical for efficient cross relaxation and thus efficient laser operation. Finally, the SRS gain coefficient \( g_B \) can be reduced for longer wavelengths, again increasing the threshold for the onset of SRS.
However, $g_B$ can also be strongly affected by a number of other properties, including fiber composition, so this benefit may be lost as composition and design in other parameters influencing SRS change from fiber to fiber [145]. Overall, thulium fiber lasers still have clear benefit for power scaling and peak power scaling, as will be evidenced by experimental performance of pulsed lasers described later.

2.1.1.2 Stimulated Brillouin Scattering

Stimulated Brillouin Scattering (SBS) is a similar effect to SRS in terms of its analysis and effects on high power laser light in a fiber. However, it differs in its physical origins, and hence in the exact manner it interacts with light. The physical phenomenon at the root of SBS is electrostriction, the change in the shape (and therefore density) of a material with an applied electric field [145, 146]. In this case, the electric field is a consequence of the light wave interacting with the material, periodically changing its shape via electrostriction and hence creating an acoustic wave in the material which, according to the acousto-optic effect, then modulates the refractive index in the material. This creates a Bragg-grating-like structure with the periodicity of the acoustic wave, which essentially reflects any incident light, while inducing a small frequency shift based on the Doppler effect [145, 146]. Alternatively, from a quantum perspective, SBS is caused by the process of an acoustic phonon and the SBS shifted photon being generated from the breakup of an incident laser photon [145, 146].

Laser signal light incident on the created Bragg grating structure is scattered in a multidirectional pattern that vanishes in the forward direction, and since in a fiber light can only really travel in two directions (forward and backwards) the grating induces SBS only in the backward direction [145].
Unlike in SRS, where the frequency shift is on the order of THz, the frequency shift of SBS is quite small, only ~10’s of GHz based on the fiber mode index and acoustic velocity in glass as given by

\[ \nu_{SBS} = \frac{2n_{laser}v_{acoustic}}{\lambda_{laser}} \]  

(5)

where \( n_{laser} \) is the laser wavelength refractive index, \( v_{acoustic} \) is the acoustic velocity in the material, and \( \lambda_{laser} \) is the laser wavelength [145]. Also like SRS, SBS onset occurs at a particular threshold power, obtained in a similar fashion as that for SRS, which is given by

\[ p_{SBS}^{max} \approx \frac{17A_{eff}}{g_{B}L} \ln (G) \]  

(6)

where \( g_{B} \) is the Brillouin gain coefficient, and the rest of the parameters are as defined and derived in 2.1.1.1 and with approximations discussed in [12]. Again, as with SRS, the factor of 17 in the above equation is not set in stone and can vary with seed input power and be as large as 26. However inaccuracies in measurement of and changes in \( g_{B} \) based on different fiber parameters make this small difference negligible [12, 145].

The gain coefficient for SBS, \( g_{B} \) can be modeled by a Lorentzian spectrum, and as follows from [145], the peak of this gain is

\[ g_{B,peak} = \frac{16\pi^3\gamma_e^2}{n_{signal}^2\lambda_{signal}^2\rho_0cv_{acoustic}\Delta

B} \]  

(7)

where \( \gamma_e \) is the electrostriction constant of the material, \( \rho_0 \) is the density, \( \Delta_{B} \) is the FWHM of the Brillouin gain spectrum and all other variables are as defined earlier [145]. The SBS gain
spectrum with peak at $g_B$ is also highly sensitive to core composition, uniformity and a number of other environmental and material factors, and as a result is usually measured to know its true magnitude [145]. In silica, this coefficient is usually on the order of $10^{-11}$, which makes it 100 times stronger than SRS gain, and hence, SBS has a much lower onset threshold power, providing that the conditions for its onset are correct [145].

It is important to note, that though it may appear that $g_B$ scales inversely with the square of wavelength, hence putting thulium lasers at a greater advantage, the bandwidth, $\Delta\nu_B$, also scales approximately inversely with the square of the wavelength, effectively canceling out the advantage of thulium in terms of possible having lower Brillouin gain [145]. However, as discussed in [145, 147], the narrower SBS linewidth inherent in thulium fiber systems, which scales inversely with the square of the wavelength actually enhances the effects of SBS mitigation techniques such as application of thermal or stress gradients, modulation of the laser signal to broaden its bandwidth or specialized waveguide designs for acoustic guidance suppression [148-152].

All of the previously mentioned suppression techniques either increase the magnitude of $\Delta\nu_B$, effectively lowering $g_B$ and increasing SBS threshold or increase the linewidth of the amplified laser, which reduces SBS gain by a factor equal to

$$f_{\text{reduction}} = 1 + \frac{\Delta\nu_{\text{laser}}}{\Delta\nu_B}$$  \hspace{1cm} (8)

where $\Delta\nu_{\text{laser}}$ is the linewidth of the laser [145]. Equation (8) also implies that for lasers where the operating linewidth is significantly larger than a typical SBS gain linewidth (on the order of 10’s to 100’s of MHz or in terms of spectral width in wavelength at thulium wavelengths ~0.1-1 pm), the SBS gain is essentially negligible. Thus in the case of most fiber lasers which are not
restricted to single frequency operation, (including any lasers used in this dissertation) SBS does not play much of a role, as SRS thresholds are significantly lower, and hence dominate any potential effects. In addition, if pulse durations are less than the phonon lifetime (in the range of 10’s of ns), SBS has a diminished effect, and completely drops out as pulse durations decrease further [145].

Despite the fact that there is not a lower SBS gain coefficient for thulium, it is still usually at an advantage compared to shorter wavelengths due to easier core expansion to increase effective area and hence raise SBS threshold. Thulium fiber lengths are also inherently shorter due to the need for high doping to achieve cross relaxation (discussed later in this chapter) and the somewhat higher thermal loading resulting from the short length, leading to thermal gradients which contribute to SBS suppression [145, 147].

2.1.1.3 Other Nonlinear Effects

SRS and SBS are the two dominating effects for CW and as short as nanosecond duration pulsed fiber lasers and those operating at very narrow linewidths; however, in the case of pulses with very short durations and the broad bandwidths associated with them, SRS and SBS begin to diminish in strength and thus other nonlinear effects begin to come into play and begin to interact with or dominate SRS and SBS. Most of these nonlinear effects are related to $\chi^3$ nonlinear optical processes and include effects such as self and cross phase modulation, four wave mixing and self focusing. The main feature that ties these effects together is their dependence on both the nonlinear refractive index $n_2$ and the laser wavelength.

Self Phase Modulation (SPM) is a an intensity sensitive phase shift in a pulse, which leads to a time varying phase on the pulse due to the variation in peak intensity in the pulse at
any given time [145]. Because phase varies in time, the spectrum must also vary in time, which
corresponds to a nonlinear chirp on the frequency spectrum of the pulse. Fourier transforming
back to the frequency domain leads to spectral broadening [145]. In a dispersion free
environment, SPM does not distort pulse shape; however when the broadening and nonlinear
chirp is combined with effects of group velocity dispersion (GVD) in a fiber, the pulse can begin
to break up. This is because temporally, different parts of the pulse have different spectra and,
therefore, travel at different speeds down the fiber, spreading out with propagation distance.
None of these effects are usually wanted in high power amplifier systems (unless
supercontinuum generation is desired, but this is not considered here) and can lead to decrease in
system performance.

When other nonlinear effects such as Cross Phase Modulation and Four Wave Mixing
(XPM and FWM) join with SPM even greater distortions to the pulse can occur, including
generation of frequency shifted sidebands in FWM processes that act similarly to the Stokes and
anti-Stokes shifts seen in SRS [145]. Though SRS dominates in fiber amplifiers due to its better
phase matching than FWM, under the correct conditions, FWM can effect laser performance as
well [145].

An important feature of the nonlinear effects previously discussed is that they all depend
on a factor called the nonlinear length, which in turn depends on a factor $\gamma$, given by

$$ L_{NL} = \frac{1}{\gamma P_0} = \frac{2\pi n_2}{\lambda P_0 A_{eff}} $$

(9)

where $P_0$ is the peak power, $\lambda$ is wavelength, and $n_2$ the nonlinear refractive index, with all other
parameters as defined earlier [145]. The inherent advantages of thulium can again be seen in this
equation, as its longer wavelength, ability to create larger effective areas and possibly smaller $n_2$ (since $n_2$ has a frequency dependence as seen in [153], however, little study of $n_2$ at thulium wavelengths has been conducted). These all translate to a smaller $\gamma$ which can be thought of as similar to the gain coefficients of SRS and SBS, and with the smaller $\gamma$ and hence longer nonlinear length, thulium fiber based lasers will be less susceptible to these detrimental nonlinear effects. However, in the pulsed regime there may also be tradeoffs associated with the larger material dispersion at thulium’s operating wavelengths which can actually cause pulse compression and possible damage in amplifiers [145].

Nonlinear self-focusing is an additional process related to $n_2$ which limits the maximum peak power of a fiber laser regardless of its effective area. As light propagates in a medium with a high peak power, the difference in induced nonlinear refractive index across the material causes a lensing effect, and hence forces the intra-fiber beam to contract in diameter; this effect occurs regardless of the nature of the medium including in fibers [146, 154, 155]. A critical power level for the onset of catastrophic self focusing (where the focusing continues unstoppably until material damage) is given in [155] by

$$P_{\text{critical}} = N_\alpha \frac{\lambda^2}{4\pi n_0 n_2}$$  \hspace{1cm} (10)

where most variables are as previously defined and $N_\alpha$ is a numerical constant which is close to 2 which accounts for the shape of the beam, waveguide or fiber structure [155]. In the case of silica glass at 1 $\mu$m, this value is $\sim$4.3 MW [154]. As is noted in (10), there is no dependence on area, so this represents a hard upper bound on peak power in a fiber of given material properties, at a given wavelength, the only way to increase the threshold is to use materials with different
linear and nonlinear refractive indices, which would lead to use of materials not possessing the superior qualities of silica fiber. However, thulium is at an advantage due to its longer wavelength and, therefore, four-times higher threshold for onset of self focusing even in the same silica material. No thulium system has been yet constructed with peak power approaching this level, so the existence of this advantage has not been verified, even though theoretically it exists.

There is even an advantage when operating slightly below the critical self focusing power, because at these powers, the effective mode of the fiber is constricted, and in the absence of gain can actually oscillate, as seen in [154]. These changes in mode diameter can lead to other types of catastrophic damage and onset of other nonlinear effects, but again at thulium wavelengths, these effects are four times lower.

Beyond the effects discussed here, there are numerous other nonlinear effects that can influence the performance of thulium doped fibers lasers and amplifiers, but the general trend is the potential advantage for power scaling of thulium wavelengths over others because of the inherently longer wavelength. Especially in the realm of the $n_2$ related nonlinear effects, there is largely unexplored area waiting, as thulium fiber lasers based on ultrashort pulsed seeds begin to move into the space with higher pulse energies and peak powers.

2.1.2 Thermal and Damage Based Limitations

At extremes in average power and peak power, the limiting factors are the nonlinear effects discussed earlier. However even at modest power levels, thermal and optical damage effects can come into play which can severely limit the performance of thulium fiber lasers. Optically induced damage can limit performance and can cause catastrophic destruction of a
fiber amplifier, even at moderate powers, if sudden misalignment occurs, causing lasing spikes. Thermal effects in the fiber polymer can cause self-destruction of the fiber quickly, even at relatively low absorbed powers if management is not done correctly. Finally, even if the fiber is handled correctly, incorrect choice of bulk optical materials as collimating lenses, intracavity elements or optical isolators can lead to severe degradation of system performance.

2.1.2.1 Optically Induced Damage

Optical damage is perhaps the most dangerous effect in a high power fiber laser or amplifier, as it can often come unexpectedly due to transient laser spikes or come after some other failure begins the process. Smith et al. discuss optical induced damage in fused silica as an multi-photon ionization process whereby the fused silica is ionized (by eight photon absorption in the case of 1064 nm light), forming a plasma, or free electron gas, in the material, and when this reached a critical density damage due to absorption of the laser energy causing melting and fracture occurs [156]. This critical density and the number of photons absorbed for ionization are both functions of wavelength, so there may be some inherent advantage (or disadvantage) to using longer wavelength light, however this has not been studied in the thulium band.

Both surface and bulk optical damage are intensity dependent effects whereby damage occurs if the critical intensity for damage threshold is reached. In a fiber the intensity is given by the peak power divided by the effective area of the mode, so mitigation of damage effects both in bulk and on the surface can be achieved by simply scaling mode field diameter. Dawson suggests that the surface damage limit for a fiber is ~10 W/μm², and that this should be considered a reasonable limit for damage regardless of the pulse duration (or CW operation) [12]. However in [156], it is experimentally shown that depending on the surface preparation method (based on
polishing technique) damage threshold for a surface can be equal to that in bulk and that bulk damage fluence, a function of pulse duration, was 3854 J/cm² for 8 ns pulses and 25.4 J/cm² at 1064 nm, yielding intensities orders of magnitude higher than those suggested by Dawson. This disparity shows the need for further investigation into this area, perhaps with the inclusion of cleaved fiber damage thresholds as well as the different surface polishes. However it is likely that the bulk damage threshold is somewhere between these two ranges, and regardless, its effects should be considered when designing a laser.

Ignoring its mitigation by techniques discussed later can lead to further damage to a fiber, such effects include initiation of fiber fuse effect. This effect is a backward propagating (towards the laser source) front of high temperature damage induced sites where the initial damage point absorbs light. This absorption leads to local heating and continuous chain reaction like propagation of the initial damage site, leaving a trail of damage “bubbles or voids” sometimes along up to meters of fiber [157-159]. Such a result of this effect observed in fibers used as part of this dissertation is seen in Figure 5.

![Figure 5: Images of voids created form the fiber fuse effect at various points along a thulium doped fiber showing the clear potential of its damaging effects](image)

2.1.2.2 Thermal Guidance Effects

Though a fiber may be thought to be completely immune to thermal lensing effects (and compared to a solid state laser they are), at sufficient temperatures associated with high power
levels, a temperature dependant, and nearly parabolic, refractive index profile induced on top of the essentially flat refractive index of the fiber core at standard temperature in the fiber core (due to the thermal profile in the fiber core discussed in subsequent sections) [3]. This either increase in refractive index or decrease in refractive index can cause significant distortion of a fiber mode and can even lead to runaway effects as the mode is constricted in the fiber core (in the case of a positive index step as in silica glass) and begins to reduce its overlap with the pumped and doped core, which reduces laser efficiency, adding more heat and more constriction etc until thermal damage may be reached. According to an analysis in [3], the heat load per unit length when this effect becomes significant can be characterized by

$$\frac{P_{\text{heat}}}{L} \geq \frac{8K_c\lambda^2}{A_{\text{eff}}n_0 \frac{dn}{dT}}$$

(11)

where $P_{\text{heat}}$ is the heat load in the fiber, given by the heat generated and deposited in the fiber core (not necessarily the quantum defect or laser slope efficiency, since other effects like unabsorbed pump can cause reduced laser efficiency and non-radiative effects can provide more heat than quantum defect as discussed in [12]), $K_c$ is the thermal conductivity, $n_0$ is the refractive index of the core, $dn/dT$ is the temperature dependent refractive index change, and the other variables are as defined elsewhere in this work. Several interesting trends are seen in this equation, including that the thermal lensing effect becomes far more significant for fibers with larger effective areas, thus ultra large core diameter techniques such as GGIAG may begin to run into limitations associated with these thermal guidance effects before they can achieve significant improvements in mode area. This thermal effect actually resists the scaling of mode field diameter, and thus becomes a limit to laser power scaling as seen in [12]. Also longer
wavelength fibers have a benefit in terms of reduced effects of thermal lensing, though not by the square of the wavelength as might be initially thought from (11), because this benefit is reduced somewhat by the larger effective area of a thulium fiber laser compared to a shorter wavelength fiber laser in a given fiber design.

In the case of any fiber used in this work, the power threshold for thermal lensing effects is well above the power levels used and even above the power levels achievable based on other limitations. However for a hypothetical ultra large core fiber laser (for instance a gain guiding index anti-guiding or photonic crystal fiber) the limit may be much lower, and since such a laser might need to be on the order of only one meter, its power handling would be somewhat limited by this effect, which may limit such large core fibers for average power scaling, though peak power scaling at lower repetition rates would still be enabled by such fibers, since heat loads are based on average powers.

2.1.2.3 Thermally Induced Mechanical Damage

There are a number of potential effects related to heat deposited in a fiber that can cause mechanical damage. One concern which is common with solid state lasers is thermal fracture of the material as it increases in temperature. There have been many analyses on the causes and nature of thermal fracture and the main equations for determining its onset is summarized in [3, 12], and given as

$$\frac{P_{\text{heat}}}{L} \geq \frac{4\pi R_m}{1 - \frac{d_{\text{core}}^2}{2d_{\text{clad}}^2}}$$

(12)
where most variables are defined as earlier and $R_m$ is the rupture modulus (or thermal shock parameter) of the material (in this case for fused silica it is between 2500 and 4000 W/m depending on the source [3, 12] which is 2-4 times larger than YAG crystal, and in the ballpark, if not higher than sapphire). Doing the calculation, even for the low end of $R_m$, yields on the order of 31 kW of heat load per meter before thermal fracture, so clearly with most fibers being several meters long this parameter does not play a significant role, however it may limit fibers of extremely short lengths (<0.3 m) if they are desired to be pushed to kW levels, especially if such fibers are made from soft glass materials rather than silica (often the case for short fibers with high dopants), which have an order of magnitude lower $R_m$.

Beyond the thermal fracture limit, there are limits associated with direct effects of high temperature in the materials making up the fiber, namely materials reaching melting points or thermal degradation points. Looking at an optical fiber, the two most likely candidates for these effects are firstly, the core temperature reaching a melting point, since this is where the majority of heat is deposited, and secondly, the polymer layer since it has a significantly lower thermal damage temperature than nearly any type of glass. Using equations on analyses from [3, 9, 12, 147], among the numerous papers outlining fiber laser, and laser thermal effects in general, solutions to the heat equation under the assumption of a uniform thermal bath with some heat transfer coefficient and circular symmetry and a parabolic thermal load profile in the core, can be written as

$$T(x, r) = T_0 + \frac{Q(x)}{4\pi} \begin{cases} - \frac{2\ln \left( \frac{r_{\text{core}}}{r_{\text{coat}}} \right)}{K_{c, \text{core}}} - \frac{2\ln \left( \frac{r_{\text{cell}}}{r_{\text{coat}}} \right)}{K_{c, \text{glass}}} + \frac{1 - \left( \frac{r}{r_{\text{cell}}} \right)^2}{2} + \frac{2}{r_{\text{cell}} H_1}, & r \leq r_{\text{cell}} \\ - \frac{2\ln \left( \frac{r_{\text{core}}}{r_{\text{coat}}} \right)}{K_{c, \text{core}}} - \frac{2\ln \left( \frac{r_{\text{cell}}}{r_{\text{coat}}} \right)}{K_{c, \text{glass}}} + \frac{2}{r_{\text{cell}} H_1}, & r_{\text{core}} < r \leq r_{\text{cell}} \\ - \frac{2\ln \left( \frac{r_{\text{cell}}}{r_{\text{coat}}} \right)}{K_{c, \text{core}}} + \frac{2}{r_{\text{cell}} H_1}, & r_{\text{cell}} < r \leq r_{\text{coat}} \end{cases}$$

(13)
where $r_i$ is the fiber radius at various points (coating, cladding, core), $T_0$ is the ambient temperature of the heat sink assumed to be uniform over the fiber, $K_{c,i}$ is the thermal conductivity of either the coating or glass, $H_t$ is the heat transfer coefficient which depends on cooling method and $Q(z)$ is the heat load per unit length along the length of the fiber, with maxima being on either end of the fiber depending on pump configuration (for the calculations here this value is a constant heat per unit length determined from the efficiency of the laser based on the heat deposited in the fiber core). Note that in this analysis heat loads of power per unit length can be translated to laser operating power via multiplying by the total fiber length and dividing by the laser efficiency with respect to absorbed pump power.

To illustrate (13), an example using typical values for $K_c$ of 0.13 W/mK for the coating and 1.4 W/mK for the glass [147], and assuming 14°C water cooled heat transfer ($H_t \sim 10^4$), the temperature profile of a fiber with $\sim 200$ W/m heat load (roughly corresponding to a hypothetical 1-2 kW thulium fiber laser with 50-65% efficiency and 5 m fiber length in the standard 25/400 fiber discussed in 2.2.2.8) can be plotted as shown in Figure 6.

![Figure 6: Temperature profile of hypothetical 25 μm core, 400 μm clad, thulium fiber laser operating at kW levels. Vertical lines represent boundaries between fiber layers.](image-url)
The temperature of the core is seen to reach just under 200°C which is well below the melting point for silica glass. Even with these relatively high kW-level heat loads, the core will remain stable, speculative calculations show that for the core to reach temperatures where it would hit its melting point in this configuration, powers of 2 kW per meter would be required, which is well above any current heat loads, and at these powers, it is likely that other thermal issues would dominate. As a consequence, core melting in silica glass is not a large issue, however, in softer glasses such as phosphates (with melting and softening points around 300-600°C which also tend to operate at much shorter lengths), this threshold value can be reached and surpassed if care is not taken.

The greater concern that one might have from Figure 6 is about the temperature of the polymer, which is likely only “long term” stable up to ~100°C. Over time degradation can occur if operation above this temperature is done over extended times [147], and most likely, the maximum value for operation with current polymer coatings is ~150°C, above which catastrophic damage can occur [3]. Figure 6 shows that for this hypothetical kW-level laser the polymer coating is just above 100°C, so it is likely just above the safe long term operating level. For further investigation of this potential limiting factor, using (13), Figure 7 is plotted to determine the required type of cooling for a given heat load and for a given fiber dimension, keeping the core diameter and all other parameters constant. The different regions are the “zones of safety” where the green is safe operation, the orange is marginal, and the red is a damage risk.
Figure 7: Plots of Heat Transfer Coefficient versus temperature at the polymer/glass interface for various fiber dimensions and heat loads. All other constants are assumed same as previously. The green regions are safe operating regimes, the orange regions are border-line where degradation may occur and the red regions are outside of safe operating range.

In terms of heat transfer coefficient with respect to real cooling methods, perfect forced water cooling over the fiber is \( \sim 10000 \, \text{W/m}^2\text{K} \), perfect forced air cooling is \( \sim 1000 \, \text{W/m}^2\text{K} \), completely passive convective cooling is \( \sim 10 \, \text{W/m}^2\text{K} \), with other schemes in between depending on the geometry of the cooling scheme with the typical water cooled mandrel likely somewhere between 1000 and 10000 W/m\(^2\)K [3, 12]. Clearly for typical 5 m fiber lengths, the amount of thermal loading can be quite significant before polymer damage, and even with \( \sim 50\% \) laser efficiency polymer safety can be assured with simple cooling schemes up to a few hundred watt operation. Note that as fiber cladding and polymer coating dimensions increase, they are actually slightly easier to keep cool, stemming from the larger surface area over which the heat load is spread.

The figures also make clear that for safe operation at the multi kW level (500 W/m and more) it may be likely that 50% efficiency leads to thermal loading beyond what current polymer technology can handle and laser efficiency improvements in the thulium band or polymer damage and thermal conductivity improvements must be made.
Thermal loading is one of the larger concerns for thulium fiber lasers compared to other types of fiber lasers (and one of its current disadvantages) due to the lower efficiency than Yb lasers. However, there is still room for improvement in laser efficiency and thus the ability to scale fiber laser powers further. In addition, improvements in fiber coatings with higher conductivity and damage thresholds (as suggested in [12]) will enable scaling well beyond current limitations and make thermal effects less of a concern. For instance, if the conductivity of the coating were to match that of glass (an order of magnitude improvement) for the example in Figure 6 the core temperature would drop to 120°C and the polymer temperature would drop to ~30°C, which is a significant improvement in both cases, and likely achievable with glass clad fibers coated with a potentially high conductivity strength layer.

2.1.2.4 Thermal Effects on 3-Level Laser Systems

Thermal effects can also have a strong effect on laser efficiency, especially in the three-level thulium fiber laser system. This stems from the fact that in thulium (and most other rare earths used in fibers) the upper laser level and the ground state are split into many sublevels, as is typical in most glass hosts and these levels have energy splitting on the order of $k_B T$. This means that in both the upper and lower laser level manifolds there will be a thermal population given by the Boltzmann distribution

$$f_{l,i} = \frac{e^{E_{l,i}/k_B T}}{\sum_l e^{E_{l,j}/k_B T}}$$

(14)

where $f$ is the fraction of population in a sublevel $i$ of laser level $l$ compared to the total population of the level, $k_B$ is the Boltzmann constant, $T$ is temperature and $E_{l,i}$ is the energy of
the sublevels [3, 160]. The fractional population of any given sublevel is directly proportional to
the emission or absorption cross section (depending on which level is being considered, emission
is upper level and absorption is lower level). This means for a higher temperature, population
shifts towards the higher energy levels in a given manifold. In terms of the ground state, which is
also the lower laser level, this causes significant reabsorption at laser wavelengths stemming
from the transition in the same levels and since thulium’s lower laser level is already thermally
populated at room temperature [100], higher temperatures serve to make the situation worse,
further increasing laser threshold and reducing efficiency due to higher reabsorption losses. In
addition, the higher temperatures in the upper manifold serve to reduce the emission cross
section, since the bottom of the manifold where emission occurs strongest begins to lose
population. The reduced emission and absorption cross sections in combination strongly affect
the laser, and hence thermal management can become critical to achieving laser efficiency. This
analysis is relatively simple and qualitative; there are likely other properties of the thulium laser
energy level structure, such as cross relaxation, which will also be adversely affected by
temperature.

2.1.2.5 Thermal Effects in Bulk Components

Bulk components are currently unavoidable in many of the highest power fiber laser
systems, especially those based in thulium, as there are simply not a sufficient number of
available fiberized components designed for the laser wavelength range of the thulium transition.
In addition, even fiberized components may have free space components integrated into them,
and if designed for high power, the potential thermal effects must be accounted for. The most
critical issue to be sure of is that the material being used is low loss at thulium wavelengths.
Many materials have an absorption edge in or near the thulium band, and hence can lead to several percent absorption. Thulium wavelengths are absorbed by water and the OH$^-$ impurity in any components can cause absorption. Even in transparent materials, small absorption at very high powers can lead to significant heating, and even thermally induced damage, as will be discussed later in the chapter.

Thermal lensing can have the effect of causing misalignment in systems as power is increased, because the lens induced in a material can cause beams to defocus in fiber coupling schemes or perhaps expand and clip on the edge of an aperture. Thermal lensing can occur in both optically neutral components (components that do no focusing), like those of an optical isolator, output coupler, grating or sampling wedge or can occur in elements like lenses which already have optical power. The effect on different components can vary in terms of the exact equations governing them depending on whether they are surface effects like thermal expansion of a metal grating surface, bulk refractive index effects, or effects in a lens, and such different situations can be characterized in numerous sources such as [3, 9, 161]. These effects are best avoided by using appropriate materials or appropriate cooling of components, however if they are left uncontrolled, any thermal lensing issue can strongly affect $M^2$. Assuming a Gaussian beam (which is a reasonable assumption for a fiber mode coupled into free space from a fiber laser) thermal lensing which is highly aberrated is induced, and has a strong effect on beam quality factor $M^2$, described by

$$M^2_{\text{actual}} = \sqrt{(M^2_{\text{laser}})^2 + (M^2_{\text{thermal}})^2}$$

(15)

where $M^2_{\text{thermal}}$ is
with most terms as described previously and $P_{\text{absorbed}}$ the power absorbed in a particular component of interest [3, 161]. Note that several terms from [3, 161] are neglected, as they deal with the overlap of a laser mode with a heat profile, and here the heat is caused by the beam, so those terms cancel to unity. As an example, using the properties of fused silica, $K_c$ is $\sim 1.3$ W/mK and $dn/dT$ is $11.8 \times 10^{-6}$, by combining (15) and (16) and plotting versus absorbed laser power for a thulium fiber laser at 2 μm, the magnitude of the effect on different $M^2$ for absorbed power up to 0.5 W (becomes nearly linear after this point), the plot is shown in Figure 8.

\[
M^2_{\text{thermal}} \approx \frac{2P_{\text{absorbed}}dn}{\lambda K_c \sqrt{2}}
\]  

(16)

Figure 8: Plot of effect on $M^2$ of power absorption in a component with a thermal lens due to a Gaussian beam. The various curves are for various initial $M^2$ values as seen by their value for zero pump absorption.

The better the beam quality, the smaller the fraction of absorbed power is required for a significant decrease in beam quality. Even with absorption of only $\sim 0.3$ W of power (that is not radiated away by a cooling system (corresponding to only 0.1% absorption in a 300 W laser path) a perfect $M^2$ can be doubled to as poor as an $M^2$ of two. Clearly, careful attention to the thermal properties of materials in the laser beam path must be paid, as a shift of that magnitude in beam quality outside the a laser cavity can cause issues with beam propagation, but inside the
cavity for instance in a bulk intracavity collimating lens, such an increase in $M^2$ can severely degrade laser efficiency.

One interesting benefit of working at the longer thulium wavelengths is that according to (16), thermal aberration is inversely proportional to wavelength and thus has a reduced effect at the longer wavelength regime. However, it is likely that any benefit is more than offset by the difficulties associated with much higher potential absorption in optical materials around the thulium wavelength band.

2.2 Surpassing of Power Scaling Limitations

Although the limitations discussed in the previous sections can be quite severe and may seem daunting, a few solutions which are quite simple in concept (though often challenging in implementation) can reduce or eliminate the impact of many of the obstacles in the way of improving fiber laser output power. The solutions discussed in this section have enabled kW class lasers in fiber form and continuing refinement of these thermal, mechanical and optical damage mitigation techniques will lead to higher performance lasers in the future.

2.2.1 Mode Field Diameter Scaling

Looking at the theoretical dependences of many of the optical damage and nonlinear limitations imposed on fiber lasers it becomes clear that many have a common dependency on the intensity of the light used. Since intensity is power per area, high average or peak power beams can have relatively low intensities if not confined to small sizes. Thus, to overcome the intensity dependent effects that come into being when small core fiber lasers are increased in
power, a simple solution is to increase the core size in which the light is confined. However, as fiber core diameter increases, multiple modes can begin to guide in a fiber, which can cause a severe degradation in beam quality, one of the fiber lasers greatest assets. In addition, modal interference in fibers can create “hot-spots” of high intensity within the fiber that can do optical damage at high powers.

Since there is a point beyond which core diameter cannot simply be scaled in size without adverse effects, alternative techniques have been and are still being developed to scale fiber laser core diameters while maintaining beam quality. This section will outline the background theory required to understand propagation of light in optical fibers and extend this analysis to the so-called large mode area (LMA) fibers in a general sense.

2.2.1.1 Light Propagation in Optical Fibers

Before the myriad techniques used for fiber mode field diameter scaling can be understood, the basic concepts of light guidance in optical fibers must be introduced. In this section the important concepts of light guidance in optical fibers are introduced with emphasis on looking at light guidance from two different perspectives. First, the ray propagation model is used to gain a qualitative understanding of fiber guidance, then the more complex electromagnetic field concepts, a far more accurate description of fiber guidance, is introduced. The section concludes with a discussion of the most important concepts as they apply to the fibers used in this dissertation.
2.2.1.1 The basic picture of optical fibers

Guidance in an optical fiber in its most basic form can be described by the phenomenon of total internal reflection with a basic ray picture. Total internal reflection (TIR) occurs when light propagating in one material comes to an interface with a second material (with different refractive index) at an angle greater than what is known as the critical angle, given from Snell’s law by

\[
\theta_c = \sin^{-1} \frac{n_2}{n_1}
\]  

(17)

where \( n_2 \) is the index of the substrate or cladding region and \( n_1 \) is the index of the fiber core (seen schematically in Figure 9). Clearly from (17), if the critical angle is to be a real quantity, the index of refraction of the substrate or cladding must be lower than that of the core. This principle comes into further use in terms of an optical fiber when one considers the sketch shown below.

![Figure 9: Schematic of 1-D optical fiber in terms of a ray picture [162].](image)

In this figure the solid line is a ray of angle \( \alpha \) incident from a medium of index \( n_0 \) that makes an angle at least as large as the critical angle, and thus is totally internally reflected [162]. The dashed line is that of a ray that is unable to undergo total internal reflection. The angle \( \theta \) is the angle that the ray makes once it is the interior of the fiber. Referring to Figure 9, one can see that \( \theta \) and \( \alpha \) can be related to each other through Snell’s law to give
\[
\frac{\sin \alpha}{\sin 90 - \theta} = \frac{n_1}{n_0} \Rightarrow \sin \alpha = \frac{n_1}{n_0} \cos \theta
\]  
(18)

and subsequently rewriting (18) for the case when the maximum possible \( \alpha \) is reached to continue to allow total internal reflection (clearly when \( \theta = \theta_c \)) and also plugging in (17) one can write

\[
n_0 \sin \alpha_{\text{max}} = n_1 (1 - \sin^2 \theta_c)^{1/2} = (n_1^2 - n_2^2)^{1/2}
\]  
(19)

where \((n_1^2 - n_2^2)^{1/2}\) is known as the numerical aperture (NA) of the fiber [162]. Further manipulation can give the value of \( \alpha_{\text{max}} \)

\[
\alpha_{\text{max}} = \sin^{-1}(\text{NA} / n_0)
\]  
(20)

which is the maximum angle of light a fiber can accept (or inversely the angle of the largest ray emanating from the fiber) [162]. In the simplest ray picture, light subsequently propagates down the fiber by simply bouncing without loss via total internal reflections until the end of the fiber; reaching the end of the fiber, light exits in the reverse of the process just described. Smaller angle input rays also propagate and as they reflect, also have evanescent components in the cladding of the fiber, as dictated by the laws of reflection. Clearly this simple picture is not sufficient, since it cannot account for bending of the fiber or the propagation of fiber modes. However in many cases it is a useful intuitive picture to have available.

2.2.1.1.2 Electromagnetic picture of optical fibers

In order to have a higher level understanding of light propagation in an optical fiber, the electromagnetic picture must be considered. This electromagnetic analysis gives the origin of the fiber modes, and allows for the calculation of the properties of each mode, if desired. The
analysis that follows is for a simple step index fiber; however, similar, but more mathematically complex methods can be used to solve fibers of arbitrary profile, including those of gain guided fibers, as will be discussed later.

To begin, following the analysis in [11, 163], the electric and magnetic field can be written in the following manner for both the longitudinal fields in the core of the fiber and in the cladding for fiber core radius $a$

$$F_z(r, z, \phi) = AJ_m(\kappa r)e^{j(m\phi - \beta z)}$$

$$\kappa^2 + \beta^2 = k_0^2 n_1^2$$

(21)

in the core and

$$F_z(r, z, \phi) = CK_m(\gamma r)e^{j(m\phi - \beta z)}$$

$$-\gamma^2 + \beta^2 = k_0^2 n_2^2$$

(22)

in the cladding, where $F$ is either electric or magnetic field, $K$ and $J$ are Bessel functions of order $m$, $k_0$ is the wave number, and $\beta$ and $\gamma$ are propagation constants [11, 163]. Transverse fields over the entire region of the fiber are defined in terms of the longitudinal fields

$$E_r = \frac{-j}{k_0^2 n_r^2 - \beta^2} (j \frac{m}{r} \sqrt{\frac{\mu_0}{\epsilon_0}} k_0 H_z + \beta \frac{\partial E_z}{\partial r})$$

$$E_\phi = \frac{1}{k_0^2 n_\phi^2 - \beta^2} (j \frac{m}{r} \frac{\partial H_z}{\partial r} + \beta \frac{E_z}{r})$$

(23)

$$H_r = \frac{-1}{k_0^2 n_r^2 - \beta^2} (j \beta \frac{\partial H_z}{\partial r} + k_0 n_r^2 \frac{\epsilon_0 m}{\mu_0} E_z)$$

$$H_\phi = \frac{-j}{k_0^2 n_\phi^2 - \beta^2} (j \beta \frac{m}{r} H_z + k_0 n_\phi^2 \frac{\epsilon_0}{\mu_0} \frac{\partial E_z}{\partial r})$$
where \( m \) is the order of the Bessel function and \( H_z \) or \( E_z \) are the longitudinal components of the electric field given by the earlier expressions \([11, 163]\). Replacing the longitudinal components of electric and magnetic fields into the expressions for tangential fields, taking the appropriate derivatives and using some useful properties of Bessel functions, the total expression for the electric fields in a fiber core and cladding can be finally written as

\[
E_{r,\text{core}}(r) = \frac{j}{2k}[(k_1B + \beta A)J_{m-1}(kr) + (k_1B - \beta A)J_{m+1}(kr)]
\]

\[
E_{\phi,\text{core}}(r) = \frac{1}{2k} [(k_1B + \beta A)J_{m-1}(kr) - (k_1B - \beta A)J_{m+1}(kr)]
\]

\[
H_{r,\text{core}}(r) = -\frac{n_1}{2} \frac{\mu_0}{\varepsilon_0 k} [(\beta B + k_1A)J_{m-1}(kr) - (\beta B - k_1A)J_{m+1}(kr)]
\]

\[
H_{\phi,\text{core}}(r) = -\frac{n_1}{2} \frac{\mu_0}{\varepsilon_0 k} [(\beta B + k_1A)J_{m-1}(kr) + (\beta B - k_1A)J_{m+1}(kr)]
\]

in the core and

\[
E_{r,\text{clad}}(r) = \frac{j}{2Y}[(k_2D + \beta C)K_{m-1}(yr) - (k_2D - \beta C)K_{m+1}(yr)]
\]

\[
E_{\phi,\text{clad}}(r) = \frac{1}{2Y} [(k_2D + \beta C)K_{m-1}(yr) + (k_2D - \beta C)K_{m+1}(yr)]
\]

\[
H_{r,\text{clad}}(r) = -\frac{n_2}{2} \frac{\mu_0}{\varepsilon_0 Y} [(\beta D + k_2C)K_{m-1}(yr) + (\beta D - k_2C)K_{m+1}(yr)]
\]

\[
H_{\phi,\text{clad}}(r) = -\frac{jn_2}{2} \frac{\mu_0}{\varepsilon_0 Y} [(\beta D + k_2C)K_{m-1}(yr) - (\beta D - k_2C)K_{m+1}(yr)]
\]

in the cladding, where \( A, B, C, \) and \( D \) are arbitrary constants, \( k_i = k_0 n_i \), and the rest of the constants are as defined earlier \([11, 163]\). Now, by matching electric and magnetic fields at the boundary between the core and cladding (hence setting \( r = a \)) for each field component and making some definitions as shown, the following expressions can be obtained.
\[ E_z(a, z, \phi): \quad Al_m(u) = CK_m(w) \]
\[ H_z(a, z, \phi): n_1Bf_m(u) = n_2DK_m(w) \]
\[ E_\phi(a, z, \phi): \quad \frac{1}{u} \left( Bk_1 \frac{df_m(u)}{du} + A\beta \frac{m}{u} J_m(u) \right) = \frac{-1}{w} \left( Dk_2 \frac{\partial K_m(w)}{\partial w} + C\beta \frac{m}{w} K_m(w) \right) \]  
(26)
\[ H_\phi(a, z, \phi): \quad \frac{n_1}{u} \left( B\beta \frac{m}{u} J_m(u) + Ak_1 \frac{df_m(u)}{du} \right) = \frac{-n_2}{w} \left( D\beta \frac{m}{w} K_m(w) + Ck_2 \frac{\partial K_m(w)}{\partial w} \right) \]

where \( u = \kappa a \) and \( w = \kappa a \) [11, 163]. Combining these equations to eliminate the constants \( A, B, C \) and \( D \), a single dispersion relation can be obtained, and with some additional manipulation based on the definitions of \( \beta, \kappa, \gamma, u \) and \( w \) leads to the final form of the dispersion relation
\[ \left( \frac{J_m'(u)}{uJ_m(u)} + \frac{K_m'(w)}{wK_m(w)} \right) \left( \frac{n_1^2 J_m'(u)}{uJ_m(u)} + \frac{K_m'(w)}{wK_m(w)} \right) = m \left( \frac{1}{u^2} + \frac{1}{w^2} \right) \left( \frac{n_1^2}{n_2^2 u^2} + \frac{1}{w^2} \right) \]
(27)
which is the key to solving for the propagation constants of an optical fiber [11, 163]. The final piece of information is in the core region
\[ \kappa^2 + \beta^2 = k_0^2 n_1^2 \]
(28)
and in the cladding,
\[ -\gamma^2 + \beta^2 = k_0^2 n_2^2 \]
(29)
which can be combined through the \( \beta \) parameter and rewritten in terms of \( w \) and \( u \) to give
\[ u^2 + w^2 = V^2 \]
(30)
where \( V \) is defined as follows
with the variables defined as before and with \( \sqrt{n_1^2 - n_2^2} \) alternately written as NA (fiber numerical aperture) [11, 163]. Solving the dispersion relation for different values of \( m \), the mode number based on (27) - (31) and using subsequent \( p^{th} \) order solutions (zeroes of the Bessel function) of the \( m^{th} \) order Bessel functions allows for solution of individual modes. These families of solutions to the dispersion relation under specific boundary conditions imposed by the fiber core and cladding layers are the modes of the fiber ad discussed on numerous occasions through the remainder of this work. The distribution of these modes fields can be obtained by plugging back into the equations for electric or magnetic field in the core and cladding; relative amplitude of the modes can be found by finding \( A, B, C \) and \( D \) based on initial conditions.

The modes can be grouped into one of four basic categories. The first two are the TE and TM modes, where polarization is either TE\(_{0p}\) or TM\(_{0p}\) and \( m=0 \), where \( p \) is the \( p^{th} \) solution to the associated dispersion relation. When \( m=0 \), the dispersion is simplified to the form

\[
\left( \frac{J'_0(u)}{uJ_0(u)} + \frac{K'_0(w)}{wK_0(w)} \right) \left( \frac{n_1^2 J'_0(u)}{n_2^2 uJ_0(u)} + \frac{K'_0(w)}{wK_0(w)} \right) = 0
\]

(32)

where setting one term or the other equal to zero give the TE and TM family of modes [11, 163]. The other two families of modes (which are the modes that exist when \( m \geq 1 \)) require one additional assumption, the weakly guiding approximation, or in other words that \( n_1 \approx n_2 \), hence the core and cladding indices are approximately equal. In most optical fibers, this is true, as typical refractive index steps do not exceed \( \sim 0.01 \). In this approximation then, the ratios of indices seen in the original dispersion relation (27) cancel out, leaving the expression
\[
\left( \frac{f'_m(u)}{uf'_m(u)} + \frac{K'_m(w)}{wK_m(w)} \right) = \pm m \left( \frac{1}{u^2} + \frac{1}{w^2} \right)
\]

(33)

where the ± in the expression indicates whether the mode family is the EH (+) or HE(-) [11, 163]. The HE_{mp} and EH_{mp} modes are known as hybrid modes, where polarization is a combination of both orientations. In order to simplify further, the HE, EH, TE and TM mode families can be written together as sets of degenerate modes, the LP modes, beginning with LP_{0,1} which is considered the lowest order mode. Table 1 shows the way in which the LP modes are defined in terms of the other families of modes.

Table 1: Designations of LP modes based on the hybrid, TE and TM modes of a fiber [163]

<table>
<thead>
<tr>
<th>LP Mode</th>
<th>Hybrid Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP_{0,p}</td>
<td>HE_{1,p}</td>
</tr>
<tr>
<td>LP_{1,p}</td>
<td>HE_{2,p}, TE_{0,p}, TM_{0,p}</td>
</tr>
<tr>
<td>LP_{q,p}</td>
<td>HE_{q+1,p}, EH_{q-1,p} for q\geq2</td>
</tr>
</tbody>
</table>

Figure 10 shows the intensity distributions for some of the lowest order fiber modes based on calculations using the previously derived equations and matching fields at the core and cladding boundaries. The calculated distributions are done for a hypothetical 50 µm core, 0.06 NA fiber at thulium wavelengths. The modes shown are all of the existing modes. In LMA fibers, (which are later detailed) are slightly multimode, a superposition (weighted by power contained in each mode) of some of these field distributions are observed.
The set of equations defined above give the framework for the entire set of solutions to the propagation of light in an optical fiber. Making more sophisticated modifications to the methods used above, all of the properties of fibers can be derived, including fiber dispersion, bending losses and other important parameters. The most critical of these parameters for high average power LMA fibers are bending losses, which are discussed briefly in a later section.

2.2.1.1.3 Practical considerations for LMA fibers

In the realm of LMA cladding pumped fiber lasers the only important regimes to consider are the single mode (or few mode V < ~5) regime and the highly multimode regime. The former regime is important in terms of the guidance properties of the laser light in the fiber, and must be taken into account in order to keep the fiber operating on a single mode. Doing so ensures maintenance of the high beam quality that is associated with high power LMA fiber lasers. The later regime applies to the way pump light travels in the cladding of the fiber; the distribution of
the numerous higher order modes is important to consider when pump light absorption and distribution in the fiber is considered.

2.2.1.4 The single mode regime

The equations in the previous section on the electromagnetic field modeling of an optical fiber dictate under what conditions a mode can no longer propagate, the “cutoff condition” for different fiber modes. At the cutoff for any particular mode, \( w \to 0 \), imposing this condition on any of the mode families shown in (32) and (33) allows for the cutoff condition for any particular fiber mode to be calculated. In the case of the lowest order mode, the HE\(_{11} \), there is no cutoff and it can always propagate \([11, 163]\). If purely single mode operation is desired, no other modes must be allowed to exist; hence, there is concern with the cutoff condition of the next highest order mode family, that of the TE, TM and HE\(_{21} \) modes. By imposing \( w=0 \) in equations (32) and (33), it can be shown using some useful Bessel identities that the cutoff condition is

\[
J_1(u) = 0
\]

and the first zero for this case occurs for \( u=2.405 \) \([11, 163]\). Because \( w \) has been set to zero, equation (30) says that therefore \( V \) must be equal to \( u \). Since \( V \) is defined in (31) in terms of physical fiber laser parameters, the conditions for propagation of a single mode can be determined for any given fiber core size, NA and wavelength, and a single mode fiber laser can be designed.

In many LMA fibers, the fiber is not actually designed to be perfectly single mode, but rather slightly multimode to allow for larger mode areas. However, beam quality is maintained
by using special techniques to eliminate the lasing of higher order fiber modes as will be discussed later [13].

2.2.1.1.5 Highly multimode regime

The other regime that must be briefly considered is the highly multimode regime. In this case hundreds to thousands of fiber modes exist. The actual number of modes in any fiber can be estimated based on the V-parameter, assuming $V >> 1$ it is given by

$$N_{\text{modes}} \approx \frac{V^2}{2}$$

from [162]. It turns out that as mode number increases, the location of much of the energy in many of the higher order modes moves outward from the center of the fiber. As a consequence, when light is propagating in the highly multimode pump cladding of a double clad LMA fiber there is a significant portion of energy that may never cross into the core. This is bad news in terms of using that light to pump the active core as a large portion of pump power can be wasted if it cannot be forced into modes that cross the core. As a result double clad fibers must design in some deviations from perfectly round claddings to reduce the higher order modes that do not cross the core.

2.2.1.1.6 Fiber bend loss

When working with LMA fibers, the concept of bend loss is critical in order to understand how the different modes of the fiber are affected by bending, since different modes experience different amounts of bend loss, which can be exploited in controlling the beam
quality of LMA fibers as discussed later [53, 164-166]. In addition, as LMA fiber core diameters increase, their sensitivity to bending becomes significantly higher, meaning that when being packaged into systems, care must be taken not to coil so tightly that excessive loss is induced on the fundamental mode. Additional analysis beyond the scope of this section is also critical for determining how the actual fiber mode distorts in bends, as the shape of the mode gets “squeezed” against one side of the fiber core. This effectively reduces the effective area, which plays a role in onset of nonlinear and other effects and the overlap of the fiber mode with the doped core, which can affect laser efficiency [164-167].

Though the shape of the mode is a somewhat difficult quantitatively to model, the loss of individual modes is relatively simple to model, at least to a reasonable estimate. Marcuse outlines a simple equation for the loss per unit length for any mode, assuming the mode index and other propagation parameters of the mode is known, given in [168] by

$$2\alpha = \frac{P_{bent}}{P_{straight}}/L = \frac{\sqrt{\pi}k^2e^{\left(-\frac{2\gamma^3}{3\beta^2}\right)^R}}{e_\nu \gamma^2 V^2 K_{\nu+1}(\gamma a)K_{\nu-1}(\gamma a)\sqrt{R}}$$

where $a$ is the fiber core radius, $k$, $\gamma$ and $\beta$ are the propagation constants (discussed in the previous sections) of a particular mode with the mode number of LP$_{\nu,i}$ mode $\nu$, $e_\nu$ is a parameter which is equal to 2 when $\nu=0$ and 1 otherwise, $V$ is the fiber V parameter, $R$ is the bend radius and $K_i$ is the K-type Bessel function of the $i^{th}$ order.

By evaluating this equation versus bend radius for the propagation parameters of different modes in a fiber which can be found from a simple fiber mode solver, the bend loss in dB/m can be evaluated, as is seen for a variety of fibers shown in Figure 11.
Figure 11: Loss in different fiber modes for various fiber core diameter designs in both Yb and Tm wavelength regimes. The top two figures are real fibers, commonly used (one in thulium and one in ytterbium). The bottom two plots are hypothetical thulium fibers to showcase the potential thulium fiber performance. Only the 4 or 5 lowest modes are shown, though the 40 μm fiber has 6 total modes and the 70 μm fiber has 7 modes.

The top two plots in Figure 11 show fibers that are commonly used at thulium and ytterbium wavelengths, with the thulium fiber modeled being the main fiber design used in most of the experimental work in this dissertation (neglecting the effect of the pedestal). For the Yb fiber, only the first four of six total modes are shown and the comparison of the two reveals an advantage of thulium due to its longer wavelength. This advantage is seen in the mode confinement (hence immunity of the fundamental mode to bend loss) as the thulium fiber can be bent 25% tighter with minimal loss because it is able to use a higher NA. In addition, for two fibers with similar core diameters and the thulium fiber with the much higher NA, the small number of thulium fiber modes (only two exist) can be compared to the larger number of modes for ytterbium. Also, coiling either fiber to ~10 cm diameters will yield significant differential losses between the fundamental mode and the next highest order mode, which is important in maintaining beam quality.
In addition, the bottom two plots in Figure 11 show hypothetical thulium fibers that are within the capabilities of fabrication technology, but have not been tested. The 40 \( \mu \text{m} \) fiber displays similar bend loss and other characteristics to the ytterbium fiber, and still has better confinement due to a larger NA and core than the ytterbium fiber. The 70 \( \mu \text{m} \) fiber represents what might be a fabrication limit for thulium fibers and shows again that thulium can achieve mode field diameters double that of ytterbium with the same number of modes. However with the low NA, the downside of longer wavelength is seen in poorer confinement and hence less tolerance to bending, with only \( \sim 20 \) cm bending allowable. It also becomes more difficult to achieve significant differential loss between the fundamental and next highest modes, as with larger cores they become squeezed together in the fiber. In addition, the effective mode field diameter (as seen in the next section) in these larger fibers is much smaller than the actual core, likely requiring the need for doping only a small section of the core to keep efficient amplifier operation.

Overall, bending loss is a critical concept to understand when designing a fiber laser or amplifier with LMA fibers. Estimation of the bend loss by simple mode index calculation followed by use of the Marcuse equation enables a better understanding of mode propagation in a fiber and inherent advantages of the use of thulium for LMA, high power fiber amplifiers.

2.2.1.2 Simple Mode Field Diameter Calculations and Comparisons

Mode field diameter of a fiber is another parameter, like bending loss which can require in-depth modeling to find accurately, especially in fibers with complex refractive index profiles, however similar to bend loss, it can also be modeled relatively simply. Since single mode lasers are the desired goal for this work and most all high power fiber laser work (as high beam quality
is an inherent advantage of fiber lasers) this discussion is limited to the mode field diameter of the fundamental mode. Since the majority of power, even in an LMA fiber is carried in this mode and the values of mode field diameter translates directly to mode area (which is the critical parameter in the detrimental nonlinear and thermal effects discussed earlier) it is important to have tools to estimate it. In addition, the fabrication of all-fiber components, such as mode field adaptors and taper fiber bundles where two fibers must be matched to each other, requires the estimation of mode field diameter. Marcuse, in [169], derives an approximate relation for the mode field diameter of the fundamental mode of a fiber under a Gaussian approximation given by

\[ MFD = 2a(0.65 + \frac{1.619}{V^2} + \frac{2.879}{V^6}) \]  

(37)

where \( V \) is the V-parameter defined earlier, MFD is mode field diameter and \( a \) is the fiber core radius. In the region from 0.8 to 2.5 in V-parameter, the equation is accurate to \( \sim 1\% \) and in the range beyond \( V=2.5 \), the equation gives only the fundamental mode field diameter, which is still the only mode of interest in LMA fibers, despite their slightly multimode nature (since usually the goal is to reduce the presence of any other modes as much as possible), so the equation still has use [169]. Figure 12 is a plot of (37) for a variety of fiber NAs at 2 \( \mu m \) in wavelength. It is plotted by substituting (31) into (37) and plotting against the fiber core radius.
Looking at the figure, it is seen, as expected, smaller MFD for higher NAs, since the larger refractive index difference leads to mode confinement. Due to its longer wavelength, thulium tends to have a larger MFD for a given core diameter and NA than a typical ytterbium fiber. An interesting feature of the plot is that there is always a minimum MFD for a fiber, regardless of how small the core becomes. If the core becomes too small, confinement cannot be maintained and the mode begins to expand rapidly. This minimal MFD feature can lead to issues in fabrication of mode field adaptor devices. If tapering one fiber with a constant NA cannot make the MFD small enough to match to another fiber, the two can never be spliced with low loss [169]. As a result, a number of alternative techniques and added complexity must be added to component fabrication. It is important to note that in most LMA fiber designs, as seen in the above figure, the mode field diameter is smaller than the actual core diameter, which can lead to issues with mode overlap of the gain region (usually the entire core). In addition, as core diameter becomes larger and larger, the MFD does not grow as rapidly. Therefore it is important to use MFD and not core diameter when calculating detrimental nonlinear effects and other damage thresholds, as using the core diameter will become a worse and worse estimate of the mode area. Overall, simple mode field diameter calculations can reveal a good deal about the
nature of a fiber and enable simple modeling of spliced fiber components. In addition, splice losses can be easily estimated by considering the overlap of the mode field diameter of two dissimilar fibers [169], which is critical in the construction of “all-fiber” systems.

2.2.2 Large Mode Area Fiber Designs for Power Scaling

The area of high power fiber lasers which is most unique in comparison to other conventional fiber lasers is the design of the core and cladding systems to enable the increase of core size, or more appropriately mode area. A conventional optical fiber achieves single mode performance by using fairly small core dimensions and reasonably large core numerical apertures. The difficulty in achieving high powers from such small fiber cores lies with potential for optical damage stemming from extremely high peak intensities as well as potential deleterious nonlinear effects in the fiber core, detracting from the performance some systems [13, 153]. In order to avoid these effects, the core diameter, and hence mode area must be increased.

However, one of the main advantages of fiber lasers lies in their inherent high beam quality; increasing the core size will allow more modes to propagate, and thus, cause detrimental effects to the beam quality. LMA fibers have the added benefit of being able to store more energy due to a larger core and hence larger volume of doped and pumped gain medium. As a consequence LMA fibers are well suited for higher energy applications [50, 170]. A number of innovative methods for scaling mode diameter while preserving beam quality exist and are reviewed in the following sections. Following this is a brief discussion of the LMA techniques used in the experimental work conducted in this dissertation.
2.2.2.1 Conventional Large Mode Area Techniques

The earliest and conceptually simplest methods used to increase mode area while maintaining beam quality strive to achieve extremely low numerical apertures in the fiber core. A low numerical aperture balances the increase in core size help to keep the V-parameter close to its threshold value for single mode operation, 2.405. There are two difficulties associated with using this technique, first decreasing the NA causes weaker guidance of the light in the core, and as a result increases fiber sensitivity to bending losses (see section 2.2.1.1.6). In addition, achieving very small NA values is a fabrication challenge, as very precise control of the preform manufacture process is required [13, 171]. Using the basic idea of weak guidance and large cores, several conventional-based techniques have been developed to achieve high beam quality and power in fiber lasers and amplifiers.

2.2.2.1.1 Early LMA fibers and dopant profiling

The first conventional designs for LMA fibers were used in [51, 52, 171] to achieve high powers from Q-switched lasers. In order to improve beam quality in addition to using very small NAs, the fiber core was given a tailored dopant and refractive index profile to help give preferential gain to the lowest order mode [51, 52]. The doped section of the fiber existing only in the center gives preferential gain to the fundamental mode since that mode has the majority of its power along the center of the fiber. As discussed in 2.2.1.1.1, higher order modes have more of their energy away from the center of the core and hence will experience significantly less gain. A more detailed theoretical study of tailored gain is given in [172]. Using this technique the
core diameter of Yb fiber lasers was stretched to ~21 μm and output powers of up to 0.5 mJ at 500 kHz were achieved with $M^2$ of ~1.3 [51].

2.2.2.1.2 Coiling and weak NA guidance

The technique of fiber coiling first used in [53] takes advantage of the added bend losses on higher order modes (discussed in 2.2.1.1.6) of a weakly guided, slightly multimode LMA fiber. The fiber is coiled to a consistent diameter to strip off the higher order modes that are present. When the NA is small, high order modes are very weakly guided, and hence, are easily given higher losses and kept from lasing, while the less bend-sensitive lowest order mode is minimally affected. The exact theory of how bend loss can be treated in weakly guided fibers is given in [166, 168, 173-175], but in general the method for determining optimal bending can be done experimentally by coiling the fiber to tighter and tighter radii until desired beam quality performance is achieved with minimal effect to the laser efficiency. The loss of different modes for a given fiber is seen in 2.2.1.1.6.

The advantage of the bending technique is that it is straightforward to implement, as most fibers are coiled in packaging anyway; therefore, coiling with slightly more thought about fiber coiling diameter is of minimal difficulty. No special gain profiles are necessary to give preferential gain to fiber modes, and thus the fibers are much simpler to manufacture.
2.2.2.1.3 **Large flat mode fibers**

An extension of the use of specialized index profiles to enhance the performance of LMA type fibers involves the use of “M” shaped doping whereby a slightly higher index step is placed on either side of the fiber core (Figure 13) [176, 177].

![Large Flattened Mode fiber index profile](image)

Figure 13: Large Flattened Mode fiber index profile [176].

This addition causes “flattening” of the mode field diameter and thus a larger but more flat topped fundamental mode is achieved. The mode area is significantly increased (by up to a factor of 2 or 3) while maintaining near single mode operation. This design described by [176-178] has been successfully used in several cases, mostly for achieving high peak power ultrashort pulses, as these are especially sensitive to small fiber cores due their extremely high peak powers. By implementing these cores, the threshold for nonlinear interactions in the fiber core was increased by a factor of 2.5 [176].

2.2.2.1.4 **Single mode excitation**

A technique that is related to conventional techniques is the single mode excitation technique. This method, outlined by [179-181], is most applicable to high power fiber based free space MOPA systems. Using significant care, the fundamental mode can be launched in a fiber
which has multiple modes by matching the mode field diameter of the fundamental mode of the launching fiber to the mode field diameter of the fundamental mode of the receiving fiber [180, 181]. This technique can be done in free space by carefully selecting and aligning the seed launch optics of a free space MOPA chain or it can be done “all-fiber” by appropriately designing a mode field adapter (usually a tapered section of fiber or a taper plus a thermally expanded core region) which matches mode field diameters appropriately.

Though it technically works in any index guided fiber, one difficulty with this method is that light launched into the fundamental mode can “leak” in higher order modes over the length of the fiber due to perturbations caused by mechanical stress, defects or other small variations, and hence in [181] precision milled fiber mounts and relatively short (< 20 cm) lengths of fiber were used. This can have a detrimental effect on beam quality, however if the fundamental mode excitation method is combined with weakly guiding and tightly coiled LMA fibers which allow much higher leakage of higher order modes than the conventional fiber used in [181], it can be a very effective technique and has been used in many high peak power fiber lasers including in [56, 182, 183].

2.2.2.1.5 Inclusion of single mode sections via tapering

A final technique used to limit the propagation of higher order modes is the used of tapered fiber sections. A tapered section fiber was demonstrated in [184] where a small section of multimode fiber was tapered to a diameter that allowed it to be single mode. When inserted into an oscillator (at the output end), the section cleaned up the beam quality, however the slope efficiency was detrimentally effected.
As part of the work leading to the final system design of the high power MOPA system discussed in 4.2.2, a similar concept was used. In order to make the LMA laser oscillator output truly single mode, a mode field adaptor (MFA) was included in the resonator which originally consisted of LMA fiber. The MFA enabled the oscillator to operate in a truly single mode, at the expense of the slope efficiency of the laser.

The limitation of this technique for very high powers is that bulk core damage can still occur in the tapered section, though the probability of nonlinear effects is low due to only a small interaction length in the small core they may also still occur. Distributing the mode filtering over the length of the fiber (by such techniques as coiling) is more effective since loss is better distributed [3, 184].

Along the lines of using more distributed losses, an alternative tapering technique that allows much more gradual mode filtering has been recently demonstrated using a 27 μm core 834 μm clad fiber tapered gradually down over its ~10 m of length [185]. This technique is quite new and does have high potential, as more than 100 W and a nearly perfect M² was demonstrated. However fabrication is not simple, as tapering a long (~10 m) fiber so gradually requires specialized fiber pulling methods.

2.2.2.1.6 Very low NA, very large mode area fibers

Conventional preform MCVD fabrication techniques limit the smallest NA achievable in a fiber to ~0.06 [171]; in order to increase fiber core diameters from their current levels in conventional fibers this NA limitation must be surpassed. A new and novel technique to achieve this involves “freezing” in thermal stresses in a preform by using a hexagonal array of stress rods to induce a longitudinal stress in the preform that remains even after pulling. In doing this, core
diameters with gradient index profiles have been fabricated as large as 84 μm core diameters in a truly single mode fiber and a 252 μm core diameter with in a slightly multimode fiber which can be forced to be single mode by coiling [186]. The NA required to achieve this is around 0.013 meaning a refractive index difference of $6 \times 10^{-5}$, and both records for conventional fibers [186]. The current fibers are passive in nature, however there is a potential for active fibers to be made by similar methods. This technique has shown a promising future for the further scaling of conventional fiber mode field diameters.

2.2.2.2 Photonic Crystal Fibers

Limitations of precision in fabrication of conventional step index fiber preforms leads to difficulties in obtaining fiber core numerical apertures less than ~0.06 [13, 187]. In response, a class of fibers called photonic crystal fibers have been developed [188, 189]. These fibers utilize an organized structure of refractive index differences (air holes or different high or low index glasses) to either tailor the core numerical aperture to sufficiently small values or to create a photonic bandgap where only certain wavelengths of light are allowed to propagate. Versions of these fibers have been developed for their beneficial nonlinear, dispersive and loss properties in studies since the mid 1990s [188, 190-192]. The first fiber lasers based on PCFs were demonstrated in the early 2000s and had core sizes around 10-15 μm [193, 194]. Current state of the art in PCF technology allows core sizes of up to 100 μm [93, 195] with powers of up to 4.3 mJ pulsed, corresponding to 4.5 MW peak power in approximately nanosecond pulses.
2.2.2.2.1 Air filled or “holey” fibers

Air filled PCFs are the most common and first demonstrated PCFs for fiber lasers [188, 194]. The air holes function to alter the NA giving it the desired value to maintain single mode guidance. Figure 14 shows a sketch of a typical PCF design.

![Figure 14: Sketch of a typical generic PCF design](image)

The V parameter is still the limiting factor in the guidance of single mode beams in a PCF and its value is approximately calculated by

\[ V_{eff} = \frac{2\pi}{\lambda} AF^2 \left( n_0^2 - n_a^2 \right)^{1/2} \]  

(38)

where \( V_{eff} \) is the effective V parameter (still < 2.405 for single mode propagation), \( A \) is the spacing of the air holes (pitch), \( F \) is the filling factor of air to glass, \( n_0 \) is the index of the glass, and \( n_a \) is the index of the air (or whatever material fills the holes) [196]. This is only an approximate model, giving rule of thumb results, and [197] covers PCF analysis in further detail. Thus control of the pitch and hole size of the PCF structure allow production of endlessly single mode structures [198].

As most PCFs manufactured for high power laser purposes are double clad designs, they must also be designed with cladding pumping in mind. Since the largest core PCFs must not be
bent sharply they must be able to absorb pump power in relatively short lengths [199]. To achieve this with reasonable doping levels in the core the core to cladding ratio must be kept as large as possible which is usually achieved by using an “air cladding.” The “air cladding” is simply a ring of very thin silica “bridges” or alternatively very large air holes with small connections to the outer glass fiber [199]. Using this technique, air claddings with NAs as large as 0.8 have been realized [200]. The one detrimental effect of the air cladding is that it does not allow for efficient thermal conduction of heat generated in the fiber core out to the cladding. An analysis of heat transport in PCFs is given in [201]. Despite this, the highest average power from a rod-like air clad PCF reported to date is 320 W [202] and 1.53 kW from a longer, coilable PCF [203]. The highest pulse energy is 4.3 mJ [93]. A polarization maintaining PCF with 2300 μm² mode area was also demonstrated to have 161 W output power in a single polarization [204].

2.2.2.2.2 All solid core PCFs

The main issue with the use of PCFs, especially in their adoption to all-fiber systems lies in their air holes. It is challenging and complicated to form and fabricate a pre-form and fiber with air-holes [205] (though extrusion techniques may make this process simpler for instance in [206, 207]). It is also difficult to splice and cleave a fiber with air holes. There are further difficulties associated with contamination presented by particles working their way into the air holes and in finding fiber based components compatible with PCFs [195]. All-solid PCF fibers simply replace the air holes with a low or high index material to avoid the air hole issues. In addition the solid defects can be engineered to provide a photonic bandgap which is a more complex way of guidance providing single mode performance with the potential additional benefits of polarization maintenance and dispersion management. Novel uses for bandgap PCF’s
such as low dispersion femtosecond lasers and 900 nm Nd lasers (using a bandgap to suppress 1064 nm operation) have been constructed [208, 209] and other lasers have also been proposed [210].

2.2.2.3 Chirally Coupled Core

Another less conventional and relatively new type of LMA fiber laser is the Chirally Coupled Core (CCC) fiber. These fibers utilize specially designed satellite cores which wrap around the central LMA gain core to couple out the higher order modes into the lossy satellite while maintaining the lowest order mode [211, 212].

![Figure 15: Schematic of the CCC structure [212].](image)

Designing the helical core or multiple cores with proper pitch and size leads to strong coupling of high order modes to the intentionally lossy satellite [211, 212]. The loss in the different modes of a CCC fiber can be modeled and the loss in individual modes can be calculated and optimized for a particular helix pitch and size. Several CCC fibers have been fabricated and tested in two common wavelength regimes, both 1060 nm and 1550 nm and been shown to exhibit excellent beam qualities from al large as 50 μm cores. CCC fibers are extremely promising for achieving large cores in single modes especially because they do not require extremely small core NAs and thus, can handle strong bending and can be used for very long lengths to achieve high CW
powers with less thermal load. They also enjoy the additional advantage of being intrinsically polarization maintaining due to the satellite cores [211, 212]. One difficulty with CCC fibers is their fabrication. Though the core is formed by standard MCVD, a hole must be bored for insertion of the satellite rod and during drawing the preform must be spun at a set speed to achieve the chirality of the satellite at the desired pitch. However, with well optimized processes this can be readily achieved and CCC fibers can be accurately manufactured [213].

2.2.2.4 Higher Order Modes

Another newly emerging class of LMA fiber designs is the higher order mode fiber (HOM). These rely on using mode conversion techniques usually based on long period fiber Bragg gratings [214, 215]. HOM beams have Bessel function spatial distribution [216]. The gratings are specifically designed so that they efficiently couple energy to only one HOM and are then used in tandem to subsequently de-excite the HOM back into a more useful LP_{01} mode at the fiber output. (though leaving the beam in a HOM may also be useful). Typically the LP_{0X} mode (where X is an integer > 1) is excited. Modes as high as LP_{08} have been launched and through this process mode areas of ~3200 μm achieved [215]. A review of the theory is described in [214] in terms of their use in cladding modes of fibers, where this same theory applies to launching of HOMs into large core multimode fibers as well. An experimental investigation into launching HOMs in custom large core fibers is reported in [215]. Currently HOMs have only been used once in an actual laser resonator [217], however HOM based modules have also been exploited for their ability to produce anomalous dispersion in silica fiber allowing generation of pulses as short as 60 fs in Yb fiber lasers [218, 219]. An investigation of
HOMs ability to reduce SBS in fibers has been carried out in [220] where it was determined that SBS in HOM fibers can be reduced by using higher order modes.

2.2.2.5 Leakage Channel Fibers

Leakage channel fibers (LCF) [221-225] sketched in Figure 16, employ low index of refraction regions surrounding a large core with “bridge regions” of the same index as core glass connecting core and cladding where in the ray picture, light bouncing down the fiber will not be totally internally reflected and hence leak out of the core [225]. Such fibers are inherently leaky, meaning that all modes of the fiber will decay along the length of the fiber, but with appropriate design, the loss of the fundamental mode can be made to be sufficiently small as to be considered negligible while all other higher order modes have significant loss [224, 225].

![Figure 16: Sketch of a simple leakage channel fiber structure](image_url)

The loss in the different modes can be tailored by selecting the ratio of the diameter of the round low index features to the spacing between them in their hexagonal arrangement around the core region [225]. Such designs are usually optimized on sophisticated fiber mode-solving software by plotting the ratio of the feature diameter to the feature spacing versus the loss in the few lowest fiber modes for a given fiber length, as there are not analytical solutions [225].
The early types of these fibers resembled PCFs as they used air filled regions to create the contrast between the silica “bridges” [225]. These air-based LCFs suffered from the same splicing difficulty issues as PCFs, and required significantly more care to work with. In order to combat such issues, the air can be replaced with a glass that is lower refractive index than the background silica. In the case of LCFs the glass is usually a low dopant concentration fluorine doped glass [224]. Recently all solid designs have been demonstrated with core diameters as large as 170 μm [221]. Because of the all glass nature of such fibers, cleaving and splicing is no more challenging than for conventional fibers provided the active and passive fibers are matched LCFs. In addition, such fibers can be bent even with core diameters as large as 170 μm, an advantage over PCFs, which need to be kept straight when core diameter is more than ~40 μm due to their weakly guiding nature [224]. This means that LCF fiber lasers can use a compromise between longer fibers to spread heat in high average power applications and shorter lengths when high peak power applications are desired with nonlinear effects being the critical problem. PM fibers can also be easily fabricated by replacing two of the low index rods with stress rods, introducing the required birefringence [224]. The main downfall of such fibers is that they can be more challenging to fabricate than conventional fibers due to the complex structure of glass rods. Currently these fibers have only been tested in Yb based lasers, as they are of the most immediate interest for applications in the ultrashort pulse regime where these LCFs are highly advantageous [224]. The use of thulium based LCFs should push the limits of nonlinear effects even higher due to the inherent long wavelength advantages of thulium as discussed in several places in this dissertation.
2.2.2.6 Gain Guiding Index Anti-guiding

Gain guiding index anti-guiding (GGIAG) fibers are another new class of potential LMA technologies first proposed by Siegman in 2003 [226]. These fibers consist of low refractive index cores surrounded by higher refractive index claddings, hence their so-called anti-guiding nature. The core does not support conventionally index-guided modes. Instead it does support these modes in their “leaky” form. These the modes exist in the core, but constantly leak energy to the cladding if the fiber core is not excited. These modes can be thought of as existing due to Fresnel reflections at the core-cladding interface. Though these reflections can be low loss they can never be lossless as are total internal reflections. When the fiber is pumped gain in the core can compensate for the loss in the leaky modes resulting in lossless modes confined in the core.

To maintain single mode operation gain must be supplied such that it makes up for the loss in the lowest order mode but not for higher order modes. The basic theory for GGIAG fibers is laid out in two papers by Siegman [226, 227]. Based on this principle laser oscillators can be designed with their gain and oscillation threshold conditions optimized to attain single mode operation by using analysis given in [228, 229]. The first gain guided fiber lasers were demonstrated in flashlamp pumped cavities with core sizes from 100-400 µm [228, 230, 231] and M²<1.5. Diode pumping through the fiber end was subsequently demonstrated [229]. The mode areas reported by these papers are the largest reported in any fiber laser; however, efficiency and output power scaling of GGIAG fibers using new techniques and pumping schemes must still be addressed before the technology can become competitive with other LMA technologies. Gain guiding effects have also been seen in conventional fibers. Recently a dramatic change in the guidance properties in highly doped optical fibers was reported at very high pump powers where the gain
and refractive index changed due to very strong pumping [232]. Chapter 3 is devoted to discussion and demonstration of GGIAG fiber lasers.

2.2.2.7 Techniques Implemented in this Work

Research in many of the techniques discussed in earlier sections is currently ongoing and several techniques are still in immature phases. Because of this, the majority of the previously listed techniques only exist and have only been tested in fibers based on Yb (or Nd). This dopant is well understood and the technology for making it into fiber lasers including pump diodes, optics and diagnostics are readily available and reliable. This leads the newest LMA fiber designs to be fabricated and tested in Yb first and to not be available with the dopant of interest in this work, thulium, until the fiber design is mature. As a result the type of LMA fibers available for this dissertation work is limited to standard conventional designs. The techniques used herein are based around standard small refractive index step LMA fibers doped with thulium with reasonably small V parameters. These fibers are coupled with the conventional beam quality control techniques of fiber coiling and in some cases single mode excitation. The one unique design feature of these thulium doped LMA fibers is a “pedestal.” Because of the high amount of thulium and other additives including aluminum (for thulium ion clustering reduction [75]), which are put into these LMA fiber cores it is nearly impossible to make a very small direct core to clad refractive index step since these materials raise the refractive index of silica glass with respect to undoped silica. In order to combat this, a pedestal of passively doped (germanium) high refractive index material is built up around the doped core to make a very small index step. This allows the small NA fiber with a large thulium concentration. Figure 17 shows a sketch of this design.
In addition to the conventional thulium doped fibers used in the majority of this work, research as part of this dissertation was conducted into the new and novel GGIAG fibers based on Nd doping with the idea that in the near future the knowledge gained by working with the fiber design would lead to thulium based GGIAG fibers. As discussed in 3.5 GGIAG fibers may have distinct advantages when doped with thulium.

2.2.2.8 Thulium Doped Fibers Utilized

A wide variety of thulium doped fibers were used in various experimental work in this dissertation, and in order to simplify referring to them later their parameters and properties are collected in this section. All of the fibers come from a single vendor, Nufern Inc, and have a variety of sizes, shapes and parameters. In addition, every active fiber used has a matching passive fiber twin, for use in making fiberized components or for thermal mitigation schemes as discussed later.

The main fiber employed in a majority of experiments is an LMA thulium doped fiber with \( \sim 4 \) wt% thulium. As pictured in Figure 18, the fiber has a 25 \( \mu \text{m} \) diameter core and a 400 \( \mu \text{m} \) diameter cladding.
The NA of the core is in the range of 0.08-0.09 depending on the exact batch of fiber used, and is typically closer to 0.09 than 0.08. An interesting figure to note is the “pedestal” structure of the fiber in the core region. There is an additional region of refractive index around the core which is used to enable the low NA of the fiber, which can be seen as a secondary ring around the core in Figure 18. This is required in thulium doped fiber because the core must be highly doped with aluminum as well as thulium to enable efficient operation. Because the additional aluminum significantly raises the refractive index of the core glass, it becomes difficult to achieve the low NA required with respect to the background silica fiber. To combat this effect, a “pedestal” or region of raised refractive index around the core is produced by germanium doping to raise the refractive index in the region around the core sufficiently to make the NA correct. The region has no effect on the pumping scheme and works well to enable the desirable NA, it simply has to be thick enough so that the fiber modes in the core do not “see” the lower refractive cladding region. With this core and NA, the fiber $V$ parameter is $\sim 3.5$ at thulium wavelengths, meaning that it has only two modes, giving it excellent beam quality. At shorter wavelengths, a fiber with similar dimensions would have more than 6 modes, making achieving excellent beam quality somewhat more difficult. As seen in the figure, the fiber has an octagonal shaped cladding, rather
than a round one, and in addition, though it is not pictured, the fiber also has a 550 \( \mu \text{m} \) diameter polymer cladding which has a low refractive index compared to silica and thus gives the pump cladding an NA of \( \sim 0.46 \). The reason for the octagonal shape lies in the need for excellent distribution of pump light. Because the pump cladding is highly multimode, there are actually some modes in the many families that can exist which have essentially zero field at the fiber core, meaning that no power carried in these modes could be absorbed in the core to provide pumping, in which case the pump light launched into them would be wasted. In order to reduce the effect of these modes, a shaped cladding is employed to break the circular symmetry that causes the “so called” helical modes (because in the ray picture they represent modes spiraling down the fiber, never crossing the core). A number of potential shapes are possible from “D” shaped to square to having the core offset from the central fiber axis. However there is an additional compromise that must be made, in terms of making the fiber not only absorb pump light well, but also be able to interface with other fibers in terms of the ability to be easily spliced. Square, D shaped and offset core fibers can be difficult to splice because of the cladding shape’s large mismatch with a conventional round fiber. The case of the octagonal fibers used here makes them as easy to splice as conventional round fibers, because they can match to something round relatively easily. The shape is not the ideal shape for reducing the helical modes, but the compatibility with round fibers makes up for the deficiency.

The next fiber employed occasionally is a PM version of the previously described fiber. As seen in Figure 19, the fiber is made PM by simply introducing two stress rods in close proximity to the fiber core, which causes a stress in the core that is greater along one axis that the other (parallel versus perpendicular to the rods). The fiber still has a 25 \( \mu \text{m} \) core and 400 \( \mu \text{m} \) 0.46 NA clad, but the core NA is slightly higher with a value of \( \sim 0.1 \).
Figure 19: PM 25/400 Thulium doped fiber

It has the same pedestal structure as the previous fiber, used to achieve the low core NA, but is not octagonal shaped in the cladding. This is because the stress rods themselves do a sufficient job to break the circular symmetry, and thus there is no need to make an octagonal fiber.

Another LMA fiber used is similar in the doping, core dimensions and NA (25 µm, 0.1 NA) to both the 400 µm outside diameter cladding fibers previously discussed, but with a 250 diameter outer cladding. Since it is not PM, it has an octagonal cladding to enhance pump absorption as seen in Figure 20.

Figure 20: 25/250 Thulium Doped Fiber

The reason for using the smaller cladding is for enhancement of pump absorption, since the effective pump absorption is reduced from the absorption of the core by a factor equal to the ratio of the squares of the fiber diameters. Effectively, the smaller cladding forces more light to
be overlapped with the core and hence enhances pumping. This is a critical fiber to use in situations where the fiber length is to be kept short, as in short pulse amplifiers where nonlinear effects that grow with length are to be avoided or when thulium laser operation below the 1950 nm regime where reabsorption in longer fibers would not allow lasing or amplification.

The final fiber used in this work is a truly single mode fiber, which has the advantage of higher beam quality and lower laser thresholds that are due to the smaller core dimensions, making it useful in a number of applications. The fiber has similar doping levels to the fibers discussed earlier and a 10 μm core with 0.16NA. As seen in Figure 21, the fiber is PM so there is no need for octagonal shaping of the 130 μm diameter cladding which is coated with low index polymer to achieve the desired 0.46 NA.

![Figure 21: PM 10/130 Thulium Doped Fiber](image)

In addition to the 4 wt % thulium doped version of this fiber, a fiber with around half that value is also used. The fiber is otherwise identical to the higher concentration fiber.

There is still a potential for the design of future thulium fibers with more favorable dimensions allowing further enhancement of power handling capabilities, because of the inherent advantages associated with the longer thulium wavelength. By implementing the same pedestal design tricks, a very useful 40-50 μm core diameter fiber can be produced in a 400 μm cladding
fiber, making it similar in pump absorption to a 25/250 fiber, enabling a very large core and short
length amplification, while putting less constraints on the brightness of the pump diodes required
This would enable higher powers to be coupled into the fiber. It may even be possible to push the
fiber dimensions to 70 or more μm in the core, but it is best to keep the cladding below 400 μm,
as beyond this dimension, cleaving and splicing of the fiber becomes difficult.

2.2.3 Thermal and Mechanical Damage Mitigation

Mitigation of the potential for optical damage and nonlinear effects is covered in the
previous sections in terms of techniques for increasing mode area; however as discussed in 2.1.2,
there are also thermal limitations to high power thulium fiber laser operation and such limitations
must be mitigated by use of thermal management schemes to enable high power operation. In
addition to thermal effects that must be mitigated, mechanical issues with fibers are also
important in terms of techniques for splicing fibers together and for preparing their end facets to
avoid optical damage. These topic areas are discussed in the following sections with a focus on
the techniques used in experimental work for this dissertation.

2.2.3.1 Discussion of Thermal Management

In order to present issues with thermal management pertinent to this dissertation, the laser
with the most demanding thermal mitigation requirement, the high power atmospheric
propagation system from section 4.2.2, is discussed. The thermal management of the system can
be broken down into different components which must respond to differing thermal problems,
the overall thermal management solution is seen in Figure 22.
Figure 22: View of cooling scheme used on high power thulium fiber laser systems

The active fiber itself must be cooled to keep the laser operating efficiently and to avoid thermal damage to the polymer. This is achieved by wrapping the fiber around a mandrel with a “V” groove spirally cut around it. The groove holds the fiber in place and helps provide slightly more cooling than if the fiber were simply wrapped around a drum. The ideal situation would be to replace the “V” groove with a “U” groove which had a bottom curve matching the fiber outside diameter to enable the best thermal contact; however this precision was outside the mechanical fabrication capabilities with the available machine shop equipment. The mandrel itself is conductively cooled by water on one surface to keep it at a constant temperature. Wrapping a fiber around a mandrel is a simple solution for achieving thermal management, however the use of passive fibers on both ends of the active fiber to reduce the impact to heating directly on the fiber end is also critical. This leads to a further challenge in thermal management, because when splices to the passive fiber are made, the region must be stripped of polymer and recoated. The resulting “recoat” is not as mechanically strong as the original polymer coating, so the fiber cannot be bent without fear of breaking the splice. The fiber must thus be held straight, and thermal management is accomplished by putting the fiber in a straight groove and butting that groove to the mandrel at the appropriate height such that the entire fiber still remains in
contact with a heat sink, as seen in Figure 22. Because the V groove does not completely contact the entire surface of the fiber and because there may be small air gaps at the interface between straight V grooves and mandrel, the fiber is also coated in a thermally conductive paste with conductivity of ~0.7 W/mK. Though the conductivity of the paste is lower than even the glass, it is much higher than air, and will enhance cooling to some extent compared to air surrounding the fiber, as it helps to spread the cooling over the entire fiber surface, despite that fiber only being in contact with the heat sink at two points in the V groove. The usefulness of the paste can be illustrated by using a similar equation to (13), but with an additional term to the piecewise function and an additional term in each piece, essentially to account for an extra layer of thinly distributed thermal paste. Doing so still makes the assumption that the fiber is immersed in its heat sink constant temperature, but with a layer of either air, thermal paste, or aluminum impeding progress of heat from the fiber to the heat sink. Figure 23 shows an example of this for a typical heat load on 25/400 LMA fiber used in this work (50 W/m) assuming relatively high heat transfer coefficient of the outside heat sink layer itself, corresponding to reasonably efficient water cooling.

Figure 23: Comparison of temperature of 25/400 μm fiber under 50 W/m heat load with various surrounding materials. Lines indicate boundaries between layers inside and outside the fiber

The temperature at the fiber polymer in all three cases is well below the critical value of ~105°C, but clearly the air encased fiber is significantly hotter at the fiber-polymer interface with a nearly
20°C higher temperature than the thermal paste encased fiber at the polymer interface, and 10°C higher core temperature, however the difference between thermal paste and a perfect heat sink is relatively small, only a few degrees. Essentially, the material surrounding the fiber before the heat sink must be larger than the conductivity of the fiber polymer layer to keep temperatures under control. This example is rather crude and by no means an exact model, but it shows the effectiveness of using thermal paste and that using the heat sinking scheme devised is more than sufficient to protect the fiber from polymer damage. According to the simple model used, the cooling scheme should be sufficient for heat loads three to four times higher than the current laser, corresponding to a kW level laser. However, it is likely that the model underestimates the temperature of the fiber, as it assumes “too perfect” of a heat sink and does not take into account other more localized sources of heat, such as absorption of 2 μm light propagating in the cladding (caused by imperfect feedback of light, or imperfect splices for example) which becomes absorbed locally in the polymer coating, especially at the polymer coating of a splice.

The second critical position where thermal management is crucial is at the tips of the passive fibers where pump light is incident. They are usually cleaved at some angle to as clean a surface as possible to avoid scattering of pump light and localized heating on surface defects of the fiber tip, as discussed later. Theoretically the tips should not heat up, since there is only a very minimal absorption at pump wavelengths, however the polymer coating of a fiber can have a more significant absorption and again can be a cause for laser damage. To mitigate this, the fiber tip is held in a water cooled groove to keep any stray pump light absorbed in the polymer from causing heating damage. In addition, a short section of fiber polymer must be stripped in order to achieve a cleave. If the fiber polymer is not stripped back far enough when pumping, stray pump light caused by aberrations or slight misalignments can be incident on the polymer
with the potential to cause it to heat and burn. Stripping too far back can cause issues with fiber mechanical strength, and it is found experimentally that a “happy medium” for strip length is ~5 mm. Another source of damage in the polymer can occur because of the stripped section. In the stripped section, the NA is determined by air to glass refractive index difference, giving a larger NA than that of the polymer. This means that higher-order pump power which cannot be guided by the glass-polymer interface can propagate in the glass-air region, especially if pump alignment is poor. These higher order modes are immediately stripped out at the point the polymer begins, causing potentially large localized heating and fiber failure. This type of failure is typically the most common failure mode and cannot be compensated for by heat sinking, as the heat loads can be too high. Thus careful pump alignment and high quality pump optics are critical; the pump must also be stable over time, because if it becomes misaligned, damage can occur. These issues are all removed if “all-fiber” pump schemes are used, but those schemes bring their own unique thermal challenges not discussed here.

2.2.3.2 Free Space Optics Considerations

As discussed in 2.1.2.5, thermal management of bulk components in fiber laser systems is also a critical aspect of thermal management. Since components are not always available in an “all-fiber” format, it is critical that when a fiber laser with free space components is set up, the mechanical components used are selected such that they are stable to vibrations and especially fluctuations in temperature. Components should be kept as close to table surfaces as possible to avoid vibration effects and should be made from materials with low coefficients of thermal
expansion, with the same material used everywhere possible to avoid differential movements of materials caused by different coefficients.

It is critical that lenses with minimal absorption be used, which at thulium wavelengths means using low OH- fused silica (Infrasil). If components from correct materials cannot be used, thermal management must be implemented. One example of a situation where thermal management of optical components was used occurred in the pump optics of the high power MOPA system described in 4.2.2. Because the lenses used had to be sub-optimal for cost considerations, they tended to absorb and scatter light. Absorbed light caused the lenses to heat and the scattered light was absorbed in the mechanical mounts for the lenses. The situation was remedied as seen in Figure 24 by using water cooled tubes and heat sinks wrapped around the optics to enable maintenance of stable pump launch. Without these water cooling components, temperature rises of 30-50°C at 300 W incident pump power were measured in the pump optics mounts, leading to significant misalignment. The use of the active cooling remedied the situation.

Figure 24: Pump coupling optics thermal management scheme

Thermal instability can also occur in elements such as diffraction gratings as observe in the section on spectral beam combination 6.1, and to a lesser extent in the grating tuned laser in
4.1.3.2. Active cooling of the gratings via water or thermoelectric coolers enabled higher power and more stable operation, though the high absorption of the metal gratings still saw limitations, regardless of the amount of cooling used.

2.2.3.3 Mechanical Fiber Preparation: Splices and Cleaves

Fiber preparation is crucial for reducing the potential for optical or thermally induced damage. The typical method for preparing a fiber end facet for use in a high power laser in this dissertation is by way of cleaving using a Vytran LDC-200, a cleaver designed to cleave large diameter fibers [233]. The basic procedure for a cleave is first the fiber is put under tension, then an oscillating diamond blade is moved in until it makes a slight contact with the fiber glass surface. This forms a surface defect that propagates as a crack across the fiber, leaving a very clean fiber surface [234]. Incorrect cleave tension, either too high or too low can lead to the formation of surface defects as seen in Figure 25 as either “mist” or “hackle” which are rough surface defects that will lead to localized heating by pump light and if very poor, loss on the signal [234].

Figure 25: Cleaves showing progressively worse degradation of the surface of a 25µm core, 400µm clad TDF due to improper cleave tension. In this case the tension amount increases from left to right starting at 1155 grams and progressing to 2100 grams in steps of ~300 grams
Fiber cleaves can be very flat, with less than one degree of flatness readily achievable, however in order to do so, the fiber must be mounted in the cleaver before attempting cleave with no torsional stress (caused by rotation about the fiber axis). Small amounts of torsion lead to angled cleaves which are undesirable for splices; larger diameter fibers are more sensitive to rotation, and thus are more difficult to cleave flat. Odd shaped fibers such as the octagonal thulium doped fibers are even more difficult, as their shape tends to inherently put a torque on the fiber unless careful pre-cleave mounting is done [233, 234].

If an angle cleave is desired, it can be achieved by controllably rotating the fiber and reducing cleave tension, which is useful for amplifiers, however maximum achievable angles are in the range of 8-10°. At angles beyond this point, misting and hackle are unavoidable; this makes pumping through such cleaves difficult. To achieve larger angles, polishing techniques must be used. With use of clean cleaves, optically induced surface damage can be minimized, though to what extent compared to a perfect surface polish has not been studied.

Surface damage due to high optical powers can be further mitigated by use of fiber end caps. End capping is achieved by splicing a section of glass with no fiber core onto the end of a fiber, thus allowing the output to expand before exiting through the glass surface (where damage threshold is lowest). A schematic of an end cap is seen in Figure 26, stressing that the correct diameter of bulk glass must be spliced to avoid degradation of beam quality. The glass must be such that the expansion of the fiber mode into the end cap must not reach the end cap’s glass walls.
Figure 26: Schematic of end capped fiber

Fusion splicing is a critical task for producing high efficiency, damage free fiber lasers. It is achieved by mechanically aligning two fiber tips prepared by a cleave above a heating element such as a filament or electrical arc [234]. The heating element is activated and the fiber tips are pushed together with the correct set of parameters to achieve fusion of the two glass sections [234]. When using LMA fibers, special equipment must be used to achieve high quality splices with repeatable results, such as the Vytran-GPX 3400 used in this dissertation work [233]. The process of fusion splicing, especially of LMA fibers, is a detailed and complex process involving the balance of glass surface tension, melting point and position of fiber tips to create the desired low loss splice without mode deformation. Though modeling of splices can be achieved [234], optimization of LMA splices is best done by trial and error, which is how the optimal spliced were created for the different fibers used in this work. The temperature of the splice filament, duration of filament time and positioning of the fibers were altered to produce optimized splice performance. Specialized techniques using the GPX-3400 such as fiber tapering are also possible by using the filament at an appropriate temperature on a single fiber, and pulling the fiber ends to produce a taper. The resulting taper can then be cleaved in the center to produce part of a mode.
field adaptor as used in parts of 4.2.2 or in fabrication of a tapered saturable absorber as discussed in 5.3.1.

2.3 Power Scaling of Eye Safe Lasers

The main driving force behind the work in high power thulium fiber lasers in this dissertation is the desire for high power lasers in the eye safe regime. This section outlines considerations that are specific to power scaling in this regime, including material choice for a glass host, the alternate choices of fiber dopant, and the advantages and reasoning behind the use of thulium in terms of its superior performance characteristics. Finally, a more detailed discussion of the thulium ion itself, including pumping schemes and the reasoning behind the selection of 790 nm pumping for the majority of lasers built for this dissertation.

2.3.1 Comments on Host Materials

Though silica fiber is by far the most dominant material in all of the fiber based industries including high power fiber lasers, there are several other materials which may potentially find a niche for specific applications. Varying the doped host material may provide benefits in one of three important areas, laser properties such as upper state lifetime and emission cross section, doping properties and potential for higher doping, and finally transparency considerations when operating at mid-IR wavelengths. Each of these categories may require different types of fibers with different upsides and downfalls. These different materials and their potential benefits will be discussed in subsequent sections. Table 2, which contains glass data for several glass types, will be referred to throughout this section.
Table 2: Sample properties of different types of glasses used for fibers. Note that data even among one glass type is scattered among different compositions, hence these values may only be taken as approximate for comparison sake. From [4, 235-243].

<table>
<thead>
<tr>
<th>Glass Type</th>
<th>(T_x) (ºC)</th>
<th>Bulk Damage (GW/cm²)</th>
<th>Thermal Conductivity (W/mK)</th>
<th>(\frac{dn}{dt}) (10⁻⁵/ºC)</th>
<th>CTE (10⁻⁷)</th>
<th>Trans (µm)</th>
<th>Young’s Modulus (GPa)</th>
<th>Knoop Hardness</th>
<th>n² (10⁻²⁰ m²/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>1175</td>
<td>600</td>
<td>1.3</td>
<td>11.9</td>
<td>0.55</td>
<td>0.3-2.1</td>
<td>72</td>
<td>600</td>
<td>3.4</td>
</tr>
<tr>
<td>Phosphate</td>
<td>366</td>
<td>25</td>
<td>0.84</td>
<td>-4.5</td>
<td>104</td>
<td>0.4-2</td>
<td>71.23</td>
<td>418</td>
<td>1.2</td>
</tr>
<tr>
<td>Germanate</td>
<td>741</td>
<td>-</td>
<td>0.55</td>
<td>1.2</td>
<td>63.4</td>
<td>0.5-3.9</td>
<td>85.77</td>
<td>560</td>
<td>-</td>
</tr>
<tr>
<td>Tellurite</td>
<td>482</td>
<td>10</td>
<td>1.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>54.5</td>
<td>-</td>
</tr>
<tr>
<td>Chalcogenide</td>
<td>180</td>
<td>6</td>
<td>0.37</td>
<td>9.3</td>
<td>21.4</td>
<td>0.6-8</td>
<td>15.9</td>
<td>109</td>
<td>400</td>
</tr>
<tr>
<td>ZBLAN</td>
<td>385</td>
<td>0.025</td>
<td>0.628</td>
<td>-14.75</td>
<td>17.2</td>
<td>0.5-5</td>
<td>52.7</td>
<td>225</td>
<td>2</td>
</tr>
</tbody>
</table>

2.3.1.1 Silica glass based fibers

Silica fiber provides what may be called the “best of many worlds” in terms of fiber lasers. The predominant reasons for use of silica fiber are its extremely high damage threshold and melting point, ease of manufacture and physical strength.

Nearly all fibers used in telecommunications are based on silica and as a result the manufacture of fibers based on it has been optimized. Adapting its use for fiber lasers has been a natural transition. Silica is the only fiber commonly manufactured by the MCVD technique, which is the fastest, simplest and cheapest way to manufacture fiber preforms [36].

An additional benefit of silica fiber is its extremely high melting point and damage threshold. Silica fiber will not melt until nearly 2000ºC, significantly higher than most of its glass counterparts. As a result, silica is especially suitable for high power work, because the heat associated with high power fiber laser quantum defects can cause catastrophic melting of fibers with insufficient temperature handling capabilities. The surface damage threshold of silica is ~40
GW/cm² for nanosecond pulses, which again is extremely high and suitable for high power pulsed laser systems [244].

A final benefit of silica is its physical durability to mechanical and thermal stresses. Many of the softer glass types can easily be mechanically damaged by relatively weak physical forces; however, silica fibers are stable and sturdy, keep cleaves well and resist breaking under vibration when coiled. These traits make them suitable for many of the higher mechanical stress, portable fiber laser applications. Since these situations are seen as one of the main areas where fiber lasers are superior, it makes sense that silica should be the most popular host material. Silica fiber also splices, cleaves and polishes very well, making its use far simpler.

Reasons why silica may be inappropriate for certain fiber systems include its relatively high $\frac{dn}{dT}$ compared to some glasses as seen in Table 2. When fiber are operating with low index contrast or when fibers (such as GGIAG [228-230]) cannot tolerate positive index profiles this large positive number may not be desirable, and hence glasses with negative values may be desired. Silica also has a slightly higher $n_2$ than some glasses, which may make it undesirable in some laser situations where absolute minimum nonlinearity is required. Silica’s transparency window is also rather limited in the near IR where many fiber lasers operate. It stretches from ~0.3 μm to ~2.2 μm, after which absorption begins to become a concern, as seen in Table 2. This limits the range of silica fiber operation in the mid-IR where a great deal of interest in high power fiber lasers exists. For instance, in holmium lasers made from silica, laser performance was poorer, due to absorption associated with OH⁻ in silica glass [245]. Sometimes other host glasses provide superior laser parameters compared to silica, and when such laser parameters are an issue, use of alternate materials may be required [246, 247].
A final, and perhaps most important, limitation on silica is the relatively low dopant concentrations which in most cases are limited to a few wt. % before the onset of clustering and other detrimental effects [75, 248]. This can be improved by addition of aluminum as a way to reduce clustering, which is the method used in thulium fiber lasers to achieve the concentrations required to ensure efficient cross relaxation discussed in section 2.3.3.1 [75, 248]. This maximum doping threshold makes it difficult to form highly doped fibers. Such fibers may be advantageous where dopant concentration dependent processes such as upconversion and cross relaxation are important or where very short lasers are advantageous. It is difficult to use cladding pumped silica fiber to make short-length fiber lasers with high pump absorption per unit length. Overall, despite its flaws, silica is still usually the best fiber host for most fiber lasers and is the host of choice for the high power thulium work discussed in this dissertation.

2.3.1.2 Phosphates, Germanates and Tellurites

Glasses such as phosphates with open glass structures are capable of handling far higher dopant concentrations compared to silica [75, 248]. This higher dopant handling is the main attraction of such soft glasses. Fiber lasers have been demonstrated with doping percentages as high as 10 times that allowable in silica [249, 250]. These extremely high percentages allow for very short fiber lengths, making these fibers suitable for high peak power amplification to avoid nonlinearities, narrow linewidth generation, and for use in core designs that limit the length of the fiber due to bending losses. Though these glasses have low melting points, reasonably high powers have been obtained with careful laser design and pumping schemes. Melting is a significant challenge to these types of fibers, as pump powers in the range of 20-100 W incident on the fiber end can cause catastrophic melting as seen in Figure 27.
Figure 27: 10 wt. % doped GGIAG fiber with core region melted due to high pump powers.

However using other more evenly distributed pump schemes, pump heat can be more uniformly distributed and higher powers have been achieved [251]. In addition to the high average powers, reasonably high peak powers have also been obtained from fiber systems based on these highly doped glasses and also very narrow linewidths. Phosphate fiber lasers have achieved as high as 20 W output power based on Yb doping [250] and 4 kW peak power in single frequency Q-switched systems [252], germinate glass based fiber lasers with pulse energies of 0.25 mJ and output powers of 104 W have also been reported [78, 253]. Despite their achievements, these fibers still have a hard limitation of a few 100 W in terms of output power due to thermal effects, limiting them compared to the several kilowatt power handling abilities of silica fiber. Though some of the soft glasses may show better laser characteristics for some dopant ions in terms of cross section and lifetime as in [247], they are still much more difficult to manufacture in terms of both cost of materials and require time consuming core drilling techniques to be effectively manufactured. As a result, their difficulty in manufacture and limited power handling usually outweighs their superior laser, thermal and doping abilities compared to silica.

Phosphate fibers are used in the experimental work done for this dissertation which is centered on gain guided index anti-guided fiber lasers. Such lasers require extremely short lengths, and hence benefit from the ability to highly dope phosphate glasses. In addition, the
negative $\frac{dn}{dT}$ in phosphate helped to ensure that guiding effects observed in the pumped fibers were actually due to gain guiding and into a thermal lensing related phenomenon. A full treatment of such fibers is given in chapter 3.

2.3.1.3 Fluorides

Another common glass host for producing fiber lasers is the fluoride glass family. The most widespread of these glasses is called ZBLAN, named for its chemical composition containing ZnF$_4$, BaF$_2$, LaF$_3$, AlF$_3$, and NaF [248]. Compared to silica, ZBLAN allows many more laser lines in both the visible and farther into the IR based on a number of rare earth dopants [248]. The visible region is reached by a process known as upconversion where fibers pumped by the standard diode sources have two photon excitations due to long excited state lifetimes, resulting in visible lasers with watt level powers [248]. Several reasonably high power near and mid IR lasers have also been reported using ZBLAN including in Ho [245, 254] with outputs of 0.38 W, Er with outputs of ~10W at 2700 nm [255], and in Tm with outputs of 20 W CW and 9 W average power, pulsed with energies of 90 μJ [246, 256, 257].

ZBLAN has potential in particular laser applications where its lifetime and cross section properties make it advantageous in terms of its having a lower threshold behavior, especially in ions such as Tm which have very high laser thresholds. Eichhorn and Jackson compare the characteristics of Tm:ZBLAN and Tm:silica at ~50 W pumping levels and find ZBLAN to be superior in terms of efficiency and threshold [246]. This means for some modestly high power fiber lasers, ZBLAN and similar materials may be beneficial. Laser threshold was found to be
nearly half that of Tm:silica and efficiency is eight percentage points higher than a similar silica fiber, with a lower tendency to self pulse compared to silica fiber [246].

Despite the clear benefits of ZBLAN in some situations, there are also limitations; these limitations stem from fabrication difficulties with ZBLAN fiber which requires the core drilling method, thus making its mass quantity production cost ineffective and also the low melting points and damage threshold of ZBLAN making it difficult to produce fiber lasers with this material above the 50 W level [246]. This precludes it from generating the extreme powers of silica based fiber lasers, and as a result keeps powers limited to the sub 100 W level. ZBLAN is also a very brittle material to work with compared to silica, making it difficult to polish, cleave and splice with high quality. Despite the potential advantage in some aspects for thulium, the cost and difficulty to work with ZBLAN precludes it from further consideration and use in this dissertation research which requires hundreds of watts of output powers in stable, reliable systems.

2.3.2 Potential Gain Media for High Power Eye-Safe Lasers

There are three main potential dopants capable of reaching the eye-safe regime in fiber lasers: erbium, thulium and holmium. Each dopant offers distinct advantages and disadvantages for use in power scaled fiber lasers, these are considered in the following sections and a case for the use of thulium as the dopant of choice for this dissertation is also made.
2.3.2.1 Erbium

Because of its low absorption cross section at any commonly available wavelengths, singly doped erbium fiber lasers are difficult to scale to high powers. High power operation implies a double clad fiber design where pump radiation is guided in the fiber cladding and subsequently pumps the core as it propagates along the length of the fiber. Double clad pumping effectively decreases the absorption cross section by the ratio of the area of the core to the area of the “pump cladding.” The erbium absorption line that best matches with available high power pump diodes is in the 980 nm regime. At this wavelength, the absorption cross section of erbium is so low that an excessive amount of fiber would be required for efficient pump absorption, and due to reabsorption inherent in a three level laser system, the overall laser efficiency would suffer due to the long fiber. Higher power diodes at 1480 nm are being developed for directly pumping erbium lasers in double clad configurations where a higher absorption cross section is available, however, these diodes are only available with one or two orders of magnitude lower power compared to 980 nm diodes [258]. In addition to 1480 nm diodes a novel “in-band” pump scheme is being developed by using newly available moderate power diodes with around 11 W output power at 1532 nm [259, 260]. Theoretically this enables Er based lasers with extremely high efficiency due to the minimal quantum defect for lasing at ~1590 nm, however currently the maximum achieved efficiency is 56% with ~30 W output power [259, 260]. In addition to issues with power scaling, the use of in band pumping limits the potential available lasing bandwidth, which may be an issue if such lasers are used for spectral beam combination applications. Though diodes for this scheme are only available with ~11 W of power each and require VBG stabilization to enable efficient pumping, the potential of this method for power scaling of purely erbium doped fiber lasers does exist due to the low quantum defect. It is likely that as higher
power diodes become available, more research will be done into the optimization of the fiber composition to enable higher efficiencies.

2.3.2.2 Erbium:Ytterbium Co-Doping

A solution to the low erbium cross section and lack of high available pump powers is co-doping with ytterbium. Yb has a significantly higher absorption cross section at 976 nm compared to Er and thus it can be used to “sensitize” Er ions in a properly composed fiber. Energy from ytterbium is then nonradiatively coupled to the erbium ions, resulting in relatively high power operation with maximum powers peaking at around 300 W. However further power scaling is limited due to the onset of strong ASE and even parasitic lasing from the ytterbium ions themselves [95]. The overall quantum defect from pumping at 976 nm is also a disadvantage for erbium, as the maximum achievable efficiency is only in the ~60% range and most high power lasers based on this system struggle to break ~45% slope efficiency due to ASE issues. Readily available components designed for operation in the 1500-1600 nm erbium lasing region stemming from telecommunications development are an advantage for erbium, however for very high power operations custom components will still need to be developed to handle the higher heat loads.

2.3.2.3 Holmium

Holmium suffers similar disadvantages as erbium when it comes to a lack of available pump diodes in its absorption regimes. Direct diode pumping has been achieved with laser powers reaching multi-watt levels, however scaling to extremely high powers is still quite a way
off, as the required pump diodes are simply not available at necessary power levels [245, 254, 261]. Holmium can also be co-doped with other ions including ytterbium or thulium, although this will lead to the same ASE problems as in erbium:ytterbium systems [262]. Holmium is often directly pumped by thulium fiber lasers and in this way has reached nearly the 100 W level [263]. This direct thulium laser pumping is an advantage, as the pump wavelength of 1940 nm or 1908 nm is quite close to the lasing wavelength, and thus there is a minimal quantum defect. However, scaling to high powers in holmium requires high power thulium lasers already operating at eye-safe wavelengths with high beam quality, so it would make more sense in most applications to simply power scale thulium lasers, without the added complexity of then pumping holmium. The main advantage of holmium is that it is capable of reaching longer wavelengths than thulium due to its larger emission cross section well beyond 2100 nm. However, the cutoff wavelength for silica fiber, the main glass host for high power lasers, is around the same wavelength range (<2200 nm), and therefore, background absorption causes difficulties with efficiency. In addition, thulium fiber lasers have been demonstrated with reasonable efficiencies at wavelengths as long as 2180 nm, further reducing the need for high power holmium based fiber lasers in silica fiber except for particular special applications. As with direct erbium lasers, however, as direct diode pump sources in the 1900 nm region become available with high powers holmium my again pick up in interest as a low quantum defect laser medium in the 2 micron wavelength range [258].

2.3.2.4 Thulium

Thulium has the widest potential lasing bandwidth of any rare earth ion, with the ability to make lasers from 1720 nm out to 2180 nm. This broad bandwidth makes it attractive for
applications that are able to take advantage of its broad spectrum, including ultrashort pulse lasers and spectral beam combining. At first glance, difficulties using the thulium ion for power scaling may be foreseen because of the large quantum defects of its two main pump bands, 790 nm and 1550 nm. At 1550 nm the quantum defect is ~60%; however the only high power pump sources at this wavelength are erbium fiber lasers, so the same issue as previously discussed with thulium pumped holmium lasers apply to 1550 nm pumped thulium lasers. Consequently, 1550 nm pumping of thulium is relegated to applications where very short fiber lengths are required. This can be achieved by high absorption associated with core pumping of thulium with erbium lasers or for applications where erbium lasers are readily available and can combined to produce high pump powers (as is the case with IPG Photonics who produces large numbers of Er:Yb fiber lasers and thus is more easily able to package systems based on 1550 nm thulium pumping [92, 96, 264]).

At first glance 790 nm pumping of thulium fibers does not appear to be optimal due to the large quantum defect leading to only ~40% potential efficiency, however there is a feature in the thulium energy level structure when pumped at 790 nm known as cross relaxation, which allows two laser photons to be created from one pump photon, thus effectively doubling the potential quantum efficiency [74, 75]. The cross relaxation process will be discussed in further detail in 2.3.3.1. Thulium lasers with efficiencies of up to 70% have been demonstrated and powers of up to 885 W with >60% efficiency [78, 265]. The main disadvantage to using thulium is that to achieve efficiency, sufficient thermal management of the fiber is necessary and, in addition components at thulium laser wavelengths are not readily available. Both of these are lower level disadvantages, as thermal management is required at high power levels regardless of the dopant ion in order to prevent thermal damage to the polymer coatings on fibers. In addition,
as thulium lasers are scaled, the components will follow, based on lessons learned from 1550 nm technology from telecommunications.

2.3.2.5 Power Scaling Advantages of Thulium Doped Silica Fiber

Weighing all the advantages and disadvantages regarding pumping, thulium comes to the front as the best choice for use as a dopant to reach high powers and pulse energies in the eye-safe regime. In addition to the pumping advantages, thulium also offers the largest bandwidth (1720 nm- 2180 nm) of any of the rare earth ions in silica glass in the eye-safe regime. The large bandwidth opens up uses in ultrashort pulse amplification and applications which require wavelength flexibility, including spectral beam combining and atmospheric propagation.

Longer wavelengths compared to ytterbium or erbium lasers also lead to an advantage in terms of detrimental nonlinear-effect-limited output powers. As reported in [12], the theoretical maximum achievable output power for a single ytterbium doped fiber laser is 36 kW, based on limitations associated with nonlinear effects in the fiber core [12]. Thulium is at an advantage due to its wavelength for two reasons; larger core sizes and higher nonlinear thresholds. Larger core sizes (and hence mode field diameter sizes) are achievable at 2 μm simply due to the fiber V parameter (the value for the cutoff of modes) scaling inversely proportional to the wavelength. Larger cores can be used in thulium based LMA fibers before higher order modes can exist and distort beam quality. Nonlinear effects that limit ytterbium fiber lasers are increased in threshold at longer wavelengths, hence higher powers can theoretically be achieved. Dawson suggests this in [12] stating that potential output powers from thulium doped fiber lasers might reach twice those of ytterbium doped fiber lasers. This means that simply by working at longer wavelengths, the maximum achievable pulse energy and average power are inherently increased.
2.3.3 Techniques for Pumping of Thulium Fiber Lasers

With the recognition of thulium as one of the best potential dopants for reaching high average powers at eye safe wavelengths, the next step in understanding how high power lasers based on thulium are constructed is to understand how pumping is achieved. It is the pumping scheme of thulium that eventually gives it the advantage compared to the other eye safe wavelengths, and understanding the mechanisms is critical to optimization of laser performance. This section outlines different potential pump schemes, the origins of these schemes via a brief look into thulium spectroscopy and energy levels and finally the mechanism behind the cross relaxation mechanism driving the 790 pump schemes that gives thulium its efficiency.

2.3.3.1 Thulium Energy Level Structures and Processes

The four energy levels most important to the operation of eye-safe thulium fiber lasers are the $^3\text{H}_6$, $^3\text{F}_4$, $^3\text{H}_5$ and $^3\text{H}_4$ as shown in Figure 28. The structure of an individual level, as is typical of all rare earth ions in glasses, is that the energy level is broadened into many sublevels [160]. This broadening is caused by the local electric field that a particular ion experiences in the amorphous glass background material [160]. This field is varied in intensity by random inhomogeneities and variations in the glass, and thus (via the Stark effect) causes different ions to have slightly different energy levels and thus different transition wavelengths; this mechanism is known as inhomogeneous broadening, which is the dominant mechanism driving the large bandwidth of the thulium ion [160], though homogeneous broadening and other effects can also have an impact on the way the laser acts (as thulium in some cases can act “quasi-
homogeneously” broadened [246]). The Stark splitting is represented by arrays of individual lines in Figure 28, however in reality, the large variations in the highly amorphous silica glass and other line broadening mechanisms makes these lines run into one-another when considered for a summation of ions, rather than a single ion, effectively creating a continuum.

![Thulium energy level diagram](image)

Figure 28: Thulium energy level diagram of the four lowest levels with approximate energy levels of transitions, including the most important processes relevant to thulium laser emission with various pumping schemes [266].

The laser transition occurs from the bottom of the $^3F_4$ down to sublevels of the $^3H_6$, enabling the broad emission bandwidth from $<1.6 \ \mu m$ to $>2.2 \ \mu m$ of thulium seen when measured by spectroscopic techniques from a variety of references [266-272]. The $^3H_6$ is also the ground state, and as a result the thulium laser transition of interest is actually a three level transition, though due to thermal population distributions within the $^3H_6$, laser transitions beyond $\sim2020$-$2030$ nm act as quasi four level transitions, as the sublevels of the ground state are not highly thermally populated near the top of the band [266, 268]. This thermal population distribution also creates a potential for strong absorption in the reverse transition ($^3H_6$ to $^3F_4$),
which limits short wavelength operation, but allows for “in-band pumping” using wavelengths in this absorption band.

Based on theoretical calculations, the upper state lifetime of this transition should be relatively high, on the order of 6 ms, [271, 272]; however, silica glass has a relatively high phonon energy of ~ 1050-1100 cm\(^{-1}\) (~0.13-0.14 eV) meaning that non-radiative processes from the same \(^3\)F\(_4\) to \(^3\)H\(_6\) transition, and so multiphonon emission can become significant and compete with radiative transition which only has a magnitude of ~5500 cm\(^{-1}\) (~0.6 eV), thus resulting in a reduction of the upper state lifetime to ~230-500 \(\mu\)s (depending on the measurement and glass composition) [266-272].

As seen in Figure 28, there a numerous potential pump bands, essentially from the ground state to each of the other three levels. The high phonon energy of silica is advantageous here, as it helps to make the multiphonon emission transitions from these pumped levels very quickly to the upper laser level \(^3\)F\(_4\). However in the case of 790 nm pumping these fast transitions are potentially detrimental, as they compete with the cross relaxation process discussed later, leading to potentially lower efficiencies [266].

Figure 29 shows the emission and absorption cross section data from a particular thulium doped silica fiber used in [273], however the spectroscopic data in various sources is within reasonable agreement, though with some variation due to use of different experimental techniques and materials [266-272].
The final processes that are important to the operation of thulium fiber lasers in the eye-safe regime are those based on cross relaxation (CR) and energy transfer upconversion (ETU) [266]. These are both processes that require the interaction between two thulium ions which are able to share energy enabling either excitation of a ground state electron to an excited state (CR) or an already excited electron to an even higher state (ETU). Though the quantum mechanical theory driving this process is beyond the scope of this dissertation, the mechanism behind the transfer of energy between the two laser ions is known as Förster energy transfer and is a non-radiative process whereby the proximity of two ions enables a dipole-dipole interaction that transfers energy from electrons in one ion to another [274, 275]. The process is strongly dependent on the distance between ions (goes as $-1/r^6$ where $r$ is distance between ions) which thus ties the process to dopant concentration, as higher dopant concentrations have ion separations that are smaller [274, 275]. This process can be used to theoretically describe both ETU and CR processes. A more detailed theory of both CR and ETU is reviewed in [266] with further references for making more detailed calculations.
The use of CR to enhance the output efficiencies of lasers was first suggested in [276], and has been put into practice in many bulk laser ([277-279] only scratched the surface of such lasers) and silica based thulium fiber laser systems, first being recognized and achieved in terms of improved operating efficiency in [73]. Dopant concentrations on the order of 2-5 wt% are required to achieve these processes efficiently in thulium doped fibers [74, 75]. However, simply having high doping concentrations is not sufficient because of the relatively small size of thulium ions and tightly bonded glass structure; it is easy for them to become clustered when introduced into an SiO₂ glass matrix. This clustering has the effect of significantly enhancing the ETU processes (because ions become extremely close together) in thulium which causes a steep reduction in potential laser efficiency, as electrons with the potential of laser transition are lost to the upconversion process [74, 75, 266, 280]. To combat this, aluminum ions are added to the glass to enhance the solubility of thulium ions in the glass [74, 75, 266, 280].

The CR and ETU processes important to thulium eye-safe lasers can be modeled relatively simply in a rate equation model. Since they are nonlinear processes depending on the populations of two levels they can be represented by rates

\[
CR_{30\rightarrow11} = k_{3011}N_3N_1 + k_{1130}N_1N_1
\]

where \(N_i\) is a energy level population of level \(i\), and \(k_{abbb}\) is the cross relaxation constant for the particular transition \(aa\rightarrow bb\). The equation shown is for the ETU and CR processes (ETU acts like reverse CR) important in thulium, several others exist as discussed in [74, 75, 266, 280, 281], but their transition strengths and other traits are insignificant compared to \(k_{3011}\) and are therefore ignored. In fact, even the \(k_{1130}\) term is an order of magnitude smaller than the \(k_{3011}\) term [282], so it can be ignored as well as is done in the model discussed in 4.3 [273], though in a
more advanced model it should be included. The factor $k_{3011}$ and others are usually determined experimentally from measuring the lifetimes of the pertinent energy levels and determining the impact of the CR on the lifetime compared to the theoretical lifetime while including a term for the total number of thulium ions as seen in

$$\frac{1}{\tau_{\text{measured}}} = \frac{1}{\tau_3} + k_{3011}N_{\text{total}} \tag{40}$$

where $\tau_{\text{measured}}$ is a measured lifetime for a level, $\tau_3$ is the decay time of that level including radiative and non-radiative processes and $N_{\text{total}}$ is the number of dopant ions. Knowing these parameters, the $k_{3011}$ value can be estimated [266, 281], though the same estimation cannot be made for $k_{1130}$, however estimates for this level can also be made as in [266, 281]. Knowing the appropriate quantities and inserting them into the rate equations (as is done in section 4.3) the CR and ETU processes can be modeled I terms of their impact on laser performance.

With optimal concentration of thulium and aluminum, extremely high slope efficiencies can be achieved with one pump photon exciting two laser photons, thus enabling quantum efficiencies approaching 200%, and thus slope efficiencies approaching 80%. The highest reported optical to optical efficiency in silica fiber currently is $\sim 75\%$ in Jackson [74, 75, 266, 280]. A final note is that many of the ETU processes are also somewhat temperature dependent, becoming stronger for higher temperatures, thus having the potential for limiting the performance of thulium fiber laser if thermal effects are not correctly accounted for [266]. In addition, as doping concentrations are increased to attempt to enhance CR processes in thulium, a maximum concentration before the onset of detrimental ETU effects may occur, as both
processes are strongly tied to concentration; therefore, a balance between the two must be struck in terms of fiber laser composition [266].

2.3.3.2 Overview of Thulium Pumping Techniques

As evidenced by the energy level diagram in Figure 28, there are a number of different potential schemes for directly pumping thulium fiber lasers. There are also schemes for pumping thulium via co-doping with ions such as Yb, in order to make use of more readily available pump diode powers. Similar to limitations placed on co-doping in Er discussed earlier, this technique is not suitable for scaling to high powers and is not considered further, though reasonably high power demonstrations have been made [266, 283].

As evidenced by the three energy levels above the ground state in thulium, there are three potential regions of pump wavelengths to consider for pumping of thulium fiber lasers. The first and probably least useful for scaling to high powers is pumping into the $^3\!H_5$ which requires pumping in the 1.1-1.2 μm region. The reason for it being slightly less useful for power scaling is a combination of the “ceiling” put on efficiency of ~65% by quantum defect due to the lack of any helpful CR processes and more importantly in the current market, the lack of availability of high power, high brightness laser diodes or other pump sources in this regime. As such sources become available the regimes may become more interesting. Despite these disadvantages, work is beginning to be done using Raman shifted fiber lasers or direct diodes to reach multi-watt level powers as the available brightness of pump sources has become available [284-286].

The second region of interest is in the so called “in-band” pumping region where light is pumped directly to the top of the $^3\!F_4$ manifold before thermally decaying to the laser transition at the bottom. The potential pumping band is anywhere from 1.5-1.9 μm thus allowing for the
potential of very small quantum defect pumping, possibly with efficiencies well beyond what is possible even from CR based lasers. However the major limitation currently, is the availability of suitable pump sources in this regime. High power, high brightness laser diodes are not readily available at suitable pump powers to reach hundreds of watts in power. In order to reach these levels, high power Er:Yb lasers are used as extremely high brightness pump sources. The quantum defect in this regime is quite high, allowing up to ~75% efficiency, however the trouble is that the efficiency of the Er:Yb lasers themselves is only ~40% with respect to their 976 nm pump power, which are in turn ~50% efficient with respect to electrical power, leading to lower overall wall-plug efficiencies, compared to 790 nm pumping schemes discussed later which have only one layer of inefficiency form wall plug power. Despite the disadvantages of this regime, the availability of high power sources from vendors such as IPG Photonics has enabled upwards of 400 W systems with commercially available 100+W systems [92, 96]. An additional use for 1550nm pumping from Er:Yb fiber lasers is the potential for their use in core pumping schemes where the length of the laser must be kept extremely short to produce single frequency light or very short wavelength thulium laser operation, as demonstrated by [287-289]. Pulsed lasers in this dissertation utilize this scheme to keep fibers short, enabling short wavelength, short duration pulses in the ps and ns regimes as seen in Chapter 5.

Further potentials in the “in-band” scheme lie in the newly growing availability of direct, high power laser diode bars in the 1.5-1.9 μm regime, being available within the range of 20 W currently [258]. These lasers have been used for pumping thulium and holmium based solid state systems [290], but have never been reported as being used in thulium fiber lasers. As the brightness and power of such lasers increases, these applications can be implemented and very high average power can be reached with low quantum defects.
A final scheme for “in-band” pumping, similar to the 1.9 μm diode pumped scheme is a thulium fiber laser-pumped laser scheme, where a collection of (perhaps 790 nm pumped) lasers operating around 1.9 μm are used to cladding pump a high power thulium fiber laser (kW level) by spreading the heat load downstream to a number of small thulium fiber laser modules each operating well within reasonable limits in the 100’s of W level. The pump quantum defect is extremely low, thus the final heat loads approaching kW levels can be relatively insignificant while the pump modules are all easily within their capabilities in the 100 W range. This strategy is similar to that taken to reach 10’s of kW levels in Yb fiber lasers where 1018 nm lasers pump a 1080 nm amplifier [57], and may enable the scaling of thulium fiber lasers to their highest potential levels in the future.

The most widespread scheme for pumping thulium fiber lasers is the use of 790 nm pumping, taking advantage of the CR scheme discussed earlier. Though on the surface, due to the large pump and signal difference and ~40% quantum defect this pump scheme may seem unreasonable for power scaling; in reality it has achieved some of the highest slope efficiencies from a thulium fiber laser, regardless of the pump wavelength used, and this includes the highest operating power levels of ~1 kW [76, 291]. The CR process, if properly optimized for concentration and reduction of ETU, enables nearly 200% quantum efficiency with 75% slope efficiency in a laser being demonstrated [74, 75]. The diodes required for this pumping scheme are readily available; they are based on the well understood AlGaAs material family used for 808 nm diodes in Nd3+ based solid state lasers, and thus are highly mature. They can be fabricated with >40% wall plug efficiencies in high brightness packages with as small as 100 μm delivery fibers, thus allowing for future high power scaled systems [105]. The main downfall of this pump band is that laser efficiencies at high powers has only reached into the ~60% efficiency
regime, leading to relatively high heat loads. If further material optimization is not accomplished, these level will not be efficient enough to drive thulium lasers to the multi kW levels. To achieve the higher efficiencies, dopant optimization coupled with care in thermal management, fiber design and laser components must be made. Some of these considerations are the focus of this dissertation work.
3 GAIN GUIDING INDEX ANTIGUIDING FIBERS

Although most of this dissertation focuses on high power thulium fiber lasers based in conventional index step large mode area fibers, a portion of the work has also been dedicated to a novel technique for scaling mode field diameters of single mode fiber lasers to values larger than 400 µm, gain guiding index anti-guiding (GGIAG). Because this technology is in its infancy, the use of thulium doped gain guided fibers is not appropriate; use of the more well understood and easier to work with neodymium ion allows development of the technology to a level where it is sufficiently understood, before venturing into more complex-to-work-with ions such as thulium. As will be discussed later, there are inherent benefits to the use of thulium ions in future incarnations of GGIAG systems. This chapter describes work from myself, in collaboration with Tony Siegman, Ying Chen, Vikas Sudesh, Michael Bass and others, have put into developing this new fiber technology.

3.1 GGIAG Introduction

The following sections give a brief overview of the basic concept of GGIAG fiber lasers and why they are important techniques. In addition, these sections will discuss the extra benefits that thulium fiber lasers will provide once married to a technologically mature GGIAG technology.
3.1.1 A Novel Technique for Fiber Lasers

The scaling of fiber lasers to ever larger mode field diameters is crucial to their competition with and replacement of larger and often more complex bulk solid state lasers due to advantages in beam quality and laser size as discussed in 1.1. Current technology in fiber lasers discussed in 2.2.2 has been able to achieve core diameters up to around 170 μm in diameter while maintaining single mode beam quality [224]. These technologies can be pushed and stretched in incremental steps towards larger sizes; however making small improvements in core diameter requires more and more effort with ever increasing levels of complexity in fiber design and diminishing returns on investment of effort. GGIAG fiber technology represents a quantum jump in the increase of potential fiber core diameter with nearly diffraction limited beam quality, as is evidenced by the results discussed in this chapter. The near order of magnitude improvement in mode field diameter that GGIAG fibers enable, translates to a near two order of magnitude increase in mode area, and thus potentially a two order of magnitude increase in potential fiber laser output energy or peak power performance as limiting damage and nonlinear effects scale with area. There has yet to be an upper bound set on GGIAG diameters, or a reduction in the rate of increase in core diameter, so the potential for even greater increases lies with further development of this technology.

3.1.2 Direct Benefits to Thulium Technology

The impact of the combination of thulium fiber lasers with GGIAG technology can be more significant than the benefit of either technology on its own. This enhancement stems from the already higher nonlinear effect and damage thresholds inherent from using the longer thulium
wavelengths. This wavelength enhancement provides an additional half order of magnitude improvement potential in fiber laser technology on top of what GGIAG itself can provide. Coupled with this potential is the extremely large bandwidth of thulium which can support extremely short pulses, and hence higher peak powers that conventional fibers could not support. Finally, as discussed in further detail in 3.4.2, the use of thulium will benefit the index crossover pumping solution for GGIAG fibers. This method uses a fiber which is GGIAG at the laser wavelength but conventionally index guiding at the pump wavelength enabling conventional fiber laser double-clad pumping techniques while exploiting the GGIAG core diameter benefits for the signal. This crossover technique benefits from laser ions with large pump and signal differences since this significantly eases fabrication demands on the glass material. However, a large disparity between signal and pump leads to low laser efficiencies in most cases due to quantum defect issues. Thulium is unique in that its cross relaxation process discussed in 2.3.3.1, enables high pumping efficiency with pump and signal wavelength separated by large spectral distances, meaning that it has the potential to produce high efficiency, simple-to-fabricate index crossover fiber lasers. In order to take advantage of any potential thulium benefits, the GGIAG technology must first be brought to a more mature level, which is the goal of the work discussed in the remainder of this chapter.

3.2 GGIAG Theory

Gain guiding index anti-guiding (GGIAG) fibers are a newly emerging class of potential LMA technologies, first proposed in 2003 by Siegman [226]. Though the theory behind GGIAG is quite sophisticated (and is covered in detail in Siegman), involving the concepts of real and imaginary refractive index and hence real and imaginary fiber V-parameter, it can also be
understood in a more qualitative way which can help give insight to the real processes driving GGIAG. The following section describes both the simplistic ray optical approach and the more complex theory based on fiber guidance.

3.2.1 Ray Optics Description

GGIAG fibers consist of low refractive index cores surrounded by higher refractive index claddings. Because of this anti-guiding nature, the core supports no conventionally index-guided modes. Modes in their “leaky” form are supported. In such modes energy propagates down the fiber in mode distributions similar to index guided modes, but leaks into the cladding of the fiber during propagation. Looking at the fiber from the ray optics point of view, the propagation of light down the fiber can be roughly pictured as Fresnel reflections at the core-cladding interface. Though these reflections occur, they can never be totally internal reflections due to the negative refractive index step, a well known consequence of the Fresnel equations and Snell’s law [292]. As a consequence, a portion of the light incident on the reflection interface is lost from the core, shown schematically in Figure 30.

![Figure 30: Trajectories of high angle and low angle rays in GGIAG fibers, note the larger angle rays, representing higher order modes, experience more reflections and more loss at each reflection, thus more loss per unit length.](image)

Different fiber modes can be thought of as rays with different angles propagating down the fiber. The lowest order modes are rays with the most glancing reflections on the core-clad interface,
and as a consequence of the Fresnel equations for reflection [292], these rays are mostly reflected, with only a small portion of light leaking out. Higher order modes have larger angles of incidence, transmitting more light into the cladding and thus having more loss per unit length. In order to achieve truly single mode operation, only the rays associated with the fundamental mode should be allowed to propagate, while those associated with any other mode should be lost after a given length of fiber. For the fundamental mode to exclusively remain, gain must be provided such that this mode sees no loss during propagation (or a net gain) while all other modes see a net loss. When actively doped GGIAG fiber is pumped, gain in the core compensates for the loss in the leaky modes. In order to maintain single mode operation, gain must be supplied such that it only compensates the loss completely in the lowest order mode. This principle of providing differential loss on modes is used in most LMA fibers as described in 2.2.2, and here is simply implemented in a different way. As is described in the following sections, careful choice of laser gain can enable exclusive lossless guidance of the fundamental mode, even in anti-guiding fiber structures that would otherwise be highly multimode.

3.2.2 Overview of Full Theory

The full theory for GGIAG is laid out in two papers by Siegman, [226, 227] and only the key aspects for design of GGIAG lasers will be laid out for the purposes of this dissertation. The premise for calculating the behavior of GGIAG fibers lies in the solution of the fiber guidance equations [11], as discussed in 2.2.1.1. Because of the gain playing a role in guidance of light in the fibers, the refractive index can no longer be described as an entire real quantity; it takes on a complex value. The imaginary part of the complex refractive index represents the gain (or loss) in the fiber. When carried through the equations for fiber mode propagation, gain guided modes
can be found [226, 227]. As in conventional fibers, the V-parameter still determines whether a fiber will operate in a single or multimode regime. However, to account for the complex nature of refractive index profile, the V-parameter is slightly modified for GGIAG compared to that for conventional fibers seen in (31). The baseline parameter used is GGIAG analysis is the complex V-squared parameter which is determined from the equation for the standard V-parameter by introducing the refractive index as a complex quantity [226, 227]. Beginning with (31) and making some approximations, the NA portion of the V parameter can be rewritten as the product of the background refractive index, \( n_0 \) and the refractive index step in the fiber \( \Delta \tilde{n} \) assuming that the portion with \( \Delta \tilde{n}^2 \) is vanishingly small,

\[
\text{NA} = \sqrt{n_1^2 - n_2^2} = \sqrt{(n_0 - \Delta \tilde{n})^2 - n_0^2} \approx \sqrt{2n_0\Delta \tilde{n}}. \tag{41}
\]

Equation (31), the expression for fiber V parameter, can be rewritten as

\[
V \approx k_0 a \sqrt{2n_0\Delta \tilde{n}} \tag{42}
\]

Following Siegman in [226], the refractive index step \( \Delta \tilde{n} \) can be a complex number when there is gain or loss in the fiber expressed by

\[
\Delta \tilde{n} = \left( \Delta n + j \frac{\lambda}{2\pi} \Delta \alpha \right). \tag{43}
\]

Substituting this into (42), squaring and replacing \( k_0 \) with \( \frac{2\pi}{\lambda} \) reveals the complex V-parameter given by

\[
V^2 \approx 2n_0 \left( \frac{2\pi a}{\lambda} \right)^2 \left( \Delta n + j \frac{\lambda}{2\pi} \Delta \alpha \right). \tag{44}
\]
where $a$ is the fiber radius, $\Delta n$ is the refractive index step, $n_0$ is the glass refractive index, and $\Delta \alpha$ is the loss or gain in the fiber.

The principal conditions for gain-guiding in a fiber can be determined by considering the two dimensionless index and gain parameters $\Delta N$ and $G$, obtained by breaking the complex $V$-parameter (44) into real and imaginary parts, defined in [226, 227] as

$$V^2 = \Delta N + jG \quad (45)$$

$$\Delta N = 2n_0 \left( \frac{2\pi a}{\lambda} \right)^2 \Delta n \quad (46)$$

$$G = \frac{\lambda n_0}{2\pi} \left( \frac{2\pi a}{\lambda} \right)^2 g \quad (47)$$

where $\Delta n$ is the negative index step for an IAG fiber, $n_0$ is the index of the fiber core material, $a$ is the radius of the fiber core, $\lambda$ is the laser wavelength, and $g$ is the power gain coefficient in the fiber core.

Siegman solves the fiber guidance equations, finding the threshold for the propagation of gain guided index anti-guided modes in terms of the components of the complex $V$-parameter (45), (46) and (47). It should be noted that only the fundamental and next highest mode are considered, because keeping the second mode from propagating inherently keeps any higher order mode from losslessly propagating. From these solutions, the conditions for guidance in GGIAG fibers can be determined based on the physical parameters contained in $\Delta N$ and $G$. In addition, laser oscillators can be designed with their gain and oscillation threshold conditions optimized to attain single mode operation by using the following analysis given in [228-230] and discussed in 3.2.3.
In the case of strongly index anti-guided fibers, ($\Delta N \leq 50$) the numerical solutions for the threshold gain found by Siegman can be approximated by a linear fit. The threshold gain parameters ($G_{gg}$) of the two lowest order modes, LP$_{01}$ and LP$_{11}$, are given by [227] as

$$G_{gg01} \approx \frac{133.8}{\sqrt{-\Delta N}}$$ (48)

and

$$G_{gg11} \approx \frac{862.2}{\sqrt{-\Delta N}}.$$ (49)

These two equations, coupled with the definitions of $G$ and $\Delta N$, which contain the fiber’s physical parameters, are the keys to designing a gain guided index anti-guided fiber laser. A simple numerical model based on these solutions enables the selection of the appropriate amount of gain in a fiber with a known refractive index step. The next section outlines the use of this information to select the output coupling of a GGIAG laser oscillator.

### 3.2.3 GGIAG Output Coupler Selection Model

In order to create an oscillator that lases on a single transverse fiber mode in GGIAG fiber, the gain of the fiber laser must be tailored to fit a set of conditions that allow only the fundamental mode to experience net gain [228, 229]. This theory and model is developed in collaboration with Ying Chen, Vikas Sudesh and Michael Bass. Before the laser can be designed for a specific gain, the required value of gain must be determined. This is accomplished by combining equations (46) through (49). First, the gain coefficient for gain guiding in the lowest
order mode is determined by inserting (46) and (47) into (48) and solving for $g$, the gain coefficient in (47). Doing so yields

$$g_{gg01} = \frac{\lambda^2}{a^3} \sqrt{\frac{133.8}{32n_0^3\pi^4\Delta n}}$$

(50)

where the variables are all as previously defined. This gain represents the minimum required for gain guiding of the fundamental mode. The gain required for the next highest order gain guided mode is also important because it represents the maximum gain a fiber can have before a second mode has the potential to propagate losslessly. This gain is determined similarly to (50). Equations (46) and (47) are inserted into (49) and solved for $g$ to yield

$$g_{gg11} = \frac{\lambda^2}{a^3} \sqrt{\frac{862.2}{32n_0^3\pi^4\Delta n}}$$

(51)

An interesting note about equations (50) and (51) is that their ratio is fixed; meaning regardless of the fiber parameters, the ratio of gain for the fundamental mode and next highest mode is always ~0.394. With knowledge of these two gain parameters, a fiber amplifier or oscillator can be designed in any known GGIAG fiber.

In a laser oscillator, the gain can be controlled and determined by the parameters of laser resonator itself, since upon reaching laser threshold the gain is clamped at the threshold value [9, 10]. To achieve oscillation there must be an additional gain ($g_{osc}$) to overcome resonator losses

$$g_{osc} = \frac{\ln (R_1R_2)}{2l} + \alpha$$

(52)
where $R_1$ and $R_2$ are the reflectivities of the two cavity mirrors, $l$ is the fiber length, and $\alpha$ represents the loss per unit length in the cavity. Based on (50) and (51), two conditions can be written to ensure lasing of a GGIAG laser on a fundamental mode. As laid out in [228, 229], the gain in the laser cavity must meet the conditions

\begin{align}
(i) \quad & g_{gg01} < g_{osc} \\
(ii) \quad & g_{osc} + g_{gg01} < g_{gg11}.
\end{align}

(53)

The reasoning behind condition (i) in (53) is that, if the laser threshold for oscillation is lower than the threshold for gain guidance of the fundamental mode, parasitic lasing in a non-gain guided regime can occur before gain guiding is able to establish itself [228, 229]. This parasitic lasing might occur as “free-space lasing” within the large fiber core or by some other guidance mechanism in the fiber, perhaps on a cladding mode that has some portion of its field in the lower refractive index core. The second condition in (53) states that the total gain of the laser resonator ($g_{osc} + g_{gg01}$), must be less than the threshold for gain guiding of the second order mode. If this is not the case, there exists the possibility that the LP$_{11}$ mode can also lase, resulting in undesirable multimode lasing.

The values of the different gains must be tailored to meet the conditions required for single mode lasing. The parameters $g_{gg01}$ and $g_{gg11}$ are fixed by the fiber used, leaving the only “knobs” that can be turned to select for gain guidance of a mode are in the equation for $g_{osc}$ (52). In designing a laser, the variable parameters $R_1$ and $R_2$ and the length of the resonator $l$ can be selected to make the resonator gain “clamp” in the desired range. Usually one mirror is given 100% reflectivity to ensure that all laser power travels in one direction; therefore, in design of a gain guiding laser a balance must be struck between resonator length, $l$ and output coupling, $R$. 

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Length is often fixed by the choice of pump scheme or doping concentration of the fiber, thus the simplest parameter to vary is the output coupling. For any given laser design, an output coupler can be selected appropriately to enable gain guiding. For purposes of the experimental work described in subsequent sections, a simple model was developed to predict the output coupling for a variety of fiber parameters. The output from such a model is seen in Table 3.
Table 3: Example output from Output Coupler selection model for a 400 µm core fiber, one meter in length in Nd ions.

<table>
<thead>
<tr>
<th>OC Reflectivity</th>
<th>Threshold Cavity Loss (cm^-1)</th>
<th>LP11-GG Threshold Cavity Loss (cm^-1)</th>
<th>Can GG Happen?</th>
<th>Loss Taken Into Account</th>
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<td>Lossless Assumption</td>
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<td>OC Reflectivity</td>
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<td>LP11-GG Threshold Cavity Loss (cm^-1)</td>
<td>Can GG Happen?</td>
<td>Loss Taken Into Account</td>
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<tr>
<td>OC Reflectivity</td>
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<td>Can GG Happen?</td>
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<table>
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<tr>
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</tr>
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<td>No GG</td>
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<tr>
<td>Laser threshold too low</td>
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<tr>
<td>Threshold is reached before gain guiding can turn on</td>
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</tr>
<tr>
<td>Single mode gain-guiding can occur</td>
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<tr>
<td>Laser threshold is high enough that multimode gain-guiding can occur</td>
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</table>

<table>
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<tr>
<th>Cavity Loss (cm^-1)</th>
<th>LP11-GG Threshold Cavity Loss (cm^-1)</th>
<th>Can GG Happen?</th>
<th>Loss Taken Into Account</th>
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</tbody>
</table>
The particular example in Table 3 shows a hypothetical GGIAG laser of a meter in length with a 400 µm core, made from the same phosphate glass as other fibers in this experiment. Such a laser might be used in a very high power application where the long length enables heat spreading, while, based on the model analysis, the length also allows the reduction of output coupling reflectivity, thus likely making the laser more efficient. Changing the input parameters enables the user to determine in what range GGIAG will occur. The model takes loss into account if it is known, and gives results for both lossless and known loss lasers. Depending on the magnitude of the loss, the region where gain guiding is possible will change.

Based on analysis in the model, a few general design trends can be seen. A larger core requires higher output coupling reflectivity than a smaller core. In order to combat this effect, as usually output coupling should be kept low to keep intracavity power low and efficiency high, either the fiber length can be increased, or the refractive index step can be reduced. In addition, if the wavelength is longer, the output coupling reflectivity required is reduced, again an inherent advantage for thulium fiber lasers. However the consequence for the lower output coupling is that a higher gain is required at longer wavelengths, possibly effecting laser efficiency adversely. In order to scale to the largest core sizes possible and still achieve GGIAG lasing without excessive fiber length (>1 meter since these fibers cannot be bent), smaller refractive index steps will be required, which is acceptable provided that the value of ΔN is kept below -50 where the linear approximation for gain threshold is valid. At least an order of magnitude reduction in index step is physically possible while keeping the ΔN value reasonable, especially when using MCVD techniques in silica fiber. As seen in calculations for this model, fibers with larger core diameters have much lower gain thresholds for GGIAG lasing. This means that significantly less gain is being used by the GGIAG process, and thus significantly more gain can go towards
making an efficient laser. Thus, with GGIAG there is actually an advantage to having the largest core diameter possible in terms of laser efficiency. Based on reasonable assumptions, it may be possible to produce GGIAG lasers with core diameters of \( \sim 1 \text{ mm} \) and a length of 1 meter with appropriate attention to refractive index step at thulium laser wavelengths with reasonably large output coupling (<20% reflectivity) assuming appropriate pumping techniques can be developed for such long GGIAG fiber lengths.

3.3 Experimental GGIAG Demonstrations

Based on the model developed in the previous section, lasing in gain guided fiber lasers with core diameters of up to 400 \( \mu \text{m} \) in diameter has been demonstrated. Flashlamp pumped cavities with core sizes from 100-400 \( \mu \text{m} \) were shown in [228, 230, 231] by Ying Chen et al. with diffraction limited beam qualities. In further work by Chen, the performance of the lasers with different core diameters also validated the output coupler selection model proposed earlier. After early GGIAG fibers were demonstrated using flashlamps, there was a need to look at more practical average power scaling techniques, which of course leads to diode pumping [229]. The largest core demonstrated to date in diode pumped GGIAG lasers is 300 \( \mu \text{m} \). The following sections describe experiments in flashlamp and diode pumped GGIAG lasers.

3.3.1 Gain Guiding Fibers Used and Fiber Preparation

As outlined in [228-231], the fibers used for these experiments were made by Clemson University from Nd doped phosphate glass from Kigre Inc. Several fibers were tested in different
gain guiding experiments, made from two preforms and pulled into various dimensions with core diameters in the range of 100-500 μm and Nd concentrations of 1 wt% and 10 wt%.

Table 4: Table listing fiber dimensions and types tested in GGIAG experiments

<table>
<thead>
<tr>
<th>Core Diameter (μm)</th>
<th>Cladding Diameter (μm)</th>
<th>Index Step</th>
<th>Nd Doping Concentration (wt%)</th>
<th>Glass Material</th>
<th>Lased as GGIAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>250</td>
<td>0.0045</td>
<td>10</td>
<td>Phosphate</td>
<td>Yes</td>
</tr>
<tr>
<td>100</td>
<td>170</td>
<td>0.0045</td>
<td>1</td>
<td>Phosphate</td>
<td>No</td>
</tr>
<tr>
<td>200</td>
<td>340</td>
<td>0.0045</td>
<td>1</td>
<td>Phosphate</td>
<td>Yes</td>
</tr>
<tr>
<td>300</td>
<td>510</td>
<td>0.0045</td>
<td>1</td>
<td>Phosphate</td>
<td>Yes</td>
</tr>
<tr>
<td>400</td>
<td>680</td>
<td>0.0045</td>
<td>1</td>
<td>Phosphate</td>
<td>Yes</td>
</tr>
<tr>
<td>500</td>
<td>850</td>
<td>0.0045</td>
<td>1</td>
<td>Phosphate</td>
<td>No</td>
</tr>
</tbody>
</table>

The refractive index step in the fibers in all cases was negative, as is required by the GGIAG concept, with a Δn of -0.0045, as seen in the refractive index profile shown in Figure 31.

![Figure 31: General refractive index profile of the GGIAG fibers used for all experiments.](image)

Due to lack of an appropriate fiber cleaver at the time of most of the experiments, the fiber facets were prepared by a hand polishing technique which involved utilizing a fiber holder and a stainless steel polishing mount and moved in “figure-eight” shapes on successively finer grits of polishing film. The grit sizes of the paper used for polishing the fibers were 5 μm, 1 μm and 0.3 μm in succession. After each polishing film grit, the fiber facet was inspected on a
camera system to ensure minimal visible scratches. Water was used to facilitate the polishing process and to keep the fiber tip from sticking to the polishing film and breaking. Figure 32 shows a sequence of progressively polished fibers along with (in this case conventional Tm fibers but the principle the process is the same for any fiber) a final version of a polished GGIAG fiber.

Due to its relatively soft and brittle nature, phosphate glass can be extremely difficult to polish reliably; the fiber tips often break off with improper care. This brittle nature is evidenced in Figure 32(b), which shows various chips around the fiber edge. In addition, since the glass is extremely soft, any small particles not cleaned off between polishing steps could cause deep scratches in the fiber surface, requiring further polishing. This polishing process has been

Figure 32: (a) Photo sequence of polishing process on Tm doped fiber, but principle is the same for GGIAG fibers. (b) Image of final finish on GGIAG fiber.
replaced by use of a large diameter fiber cleaver (Vytran LDC) which provides superior surface quality and more rapid rates of fiber preparation. As described later, GGIAG fiber lasers constructed using cleaved fiber ends showed higher performance than those with hand polished ends.

### 3.3.2 M² Measurement Technique

The measurement of beam quality is arguably among the most critical measurements to be taken of a GGIAG fiber laser or any fiber laser in general, as beam quality is one of the largest advantages of fiber lasers over other laser types. In order to maintain this advantage, the higher beam quality must be quantitatively determined in a way that is repeatable and reliable. Simply looking at the image of a beam in the far field or measuring its divergence is insufficient to fully determine the quality of a laser beam. This section describes the technique used for M² measurement in all fiber laser systems described in this and subsequent chapters.

The M² of a laser is officially defined by the International Organization for Standardization (ISO) as the product of the minimum waist radius of a Gaussian beam and the half angle far field divergence of that beam, also known as the beam parameter product, divided by the wavelength of the measured light over pi [293]. Essentially the factor is a measure of the number of times a laser beam is above the diffraction limit, thus giving information on how well a beam can be focused and about its divergence after collimation and propagation. The details of this factor’s origins are found in works by Siegman, where the factor is actually derived from Gaussian beam propagation [10, 294, 295].

Measurement of M² can be conducted in a number of ways, but it officially must conform to [293] to meet ISO standards, which is of importance for attaining certification in many
commercial and industrial applications. The basic technique for finding $M^2$ is to measure the diameter of a beam at many points along an auxiliary waist produced by a lens, and fit those points to an ideal situation in order extract the quality of a beam. Figure 33 shows a schematic of the basic setup for such a measurement.

![Typical M² setup schematic.](image)

Though the beam diameter can be measured in a variety of ways, the simplest way with current technology is to use a beam camera and software to measure beam diameter at each point. This measurement must be done with appropriate filtering to ensure that the software interprets the beam diameter correctly. In addition, the minimum spot size produced by the transfer lens must be large enough for the camera to measure accurately. CCD cameras have pixel sizes in the 10’s of microns, so measuring sub 100 $\mu$m beams is not an issue; pyroelectric cameras, like the Pyrocam III used for many measurements in this dissertation, have pixel sizes in the 80 $\mu$m range which make it impossible to accurately measure spot size of beams less than around 500-600 $\mu$m. As a consequence, the lens must be selected appropriately to keep minimum spot size large enough. In addition, the lens used should be relatively free of aberrations as aberrations can distort the accurate measurement of beam quality, meaning a relatively large focal length transfer lens should be used (over $f/20$ is suggested in [296]).
The algorithm the camera software uses to determine beam diameter is also important, as depending on where beam diameter is defined (for example FWHM, \(1/e^2\), 90\% of diameter etc) the value of \(M^2\) can vary [293]. ISO specifies the use of “second moment” or \(D_{4\sigma}\), width at four times the standard deviation of the distribution of beam power, as its waist definition [293]. However this method is sensitive to background light and poses some problems especially when using the Pyrocam III to measure thulium lasers, leading to inaccurate measurements. As a consequence the 90/10 knife edge method (width at 90\%) is sometimes used instead to ensure more correct measurement of beam quality. This is reasonably accurate although this method is not the official ISO method.

The larger the number of measurements taken along the beam, the more accurate the beam quality measurement will be. For accuracy it is critical that the diameters be measured on both sides of the waist produced by the auxiliary lens. In addition the ISO specification specifies a minimum number of points to be taken as 10, with 5 being inside one Rayleigh range from the minimum waist and 5 points beyond two Rayleigh ranges both distributed relatively evenly on both sides of the minimum waist [293].

Once the data points are collected, they are plotted and fit to the equation

\[
2W(z) = 2W_0 \sqrt{1 + \left(\frac{z - z_0}{z_R^2}\right)^2}
\]

(54)

where \(z\) is the distance, \(z_0\) is the location of the beam waist from the nominal zero point in distance (often the focusing lens), \(z_R\) is the Rayleigh range, \(W\) is the beam waist radius, and \(W_0\) is the minimum waist radius [296]. Since \(W\) and \(z\) are the measured properties, the parameters \(z_0\), \(z_R\) and \(W_0\) are determined from the fit. Knowing these parameters, the equation
is then used to determine the value of $M^2$ [296]. This measurement can be done in both the vertical and horizontal directions of the beam, with variations between the two measurements helping to quantify any astigmatism or other non-uniformity in the beam. Figure 34 shows an example of a plot used to determine $M^2$ take in collaboration with Andrew Sims.

![Figure 34: Example plot of data collected during $M^2$ measurement, including error bars indicating ~5% error in measurement. The solid line is a fit to the equation described in the text which is used to pull out the parameters for calculating $M^2$.](image)

This basic technique can be applied to measurement of beam quality for any laser and is used for determination of beam quality in most of the experimental work done in this dissertation. The only other techniques applied in some cases involved the use of a commercial machine that did the entire measurement and fitting process automatically to determine beam quality.

### 3.3.3 Flashlamp Pumped Experiments

The earliest GGIAG experiments were investigated by Ying Chen et al. in the flashlamp pumped regime as this technique is the simplest and easiest way to pump when appropriate pump
diodes were not available. Though the results do not produce lasers in a modern fiber laser configuration and mode of operation (in fact they are more reminiscent of those used in the first fiber lasers [24-26]) they are still important proof-of-concept experiments that demonstrate the potential of GGIAG fibers. Due to diode pumping difficulties disused later, the flashlamp proved the easiest way to pump long sections of GGIAG fiber in order to test and verify some of the models and theories being developed about their function as are described in the coming sections.

3.3.3.1 First GGIAG Demonstration

The first demonstrations of GGIAG fiber lasers by Chen et al. took place in flashlamp pumped configurations. The reason for the selection of such a technique not used in fiber lasers since the early days of Snitzer’s first lasers was to enable the simplest pumping possible with the most pump energy possible without running into thermal issues. The goal of the earliest experiments was simply to demonstrate the gain guiding concept.

As outlined in [230, 231], the fiber in the first flashlamp pumped demonstration was made from 10 wt% Nd doped phosphate glass from Kigre Inc. with a 100 μm diameter core and 250 μm cladding. The refractive index step in the fiber was negative, as is required by the GGIAG concept, with a Δn of -0.0045, as seen in the refractive index profile shown in Figure 31. This gives a ΔN (from (46)) greater than -1000, meaning that the fiber is operating in the strongly anti-guided regime, and as such the assumptions made to produce (48) and (49) are valid, which will become important in later studies for GGIAG fibers.

The fiber was prepared by Chen as outlined in 3.3.1 to a length of ~13 cm and placed inside a capillary tube of similar length to provide support for the fiber, as even small bending of
the fiber under its own weight would significantly hamper, if not completely destroy any potential for gain guided lasing, as the bending loss induced in the fiber mode would be significant. The capillary-fiber assembly was placed in a close coupled flashlamp cavity originally designed for pumping of solid state laser rods. The flashlamp was a Xe lamp 6 mm in diameter and 8.5 cm in length, ensuring most of the fiber was pumped except for a 1-2 cm length that for mechanical constraint reasons had to extend beyond the flashlamp cavity. The laser resonator was formed by placing an HR mirror on one end of the fiber and using the Fresnel reflections on the other end as the output coupler. Figure 35 shows a schematic of the experimental setup [230, 231].

![Figure 35: Schematic of flashlamp pumped GGIAG setup [230, 231].](image)

The HR mirror was adjusted with the lamp running a 1 Hz until single mode lasing was enabled. At optimal performance the laser threshold was reduced to 15 J of flashlamp energy with as much as 1.2 mJ of long pulse laser output for 35 J of pump energy [230, 231]. Lasing was confirmed by recording of spectral narrowing at the emission wavelengths of Nd:phosphate of 1052 nm as well as by observation of distinct relaxation oscillation spiking behavior above laser threshold, and a linear output power slope with a distinct threshold condition.
With confirmation of lasing, the most critical aspect of the GGIAG fiber laser is its beam quality, since the GGIAG technique has no real benefit without fundamental mode lasing and high beam quality, \( M^2 \) measurements were carried out on this first experiment using the technique outlined in 3.3.2. In collaboration with Chen, the value of the beam quality was found at pump energies from just above threshold up to over five times threshold. The results of these measurements are summarized in Table 5.

<table>
<thead>
<tr>
<th>Pump Energy</th>
<th>Measurement Axis</th>
<th>Minimum Waist (mm)</th>
<th>Rayleigh Range (mm)</th>
<th>( M^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Horizontal</td>
<td>0.38</td>
<td>1434</td>
<td>1.3</td>
</tr>
<tr>
<td>19</td>
<td>Vertical</td>
<td>0.39</td>
<td>1452</td>
<td>1.3</td>
</tr>
<tr>
<td>30</td>
<td>Horizontal</td>
<td>0.44</td>
<td>1410</td>
<td>1.6</td>
</tr>
<tr>
<td>30</td>
<td>Vertical</td>
<td>0.41</td>
<td>1495</td>
<td>1.6</td>
</tr>
<tr>
<td>50</td>
<td>Horizontal</td>
<td>0.41</td>
<td>1482</td>
<td>1.6</td>
</tr>
<tr>
<td>50</td>
<td>Vertical</td>
<td>0.39</td>
<td>1496</td>
<td>1.5</td>
</tr>
<tr>
<td>80</td>
<td>Horizontal</td>
<td>0.39</td>
<td>1415</td>
<td>1.7</td>
</tr>
<tr>
<td>80</td>
<td>Vertical</td>
<td>0.37</td>
<td>1422</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The results show high beam quality, especially for the exceptionally large fiber core diameter. There is a slight trend towards degradation in beam quality factor with higher pump powers, which may be a consequence of getting close to the lasing threshold for the next order GGIAG mode. This change may also be related to thermal distortion of the fiber due to the high incident pump energies.

In order to prove that the high beam quality lasing must be due to GGIAG in the fiber rather than some form of free space lasing where the fiber acts simply as a laser rod the Fresnel number of a laser cavity can be implemented. The Fresnel number of a laser cavity gives information about the diffraction losses of free space modes in a resonator [9, 10, 297]. The number \( N_f \) is defined by
\[ N_f = \frac{a^2}{\lambda L} \]  

where \( L \) is the resonator length, \( a \) is the laser resonator mirror radius (in this case defined by the core radius of the fiber since the mirror is directly butted to the mirror) and \( \lambda \) is the laser wavelength. The Fresnel number of the fiber used in this experiment is approximately 0.02. In addition, the \( g \) of a resonator is given by

\[ g_n = 1 - \frac{L}{R_n} \]  

where \( L \) is again resonator lengths and \( R_n \) is the radius of curvature of the \( n^{th} \) resonator mirror. The total \( g \) is the product of the \( g \) of both resonator mirrors. In the case of plane mirrors as used in GGIAG, \( g = 1 \). Based on analysis in [297] which is reproduced in [9], the diffraction loss on the fundamental mode of free space in a resonator with \( g = 1 \) grows significantly for smaller Fresnel numbers, especially when the Fresnel number falls below unity. For the Fresnel number of this GGIAG laser, the intracavity losses are greater than 10 dB per round trip, whereas the resonator gain is \( \sim 5 \) dB, and hence free space lasing is not possible [230]. It has already been stated that due to the anti-guiding (core refractive index lower than cladding refractive index) nature of this fiber, there can be no guidance of conventional fiber modes, and in addition phosphate glass has a negative \( \frac{dn}{dT} \) (change in refractive index with temperature), so there is also not a possibility of a thermal lens causing guidance, as any thermal lens generated would be negative, and thus make the resonator more unstable. Thus, the only potential explanation for lasing in the GGIAG fiber is the gain guiding phenomenon itself.
This proof of concept for GGIAG lasing serves as the springboard for future GGIAG experiments involving confirmation of the output coupler selection model and towards finding more effective pumping schemes discussed in subsequent sections.

3.3.3.2 Flashlamp Pumped Investigation of Numerous Fiber Sizes

With the earliest experiments on proof of concept of GGIAG lasing completed, Chen et al completed a further investigation into GGIAG in different types of fibers. According to the output coupling model described in [228, 229] and 3.2.3, the 100 μm fiber used in the first GGIAG experiment [230, 231] would have required 4% output coupling, however these experiments were conducted before the first OC selection model was produced, so it was fortuitous that the fiber length and core diameter selected were in the range of the Fresnel reflection used as an output coupler. In order to provide more thorough proof of the model, a set of experiments using different fiber diameters was devised by Chen et al.

The new fiber used for this experiment was the same phosphate glass from Kigre, pulled by Clemson University, but with 1 wt. % doped Nd. The preform was fabricated with an ~1.7:1 cladding to core ratio and the single preform was pulled into fibers of several different core diameters from 100 to 500 μm as seen in Table 4, however the 100 μm and 500 μm fibers were not used for technical experimental reasons (the small fiber did not absorb enough pump to lase due to small core dimensions, and the large fiber did not fit in the experimental setup). The 100 μm core fiber tested was the same 10 wt% fiber used in 3.3.3.1 from [230, 231]. Four fiber samples with core diameters of 100, 200, 300 and 400 μm were prepared as described in 3.3.1 to a length of ~13 cm, which was suitable to fit in the flashlamp pumped cavity described in 3.3.3.1. The entire laser cavity setup including the HR mirror and fiber held in a capillary tube
with pumping by an 8.5 cm long Xe flashlamp were the same as in [230, 231] described in 3.3.3.1. The only addition was, in the case of the 200 - 400 µm fibers an output coupling mirror with appropriate reflectivity was used in place of the 4% Fresnel reflection which was used for the 100 µm fiber.

Output coupling selection for different fiber core diameters was based on the selection model described in 3.2.3. The values for output coupling of the four different lasers in order to ensure lowest order mode lasing is seen in Table 6 as is the value actually selected for the experiments conducted.

Table 6: Performance and calculations for GGIAG in the various fibers used [228].

<table>
<thead>
<tr>
<th>Fiber Core Diameter (µm)</th>
<th>$g_{gg01}$</th>
<th>$g_{gg11}$</th>
<th>Range of Potential Reflectivity</th>
<th>Output Coupler Used</th>
<th>$g_{esc,th}$ for Mirror Used</th>
<th>$M^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.1406</td>
<td>0.3506</td>
<td>4% - 10%</td>
<td>4%</td>
<td>0.1988</td>
<td>1.5</td>
</tr>
<tr>
<td>200</td>
<td>0.0176</td>
<td>0.0446</td>
<td>65% - 75%</td>
<td>75%</td>
<td>0.0178</td>
<td>1.2</td>
</tr>
<tr>
<td>300</td>
<td>0.0052</td>
<td>0.0132</td>
<td>88% - 91%</td>
<td>90%</td>
<td>0.0065</td>
<td>&lt;1.8</td>
</tr>
<tr>
<td>400</td>
<td>0.0022</td>
<td>0.0056</td>
<td>95% - 96%</td>
<td>95%</td>
<td>0.0025</td>
<td>&lt;1.8</td>
</tr>
</tbody>
</table>

The process developed by Chen for alignment of the lasers involved first pumping very hard causing parasitic lasing in a multimode regime leading to a speckled beam output, then adjusting the OC and HR mirrors and continuously lowering pump power until a single mode at the lowest laser threshold was achieved. When achieved, the pump power could be turned many times over laser threshold while maintaining the high beam quality mode.

Chen et al. achieved single mode lasing in each of the four lasers and as seen in Table 6, in collaboration with Chen, the values of $M^2$ were maintained below 1.8 for each of the lasers in question [228] as measured by the technique described in 3.3.2. These high beam qualities were
also maintained at as high as 10 times above laser threshold in the case of 300 and 400 μm fibers and 5 times above threshold for the 100 and 200 μm fiber [228]. The number of times above threshold was limited by the available flashlamp pump power. It should be noted that the laser thresholds for the 100 and 200 μm fibers were higher than the other fibers due to the significantly lower output coupling (4% and 75% respectively) compared to those of the larger core fibers. In addition to the effects of output coupling, the threshold for gain guiding of the fundamental mode is higher for smaller core diameters seen in Table 6, and since this threshold can be treated as a cavity loss, the laser threshold is increased for GGIAG lasers with smaller core diameters.

The reduction of threshold with increase in core diameter is an interesting phenomenon, as this says that GGIAG fiber lasers actually work with lower threshold and hence more efficiently when the core diameter is larger, while beam quality does not suffer from this increase in core diameter. However this also leads to a potential issue, as the output coupling for single mode lasing in a GGIAG fiber may not overlap with the output coupling required for the highest efficiency energy extraction in such a laser resonator [9, 10], leading to potential future compromises that will need to be made between core diameter, beam quality and laser efficiency. It may be that parameters such as fiber length can be added into the parameter space as well, to help select a resonator design the enables both optimal energy extraction and single mode GGIAG lasing with the same output coupling.

Overall, the results from this experiment were to validate the model that was created to select the output coupler of a GGIAG fiber laser by testing at several different points. Single mode lasing was achieved at all points, in agreement with the model and with excellent beam quality. All of the lasing observed was confirmed to be due to GGAIG lasing, due to the Fresnel argument outlined in [230] and 3.3.3.1. Attempts were made to achieve GGIAG single mode
lasing by using OCs with values above or below the predicted OC values in the model and in these cases GGIAG lasing was not achieved. Not seeing lasing outside the design ranges does not completely prove the model, as there are variables such as differences in laser alignment to consider. However, the evidence for the validity of the OC selection model to this point seems to be sufficient to justify the use of the model in future experiments until a scenario is encountered where the model appears to be invalid.

3.3.4 Diode Pumped Experiments

The greatest advantage of fiber lasers is their ability to produce extremely high average powers and high peak powers or pulse energies at high repetition rates, however this is only achievable with diode pumping. The earliest work done in GGIAG fiber lasers was done by Ying Chen in flashlamp pumped cavities at 1 Hz repetition rates, meaning that average powers were extremely low and thermal effects were negligible. The next logical step in the development of GGIAG fiber lasers is therefore diode pumping. There is one main issue with using GGIAG in the conventional cladding pumped, high power diode pumping scheme that is typical of all other conventional fiber lasers. Due to the anti-guiding nature of the core, any pump light launched into the cladding will remained trapped there and any light launched into the core will eventually leak into the cladding and then become trapped there, making both core and cladding pumping methods inefficient and impractical. Such difficulties can be circumvented by a number of techniques outlined in 3.4, however a simple way to overcome this problem, especially for the first diode pumped demonstrations, is to simply end pump a very short section of fiber and achieve as much absorption as possible over that length, in order to prove the concept of diode pumping.
3.3.4.1 First Diode Pumping Demonstration

The first demonstration of such direct diode pumping is presented in [229] in work done in conjunction with Vikas Sudesh. The fiber selected for this experiment was chosen to be as short of a length as possible to enable the best pumping conditions, while being sure to be long enough to make the Fresnel number smaller than unity, to ensure the GGIAG lasing was the only lasing achievable as discussed in 3.3.3.1. A 200 μm core fiber was selected with a length of 26 mm to form the GGIAG fiber gain medium. This is the same 1 wt% Nd doped fiber as discussed in 3.3.3.2, and was selected because 200 μm is the largest size which enabled a reasonable length while fitting the Fresnel number requirements. In addition, 1 wt% fiber was required as it was found that the direct core pumping in the 10 wt% fiber used in the first demonstration would cause absorption of most of the diode pump light in the first 0.5 mm leaving the rest of the fiber unpumped and most likely causing fiber end facet melting as seen in Figure 27.

Figure 36 and Figure 37 are a schematic and a photograph of the laser setup, respectively. The 26 mm fiber was held in a 10 mm long water cooled (10°C) aluminum “V” groove and was coated in silicone based thermal paste to enhance heat extraction and to help hold the fiber in place in the groove. The fiber ends were polished and prepared as described in 3.3.1.
The pump was an ~803 nm fiber coupled laser diode bar capable of 30 W output power, which matches the absorption spectrum of the Nd:phosphate glass used. The diode was delivered by a 200 μm diameter core 0.22 NA fiber, and its output was collimated and focused by a pair of aspheric lenses to an ~400 μm spot on the GGIAG fiber tip, through a dichroic mirror HR at 1054 nm and HT at 800 nm which was butted to that fiber tip to form one end of the laser resonator. As a result of the ~400 μm pump spot, only ~25% of the light incident on the fiber tip actually enters the core. Because of the anti-guiding nature of the fiber, only light that is incident onto the fiber core is able to pump the dopant ions, and of that light only the most glancing rays
make the trip down a long length of the fiber. As a consequence, pumping efficiency is quite low, though a quantitative number was difficult to determine, total pump absorption is likely much less than 10%.

Due to thermal damage issues associated with the small pump spot on the relatively low melting point phosphate glass, the pump light was modulated by a mechanical chopper at a rate of 14 Hz producing ~4 ms duration pump pulses, meaning that the laser operated in the quasi-CW mode (QCW).

The laser resonator was completed by a 98% output coupler mirror which is the value predicted by the output coupler model discussed in 3.2.3. The mirror was located within 1 mm of the fiber tip, butt-coupling could not be used due to issues with damaging the end facet of the brittle phosphate fiber. The closer the mirror the mirror could be brought to the fiber tip, the higher the laser efficiency became, so there was a balance between not damaging the fiber and making the best laser.

Pump alignment was optimized by adjusting the GGIAG fiber for maximum fluorescence as monitored by a spectrometer and CCD camera. With the pump optimized, the HR and OC mirror were adjusted to achieve lasing, again by watching the laser spectrum and looking for spectral narrowing which typically would reduce the ~20nm ASE spectrum to ~2 nm FWHM (Figure 38). Typically lasing at this point would be in the parasitic, highly multimode regime and additional adjustment of the OC and HR mirror was made by watching a CCD camera and looking for single mode beam quality, the sign of GGIAG lasing.

The laser performance is seen in Figure 38 which shows a clear laser threshold at ~6 W of incident pump power, and a maximum power of 11 mW at full pump power. A distinct jog in the slope is seen at 17 W pump power and is attributed to thermal misalignment in the fiber, as
no adjustments to the cavity were made as power was increased to compensate for thermal
effects. It should be noted that launched pump power is quoted, as it is unknown how much
power is actually absorbed by the Nd in the fiber. In addition, clear relaxation oscillation spiking
was observed above laser threshold, again indicating lasing.

![Figure 38: First GGIAG diode pumped laser slope efficiency, spectrum and relaxation oscillations](image)

Beam quality of the laser was observed to be good, as indicated by the image of the far
field output beam in Figure 39. Beam quality is characterized via the same $M^2$ technique
discussed in 3.3.2 and found to be between 1.2 and 1.5 in both vertical and horizontal at pump
powers are up to ~4 times laser threshold, limited by available pump power.

![Figure 39: Example M$^2$ data and image of output beam in the far field](image)

Again, based on a Fresnel number analysis as discussed in [229, 230] and in 3.3.3.1, the
only possible explanation for lasing is GGIAG. In this fiber, the Fresnel number as calculated by
(56) is ~0.36 corresponding to a per-pass loss of 4 dB (determined from a plot found in the
section on Fresnel number in [9]), which is significantly higher than the ~0.2 dB per pass gain of the laser resonator.

In this experiment, the first GGIAG diode pumped laser was demonstrated. Difficulties associated with pumping GGIAG fibers in general and especially with melting issues in phosphate based fiber kept the laser slope efficiency very low and the output powers at the mW level. However as will be discussed in the following section, some improvements to the mechanical design of the laser, and use of a slightly longer and larger fiber enables improvements in laser performance. Further improvements can be made with more advanced pumping schemes and concepts like those developed in 3.4.

3.3.4.2 Improved Diode End Pumping with Larger Core Fiber

Based on the lessons learned from the first proof of concept demonstration of diode pumped GGIAG fiber, a second experiment was set up by Andrew Sims in collaboration with myself and Vikas Sudesh to construct a more robust, stable and higher power GGIAG fiber laser with diode pumping [298]. For this experiment Sims used a 300 μm core GGIAG fiber (described in 3.3.1) with a longer length of ~6 cm. The larger core diameter necessitated the longer length to be sure to keep the Fresnel number below unity as discussed in 3.3.3.1.

The longer fiber length was made possible by use of longer focal length pump delivery optics taking the form of a pair of 50 mm focal length achromatic lenses making an image of the 200 μm pump delivery fiber core onto the GGIAG fiber core [298]. The longer Rayleigh range of the pump optics due to longer focal lengths enabled the longer 6 cm length of fiber to be more effectively pumped than previous tests (despite still battling with issues associated with the negative step refractive index of profile of the GGIAG fiber). The fiber was also held in a water
cooled “V” groove, but the groove was designed such that only ~2 mm of fiber on each side was uncooled, compared to the 15 mm of fiber that was uncooled in the previous experiment. A photograph of the experimental setup developed by Sims is seen in Figure 40 respectively [298].

The rest of the resonator was designed similarly to that described in 3.3.4.1 with updates to the optomechanical mounts and translation stages to enable better and more controllable optical alignment. Pump light was coupled through an HR dichroic mirror as before, and output coupling was achieved with a 90% reflector as prescribed by the model described in 3.2.3. The OC and HR mirrors were held a few mm from the fiber facets to prevent damage to the soft phosphate glass and to enable more aggressive adjustment to achieve the best quality lasing. System performance was also enhanced by use of a Vytran LDC-200 fiber cleaver in place of the hand polishing technique, enabling cleaner, flatter more repeatable (and rapidly produced) fiber end facets. In addition, pump diodes were pulsed at the same 14 Hz and 4 ms durations (though other repetition rates were also tested), but the pulsing was achieved via a pulsed diode power
supply rather than a chopper wheel, again enabling more stable, controlled and repeatable pulsing [298].

The improvements discussed in the previous sections lead to significantly improved laser performance. The most obvious sign of improved performance is seen in Figure 41, the slope efficiency.

Figure 41: Slope efficiency of 300 μm core GGIAG diode pumped laser

Sims found that laser threshold was higher than the previous experiment (~8 W vs. ~6 W) and is attributed to the lower output coupling (90% vs. 98%) and longer fiber length (6 cm vs. 2.6 cm). Despite the slightly higher threshold, the laser slope efficiency and maximum achieved power for the same pumping level was significantly improved. A maximum power of 0.4 W was achieved for ~20 W of power incident on the fiber facet leading to a slope efficiency of 4.5%, a more than two order of magnitude improvement over the maximum power achieved in the precious demonstration with the same available pump power. In addition, minimal roll-over was observed, due to better handling of thermal issues and more stable alignment. The wavelength of the emission was ~1054 nm with ~3 nm FWHM as measured on an Ocean Optics HR 4000.

A second sign of superior laser performance is seen in the relaxation oscillation (RO) spiking in Figure 42.
This figure demonstrates classical RO spiking behavior with pulsing decaying to CW lasing over time. RO spiking was observed in other GGIAG lasers in 3.3.3.1, 3.3.3.2, and 3.3.4.1 but was usually chaotic in nature and did not decay in the classical manner. The clean behavior is a sign the mechanical stability of the resonator and stable pumping, which enables production of repeatable pulses. If pump pulses could be made sufficiently short, the RO spiking behavior could be utilized in an advantageous way by gain switching (selecting only the first pulse with sufficiently short pump pulses) to achieve short duration, high energy pulses directly from a short GGIAG oscillator. The gain switching technique is discussed in more detail in 5.2.2.1.1 as it applies to standard fiber lasers. The repetition rate of the pulses was sufficiently stable as to enable estimation of cavity loss via equations relating RO spiking frequency to cavity photon lifetime seen in [9, 10]. This loss was estimated to be 0.02 cm$^{-1}$ [298].

Owing to the care taken with laser design and alignment Sims achieved a beam quality, especially at low output powers that is significantly higher as summarized in Table 7 and seen from the beam image and measurement in Figure 43.
Table 7: Summary of $M^2$ Performance of the 300 $\mu$m core GGIAG Diode Pumped Fiber Laser

<table>
<thead>
<tr>
<th>Input Pump Power (W)</th>
<th>Horizontal $M^2$</th>
<th>Vertical $M^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1.05</td>
<td>1.07</td>
</tr>
<tr>
<td>15</td>
<td>1.17</td>
<td>1.17</td>
</tr>
<tr>
<td>18</td>
<td>1.44</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Figure 43: Example $M^2$ fit and beam profile from 300 $\mu$m GGIAG diode pumped laser

$M^2$ values as low as 1.05 were achieved near threshold with a value of less than 1.5 at full power [298]. The upward trend in value of $M^2$ may also be due to measurement error associated with the large amount of cladding trapped fluorescence being emitted, skewing the camera software calculations. This cladding trapped light appears as a “halo” around the high quality beam seen in Figure 43.

The improved results of this experiment are promising and show the potential that with improvements GGIAG can become a useful high power laser technology. The 4% slope efficiency is based directly on launched pump power, not the power which was absorbed by the fiber. It is likely that a significant portion of the launched pump simply leaked out the opposite fiber end or was leaked out the sides of the fiber due to contact with the thermal mitigation scheme. This leads to the demand for improved pumping techniques which are discussed in subsequent sections. In addition to better pump absorption, there is a need for GGIAG fibers
based on silica glasses with higher melting points, enabling high average power operation not possible with phosphate based lasers, as seen by occurrences of melting of the fiber facets when exposed to more than ~5 W of CW power. Such improvements are key to growing the GGIAG technology beyond being simply a novel technique with promising potential.

3.4 Limitations and Techniques for Future GGIAG Improvement

The mode areas achieved in GGIAG fibers are the largest reported in any fiber laser to date, however efficiency and output power scaling of GGIAG fibers using new techniques and pumping schemes must still be addressed before the technology is to become competitive with other LMA technologies. GGIAG fibers have higher refractive index in the cladding and lower refractive index cores, causing light launched into the cladding to be trapped there by total internal reflection. The double clad pump scheme is not effective, and thus alternative methods for pumping large amounts of light into GGIAG fibers must be sought. In addition, GGIAG’s weak guidance characteristics require fibers to be held very straight, and thus the fibers are limited by practicality to short lengths on the order of a meter. This short length is actually advantageous in terms of their use for ultrashort pulse oscillator or amplifier systems, but the short length may require higher doping concentrations which can only be achieved in non-silica based fibers, which have inherently limited output powers due to fiber melting points. Due to the potential for extremely large mode areas, GGIAG could allow extremely large output powers with minimal nonlinearities. The following sections outline three potential techniques for improving pumping of GGIAG fibers which are being pursued.
3.4.1 Side Pumping

The simplest alternative way to deliver large amounts of pump light into a GGIAG fiber is to use side pumping methods as shown in Figure 44.

Figure 44: Schematic of possible side pumped GGIAG fiber laser module

The basic premise is to use linear arrays of diode bars with appropriate optics to launch light into a fiber core. Side pumping of a fiber has been demonstrated with powers reaching the kW level in fiber disk lasers [299-301], but these fibers were long coils with a large absorption path. In the case of GGIAG fibers, only a very small absorption path exists for pump light, so significant engineering must be done to arrange for a pump cavity to effectively direct pump light into the fiber core. In addition fibers must be doped very highly to effectively absorb a maximum amount of pump light. Due to the short fiber lengths, GGIAG fibers will suffer from larger thermal problems than conventional fibers and as a result the GGIAG fibers must be well thermally managed to achieve high powers. Since bulk optics will be required to align the pump light, the laser will not have the complete benefits of a fiber laser in terms of the entirety of the cavity being encased in glass, and the immunity to mechanical misalignment that is associated
with it. As core diameters of GGIAG fibers scale up beyond 400 μm, this technique will become successively easier, since larger core GGIAG fibers have a longer absorption path for light and hence can be side pumped more effectively. As core diameters in GGIAG fibers approach the millimeter diameter range, knowledge from side pumped rod lasers can be drawn on [9]. This can help improve GGIAG pumping technology, enabling extremely large core fiber lasers that actually become more like hybrids between fiber lasers and bulk lasers, having the benefits of fiber laser beam quality and perhaps longer length for heat dissipation, while having the damage threshold benefits of bulk lasers. This work is being conducted by William Hageman and Ying Chen among others in ongoing experiments.

3.4.2 Index Crossover

A technique that has been submitted for patent recently [302], jointly developed by Hageman, Sudesh, Richardson, Bass and myself, involves the tailoring of the GGIAG fiber materials to engineer a different refractive index profile for the pump light and laser signal light. This so called “crossover” technique calls for using glasses in the cladding that have a higher refractive index than the core at laser wavelengths and lower refractive index than the core at pump wavelengths, allowing effective crossing of the pump light into the fiber core in a double clad end pumping scheme or core pumping configuration, while still allowing the index anti-guiding structure required for gain guiding [302]. Figure 45 is a schematic of the required dispersion curves and index profiles for such a fiber.
Investigation of glass hosts that have this dispersion property has been conducted and it appears to be possible, as there are glasses having this index crossover trait. However, a significant amount of glass science must be done in order to fabricate fiber-pullable preforms of such dissimilar glasses.

This pumping configuration is advantageous for lasers with pump and signal wavelengths separated by a large amount, as the large spacing will make less of a demand on the ability to achieve refractive index crossover. Thulium has a very large separation and has the additional advantage of cross relaxation pumping which allows operation with slope efficiencies well beyond the quantum defect. As a result this technique may be an enabling technology for power scaling in thulium based GGIAG lasers, which as discussed earlier will enable the superposition of the benefits of thulium fibers in terms of higher nonlinear thresholds to be joined with the benefits of GGIAG fibers which enable ULMA core diameters.
3.4.3 Hybrid GGIAG

An additional concept for scaling of GGIAG fiber lasers is a so-called “hybrid” scheme patented by myself, Sudesh and Richardson in [303]. In such a scheme, sections of GGIAG fiber are spliced to conventional fiber to form a gain medium with sections that are gain guided and sections that are conventionally index guided. The conventional fiber has a very large core to match that of the GGIAG fiber but would operate in the highly multimode regime were it not for the GGIAG fiber spliced to it. The GGIAG fiber is essentially used as a mode filter with lengths of GGIAG fiber selected to be just long enough to cause significant loss on higher order modes in the conventional fiber [303]. The GGIAG fiber would still enable lossless fundamental mode propagation, enabling single mode operation in a multimode conventional fiber. A sketch of a basic version of this scheme is seen in Figure 46.

Figure 46: Simple Hybrid GGIAG Laser Schematic [303]

Using such a scheme, only low pump powers would be required in the short GGIAG sections based on side pumped modules or index crossover discussed earlier. Thus, issues associated with pumping can be circumvented, as even if the pumping of the GGIAG section is not particularly
efficient, most of the power from the laser comes from conventional cladding pumping scheme of the index guided fiber. Due to low pumping powers of the short GGIAG section, there would be minimal thermal management required and the majority of the high power would be provided by pumping conventional fiber by well established cladding pumping techniques.

Since the conventional fiber can be coiled, the length of the laser can be scaled for making thermal management far simpler at high powers. The technique also eliminates the need for careful selection of the output coupler to keep single mode guidance because the gain can be tailored by adjusting the pump power to the GGIAG section rather than worrying about choosing cavity loss to lock the gain at a particular level.

The hybrid scheme can also be scaled with multiple GGIAG sections to improve single mode hold off as shown schematically in Figure 47.

![Figure 47: Schematic of multiple GGIAG sections in a hybrid scheme](image)

In addition, there is potential to use the technique for Q-switching a laser by modulating the GGIAG pump, thus modulating the cavity loss and enabling pulsed operation. The interesting benefit of such a system is that it allows simple implementation of a laser that can run in the CW
and Q-switched regime by simply changing the way the GGIAG section is pumped without the need for external additional elements.

When used in combination with an index crossover scheme discussed in 3.4.2, pumping in the hybrid scheme can be even further simplified, as the external pump diode bar can be replaced by simply allowing the short GGIAG section to be cladding pumped with the rest of the conventional fiber shown schematically in Figure 48.

![Figure 48: Schematic of “all-fiber” hybrid GGIAG setup](image)

Such a design allows a truly “all-fiber” system which can be coiled (with the exception of the GGIAG section) and easily packaged.

### 3.5 GGIAG Potentials and Conclusion

As outlined in the previous section there are potential solutions to the GGIAG pumping problem that can be solved with clever engineering, research and development work. Power scaling of GGIAG fibers is not suitable at the time frame for this dissertation, however the
potential of the technology is clear and the initial work done in this area as part of this dissertation has set the groundwork for future scaling of GGIAG technology.

When the pumping and engineering problems are solved, GGIAG has the potential for construction of short length lasers with extremely high pulse energies and excellent beam quality. Since power scaling to kW CW power levels will likely not be possible due to the short length of GGIAG fiber, its niche will likely be found in high average power (100+ W level) fiber amplifiers and lasers operating in the pulsed regime, though use of hybrid GGIAG schemes as previously discussed may increase power handling further. In the nanosecond and especially ultrashort pulse regime, the short length and large core diameter of GGIAG fibers are a huge advantage over other fiber laser technologies. A potential for order of magnitude performance improvements will open the use of fiber lasers to new areas which were once the realm of bulk solid state laser systems. Future expansion of GGIAG technology from the Nd host, where it has been demonstrated into Yb fibers where the quantum defect can be significantly lower will enable higher laser powers with less heat and higher operating efficiency. Use of silica based host glass will enable even further power scaling. The ultimate goal of GGIAG technology may be thulium based GGAIG lasers which have pumping wavelengths spread apart that enable easier crossover pumping In addition, they have the inherent benefits of large bandwidth and higher nonlinear thresholds, making the thulium GGIAG laser the most ideal candidate for mJ level ultrashort pulse fiber laser amplifier systems with capabilities orders of magnitude above what is possible with current fiber laser technology.
4 SPECTRAL CONTROL OF THULIUM FIBER LASERS

As discussed in Chapters 1 and 2, power scaling of thulium fiber lasers to near kW level powers is a challenge, but has been achieved. However with the exception of [147], these powers were achieved with little or no control over the laser spectrum. In order make practical use of thulium fiber lasers, such as those outlined in section 1.3, some degree of spectral control must be implemented. This chapter covers the main techniques used for fiber laser spectral stabilization and includes experimental demonstrations of thulium fiber lasers based on all of them, including high power demonstrations using two techniques. A simple rate equation model of CW thulium fiber amplifiers will also be presented.

4.1 Strategies for Spectral Control of Fiber Lasers

The following sections discuss the implementation of spectral control techniques for high power thulium fiber lasers, their benefits and disadvantages. Basic theory for each spectral control technique used in this dissertation, along with data for both moderate and high power lasers constructed using these techniques will be discussed.

4.1.1 Thulium Lasers with No Spectral Control

In order to better understand the reasoning for the use of spectral control in thulium fiber lasers, it is important to observe the behavior of thulium fiber lasers with no applied spectral
control. This section discusses the underlying principles for the spectral operation of thulium fiber lasers and some of the mechanisms causing the need for spectral control techniques. It concludes with results from a high power spectrally uncontrolled laser in order to show the main characteristics of a thulium fiber laser with no spectral control.

4.1.1.1 Basic Concepts Driving Thulium Fiber Laser Spectral Output

Thulium has a large spectral bandwidth and being in a glass host, is mainly inhomogeneously broadened [9, 10, 160] (though in some cases thulium in glass can act quasi-homogeneously broadened as discussed in [246] in the case of thulium doped fluoride fibers). As a consequence of the broad bandwidth and inhomogeneous broadening, as well as the close proximity of the longitudinal modes caused by the ~8+ m cavity lengths, when no constraints are put on the cavity and the laser is allowed to run freely based on the location of the gain peak, the output spectrum tends to be very broad and can contain multiple peaks over a wide region of spectrum, lasing wherever gain is most favorable as determined by the broadband HR feedback element [9, 10, 160]. As is typical of most spectrally uncontrolled fiber lasers, at low powers, near threshold the spectrum can be quite narrow. As pump power is increased, the initial laser modes begin to deplete their gain due to inhomogeneous gain saturation and other relatively nearby modes are then able to lase. The process continues to cascade out, leading to 10’s of nm linewidths and unstable spectra. This gain competition continues with increase in power and also occurs over time, as small perturbations affect the gain profile temporally as well.

In addition to the broadening of the output spectrum with increase in power, the “center-of-mass” of the spectrum shifts (center wavelength is not really appropriate since there is usually no clearly defined structure to the output spectrum, so the qualitative center, judged by where the
highest concentration of spectral power appears is referred to here as “center of mass”). Usually a shift towards longer wavelengths occurs with an increase in pump power.

Line center is also highly sensitive to cavity construction, especially fiber length. The phenomenon is due to the three level nature of the thulium ion as discussed in 2.3.3.1. In a three level laser, the ground state and lower laser level are the same level [9, 10, 160], and thus there is a large overlap of the absorption and emission spectrum of thulium as seen in 2.3.3.1. This effect shifts the gain spectrum of the thulium laser to longer wavelengths, away from the emission peak. Depending on the fiber length (and hence the amount of reabsorption) the natural lasing wavelength can be shifted significantly. Experimentally, based on different configurations used in work for this dissertation, the LMA fibers used at around 5 m in length tend to lase around 2010-2030 nm naturally and when shorter lengths of around 3 m are used, the natural wavelength shifts down to 1980-2000 nm for cavities with one HR mirror. When allowed to completely free-lase based on two flat cleaved Fresnel reflections, the wavelengths in both cases were even shorter, as the gain peak shifts shorter due to less feedback, and hence lower reabsorption of the re-circulated beam and thus more favorable gain nearer to the emission peak, an observation that is consistent with a study conducted by [101]. In fact, with even lower feedback, for instance, in the case of parasitic lasing in an amplifier which has much less than 1% per-facet feedback, the natural wavelength of even a 5 m long fiber is close to 1950 nm.

The reason for the influence of the amount of feedback on the laser wavelength is due to the level of population inversion in the fiber [101]. When there is a large amount of feedback, inversion is lower as the upper state population is depleted by the intracavity signal. The laser threshold is lower with more feedback, and gain, and thus inversion, is clamped at a lower value. Lower inversion leads to higher reabsorption at wavelengths where there is significant absorption.
spectrum. Thus the lasers with higher threshold, lower feedback and hence higher inversion in
the fiber will tend to have lower reabsorption and lase at shorter wavelengths.

Along the same lines, in terms of the inversion argument for natural lasing wavelength,
the direction and distribution of the pump can also have an effect on wavelength [101]. In a
cavity that is bidirectionally pumped or with recycled leak pump, the inversion will tend to be
higher across the entire fiber, rather than being concentrated at one end; this leads to lower
reabsorption and thus shorter operating wavelengths.

The wavelength shifting behavior of the three level system in a thulium fiber laser can be
simply modeled by using an approximate expression for the threshold pump power for lasing at
any particular wavelength. When a particular wavelength has the minimum threshold, it should
be the first to lase, and hence be the “center-of-mass” wavelength from which spectrum spreads
outwards due to inhomogeneous gain saturation. Modeling this phenomenon begins with the
equation for small signal gain which can be derived directly from the power-evolution-with-
fiber-length equations discussed and solved in 4.3 with some simplifying assumptions [3, 304].
This equation is

\[
g_{ss} = e^{\frac{(\sigma_e(\lambda_L)+\sigma_a(\lambda_L))\tau_f\eta_q P_{abs}}{A_{core}h\nu p} - \sigma_a(\lambda_L)N_{l-\alpha_L}l} \tag{58}
\]

where \( g_{ss} \) is the small signal gain, \( \sigma_{e,a} \) are emission and absorption cross section at laser
wavelength \( \lambda_L \), \( P_{abs} \) is the absorbed pump power, with \( \tau_f \) the upper state lifetime, \( \eta_q \) the quantum
efficiency or the number of laser photons generated from a pump photon (which is usually
around 1, but for thulium can be up to 2 due to cross relaxation), \( A_{core} \) is the core area, \( h \) is
Plank’s constant, $\nu_p$ is the pump frequency, $N$ is the total number of active ions, $l$ is fiber length and $\alpha_L$ is the background loss at the laser wavelength [3, 304].

In a laser round trip, there are both loss and gain mechanisms, including reflectivity of one output coupler, loss at a second mirror and a double pass through the gain medium (for a linear cavity) [9]. The total gain is the product of these given by

$$G_{laser} = (g_{ss})^2 R_1 R_2$$  \hspace{1cm} (59)

where $G_{laser}$ is the total laser gain, $g_{ss}$ is the small signal gain as defined earlier, $R_1$ is the output coupler reflectivity and $R_2$ is the effective reflectivity of the other end of the cavity (including losses from lossy mirrors, poor coupling through lenses, etc.). In order to reach laser threshold, $G_{laser}$ must be equal to unity; setting this to be the case, substituting (58) for $g_{ss}$ and solving for $P_{abs}$ an expression for the absorbed pump power required to reach threshold is achieved [3, 304]. This is given by

$$P_{abs,th} = \frac{A_{core} \hbar \nu_p}{2\tau_f \eta_q (\sigma_a(\lambda_L) + \sigma_d(\lambda_L))} \left[ \ln(R_1 R_2) + 2\sigma_a(\lambda_L)Nl - 2\alpha_L l \right]$$ \hspace{1cm} (60)

where all variables are defined as previously. By plotting (60) using typical parameters for thulium in silica fiber (found in 2.3.3.1 and 4.3) as a function of wavelength and length, a 3D plot of laser threshold power can be determined, assuming uniform spectral reflectivity and losses in $R_1$ and $R_2$. Figure 49 shows plots of the absorbed pump power threshold for a 25 $\mu$m core, 0.09 NA LMA fiber with 4 wt% thulium doping (similar to most fibers used in this dissertation) in different output coupling configurations.
Figure 49: Maps of laser threshold in terms of absorbed pump power versus fiber length and laser wavelength for different output coupler reflectivity; based on (60) for an LMA fiber. Pink regions indicate where laser threshold is greater than 10 W (an arbitrary value selected to make the plots more clear) and contour lines indicate pump levels as labeled on the figures.

The output coupling configurations include extremely low reflectivity which would be caused by angle cleaving a fiber, for instance in an amplifier configuration that potentially could parasitically lase. The 0.16% configuration is representative of using a flat-flat cleaved cavity with output from both ends. The 4% percent reflectivity is the standard cavity configuration. Higher reflectivities represent use of output couplers, for instance the typical ~15% reflectivity of a typical FBG-based output coupler and subsequent higher OC values.

Since in a free-running laser the lowest threshold wavelength will be the natural laser wavelength, the trend in shift of natural wavelength to longer wavelength values is clearly
observed in Figure 49 when higher reflectivity output couplers are used, as is discussed earlier. In any individual figure the trend of longer laser wavelengths with longer fiber lengths is also clearly observed, and matches up reasonably well with experimental observations. The strong reabsorption effect is seen at wavelengths below ~1950 nm where it becomes clear that lasing is difficult for these fiber configurations. This matches well to performance of a tunable LMA fiber laser built for this dissertation which showed a cutoff wavelength on the short end of around 1947 nm (discussed in 4.2). Again the long wavelength cutoff is clearly seen, due to a combination of lack of emission cross section and the large amount of background silica absorption losses that become significant beyond 2100 nm. As a general trend, the laser threshold increases with increasing fiber lengths due to reabsorption. Also of interest is that the model predicts that lasing is possible even at extremely short wavelengths, but the fiber length must be very short, on the order of less than half a meter. It would be difficult to achieve lengths of a double clad fiber this short due to insufficient pump absorption, however core-pumped lasers can readily absorb pump in these lengths, so the figures suggest that to achieve wavelengths on the shortest end of the thulium spectrum, core-pumping or at least very large core-to-clad ratio double clad fibers must be used. This is seen in experimental results in [289, 305].

Core diameter itself also has an effect on the natural lasing wavelength, as when core diameter is decreased to single mode dimensions, the effect of reabsorption losses can be reduced somewhat. In addition the fundamental mode overlaps the gain medium even better than it does in an LMA fiber (for a 25 μm core LMA fiber MFD is ~23 μm, under-filling the core, while for a 10 μm core single mode fiber, MFD is ~12.5 μm, overfilling the core), allowing more efficiency operation, and because some of the mode sees no dopant, lower reabsorption losses
Figure 50 shows the threshold map for a single mode fiber (similar to those used in this dissertation work), note that threshold values are significantly reduced, and the features of the individual contours are generally broader, indicating that these single mode fibers may be more useful for selection of longer and shorter extremes of thulium fiber laser operation.

One additional interesting note is the reasoning for the ability of a spectrally selected laser to overcome the natural lasing wavelength, even if operation is far from the desired wavelength region. Figure 51 shows a 3D representation of the laser threshold in terms of absorbed power for a fiber similar to the one used to create Figure 49. The difference is that the reflectivity was not made spectrally flat, but rather at all wavelengths outside of 2049-2050 nm, spectral reflectivity is that of an angle cleaved laser, while in-band from 2049 to 2050 nm the reflectivity is 100% (simulating for instance VBG feedback).
Clearly the region with the high reflectivity feedback around 2050 nm would lase well before any other regions for reasonably long 5 meter fiber lengths, and threshold is an order of magnitude lower than for the angle cleaved feedback. Due to the much more favorable feedback, the spectrally selective element maintains its dominance even as power is increased and inhomogeneous gain saturation begins to set in. With this VBG analogue the laser would begin to lase on a very narrow band in the small region selected for by the spectrally selective element. As power increases, inhomogeneous effects would tend to broaden the line to fill the spectral bandwidth of the selective element (this is observed in 4.2.1). A large level of pump power is required before the spectral selectivity of the element is overcome, even at a wavelength that is far from the natural wavelength of the laser. If sufficient hold-off caused by angle cleaves is not supplied, eventually the inhomogeneous gain saturation will reduce the gain at 2050 nm sufficiently such that the threshold for other wavelengths can begin to compete and parasitic lasing can occur. By a combination of increased reflectivity of the feedback element and decreased reflectivity or increased losses at other wavelengths, the broadening of lasing beyond the selective element can be avoided.
4.1.1.2 Experimental Results

Most experimental systems used in this dissertation work began as HR mirror based oscillators which were tested in the free-running configuration. One particular system based on the high power amplifier used in section 4.2.2 is discussed here in terms of its spectral and power performance.

The laser is a bidirectional pumped oscillator based on the standard 25/400 LMA thulium doped fiber (discussed in 2.2.2.8) with matching passive fibers spliced for thermal management. The schematic of the laser is shown in Figure 52, with 5 meters of active fiber wrapped around an 11 cm diameter water cooled fiber mandrel with the splices between active and passive fiber held straight along the same mandrel.

![Figure 52: Layout of the high power thulium fiber laser with HR mirror feedback. FC → flat cleave; TDF and UDF are thulium doped and undoped fiber; M1 is HR at ~790 nm and HT from 1.85-2.1 μm; M2 is HR from 1.85-2.1 μm and HT at ~790 nm; L1 is a 26 mm FL aplanatic triplet; L2 is a 100 mm FL 5 cm diameter NIR achromatic lens; L3 is an output collimating lens; LD1 is a 300 W, 400 μm fiber coupled diode.](image)

The ends of the fiber are held in water cooled “V” grooves for thermal management and to protect the polymer from damage due to heating from residual pump light. Pumping is achieved by light launched from a pair of 300 W, 400 μm core, 790 nm fiber coupled diodes through a pair of 100 mm focal length achromatic triplet lenses and off of or through the
appropriate dichroic mirror. For this particular experiment, both ends of the fiber are perpendicularly cleaved and one end is collimated with a 26 mm AR coated Infrasil aplanatic triplet. This beam is reflected back into the cavity by a broadband HR mirror.

Power performance of the laser is seen in Figure 53 with a slope efficiency of 63% and a threshold of between 8 and 9 W with respect to launched pump power (which is launched with ~75% efficiency).

![Figure 53: Power performance of the HR mirror based high power thulium fiber laser](image)

This threshold value is reasonably close to the threshold predicted by the corresponding plot in Figure 49, within the errors in the input parameters and approximations of the model used to produce the figure. The slight roll-off in power at the high end is due to the pump diodes drifting from optimal wavelength, causing a reduction in pump absorption which can be avoided in future systems by use of diodes with closer-to-optimal wavelengths.

The spectrum of the free running laser at 50, 110 and 220 W of output power, shown in Figure 54, demonstrates the expected behavior of the broadening of the linewidth with increase in pump power predicted by theory discussed earlier.
Figure 54: Spectra of HR mirror based lasers at 50, 111 and 500 W output powers.

One interesting note about the spectra is that rather than broadening in a smooth Gaussian or similar distribution, the broadening jumps around and results in a spiky output. This is likely due to a combination of effects including loss variances in the AR coatings in the intracavity lens, reflectivity variations in the HR mirror, small, local fluctuations in the emission cross section and wavelength dependent losses in the splices. The combinations of these variations conspire to give certain local regions in the favorable lasing bandwidth more gain than others, producing the spiked output. As power is increased the spikes begin to come together into a single broad spectrum as seen for the 200 W spectrum, and likely would continue to join together due to inhomogeneous gain saturation.

The laser spectrum is also observed at low powers with both ends flat cleaved and no feedback, and in other experiments with angle cleaves and no feedback, meaning that total reflectivity was around 0.16% and 0.0001% respectively modeled earlier in 4.1.1.1. When these configurations were brought above threshold, the natural lasing wavelengths were observed to be around 2007 nm and 1970 nm respectively, which are again in reasonable agreement with the theory.

Final notes on the performance of the HR mirror based oscillator include that M² is <1.2 at powers up to full operation tested as discussed in 3.3.2. The laser system was also a test bed
for thermal and mechanical stress mitigation techniques for future systems, and as such the performance of the laser was tested for >1 hour operation and found to vary by less than 2% in output power after an initial drift of ~4% as seen in Figure 55. Such stability is critical in the design of future systems discussed in this chapter which are designed for making measurements over long time durations.

![Figure 55: Hour duration stability test of HR mirror based laser at 200 W output power.](image)

In sum, the performance of the high power thulium laser is a useful window on some of the functioning of the physics behind thulium fiber laser operation. The experimental results for a free running laser agree reasonably with the theory discussed. With the knowledge of the performance of a spectrally uncontrolled system the need for spectral control becomes completely clear and the randomly fluctuating and changing spectra of free running lasers are not sufficient for most spectrally demanding applications.

4.1.2 Fiber Bragg Gratings

Fiber Bragg gratings (FBGs) are the standard technique for control of low to moderate power fiber lasers, and use of this technology enables a reasonable degree of spectral control in single mode fiber lasers. This is due to long term development of such grating in the
telecommunications area, however as FBGs scale to LMA fibers they may begin to run into difficulties in terms of maintaining spectral linewidths and handling high powers, as since they are part of the fiber, they may see the heat load the fiber experiences and deform as a consequence. Despite some of their disadvantages, FBGs remain the only way to truly have an “all-fiber” resonator and the inherent stability that goes along with it. The following sections discuss the basic theory of FBGs and the results of a spectrally controlled thulium fiber laser with moderate powers.

4.1.2.1 Basic Theory

The vast majority of fiber laser applications do not call for extremely narrow linewidths, but rather control in the range of spectral combining around a nanometer or a few hundred picometers [3]. The most common method for achieving these modest linewidths is the fiber Bragg grating (FBG). FBGs are layers of high and low refractive index written into fibers using either photosensitive glass or direct femtosecond laser writing processes. Photosensitive glass is most commonly used and works by way of glass doped with photosensitive ions reacting to exposure by UV light through a mask [306]. The UV light changes the refractive index in the exposed region and hence the grating is formed in the fiber. UV written FBGs are the standard for most fiber lasers due to their quicker, high volume fabrication once the initial mask is set. Direct femtosecond writing of FBGs into fiber lasers has the advantage of potentially being written directly into gain fibers with no special sensitized glass. In addition, the ability to make gratings without phase masks makes the technique more flexible, enabling fabrication of FBGs at any wavelength without the need for an expensive, custom designed mask for each wavelength.
Such direct written lasers have achieved comparable powers and linewidths to phase mask written FBGs as seen in [307, 308].

Regardless of the technique used for fabrication, the design of an FBG involves first determining the desired center wavelength (Bragg wavelength, \(\lambda_b\)), which leads to the desired spacing of grating, \(d\), the relationship is given by

\[
\lambda_B = 2n_{eff}d
\]

(61)

where \(n_{eff}\) is the effective index of the fundamental core mode [306]. There are a number of types of FBGs and a large potential variation in designs depending on the exact application.

Even within the simple regime of FBGs for used as reflectors, several different designs can be used beyond the simple Bragg stack, including such designs as apodization, used to reduce side lobes or chirping to enable dispersion compensation [306]. Analyzing these more complex gratings usually requires turning to coupled mode theories or other more complicated techniques, especially when information beyond reflectivity and linewidth, such as chromatic dispersion, multiple fiber modes performance or fiber mode conversion is desired [274, 306, 309]. In these cases, more sophisticated models must be undertaken, or commercial software must be used.

The simple laser mirrors used in the experiments described within this dissertation can be understood with simple analytical approximations, providing reasonable accuracy to give an understanding of FBG performance. In the simplest approximation, the reflectivity of the grating is given by

\[
R = \tanh^2 \left( \frac{\pi \delta n_g g \eta_g}{\lambda} \right)
\]

(62)
where $\delta n$ is the refractive index step caused by the writing process, $l_g$ is the total length of the grating, $g$ is the average value of the envelope weighting function and $\eta_g$ is the overlap factor of the fiber mode with the grating structure [306]. The linewidth of an FBG is given by

$$\Delta \lambda_L = \frac{2\delta n \eta_g \lambda_B}{\pi}$$  \hfill (63)

where the variables are defined as before and $\Delta \lambda_L$ is the full width of the reflectivity curve given by plotting (62) versus wavelength [306]. By using the appropriate number of layers with appropriate contrast in index and spacing between layers, the grating can be completely tailored to the desired values for laser design. Gratings with linewidth as narrow as 0.01 nm have been fabricated in single mode fibers, however it is significantly more difficult to achieve narrow linewidths in larger core LMA fibers due to their slightly multimode nature and larger core sizes [3].

The simplest way to implement fiber lasers using an FBG is via a single FBG as the HR mirror and a cleaved facet as a 4% broadband output coupler. Use of a single FBG reduces system complexity, but has disadvantages in that the linewidth limitation of the laser will be determined only by the width of the reflectivity of the FBG, as the OC of such lasers is the broadband Fresnel reflection. In addition, since the output coupler of such fiber lasers is the cleaved facet itself, the laser cannot be spliced into further components in a system, as the splice would eliminate the feedback from the cleaved facet. To combat this, a second, low reflectivity FBG (usually around 15% to be sure feedback is above any spurious Fresnel reflections) is used as an output coupler. This enables the fiber laser to be spliced into a system without concern for
the end facet. In addition, careful selection of the two FBGs (or tuning of reflectivity after cavity construction by stretching or heating the gratings [310]) to have only a very small spectral overlap as seen in Figure 56 can enable the production of lasers with linewidths smaller than either individual FBG.

![Figure 56: Overlapping two FBGs to control linewidth, lasing is only possible where reflectivity of both FBGs overlap. HR or OC FBG center wavelength can be controlled by stretching or other tuning techniques to fine tune laser linewidth.](image)

A final advantage of the two-FBG technique is that often lower gain wavelengths near the edges of emission spectra can be accessed by using slightly higher output coupling percentages, thus enabling achievement of more difficult to reach laser wavelengths, for instance beyond 2100 nm or below 1930 nm in high power thulium fiber lasers as seen by the analysis in 4.1.1.1. The difficulties of using two FBGs includes increased system costs and complexity and also the practical challenge associated with fabricating two completely different FBGs with different reflectivities having matched reflectivity peaks.

Using a single FBG, laser tunability can also be achieved to some extent by stretching, compressing, bending, heating or otherwise inducing a change either to glass refractive index or grating spacing [310]. These changes in index or spacing influence the Bragg wavelength from (61) and thus enable tunability. The limitations are only set by the physical or thermal strength of the FBG which is usually in the range of a few tens of nanometers of tuning.
FBGs have been proven able to handle very high powers, as they were incorporated into several of the highest power lasers reported [55]. Despite their power handling capability, they are not always compatible with some of the newest, extremely large mode area fibers such as GGIAG, PCF, leakage channel and CCC. This is because core sizes in FBGs cannot currently be made large enough and also due to problems with their fabrication in soft glasses (though direct femtosecond writing may relieve these issues).

4.1.2.2 Simple Experimental Results

A basic LMA fiber based FBG stabilized thulium fiber laser was constructed and tested. The laser was built in collaboration with Gavin Frith at Nufern Inc. seen in [311] and was tested at both Nufern and the University of Central Florida. The resonator design as seen in Figure 57 is terminated on one end by an LMA HR FBG written by traditional FBG fabrication methods [306, 312] in a 0.09NA, 25 μm core, 0.46NA, 400 μm clad photosensitive LMA fiber. The FBG is designed to be >99% reflective around 2052 nm with a FWHM <3 nm though the FBG was fabricated “by design” by the vendor and not tested at 2 μm due to lack of available instrumentation at the fabrication location.

Figure 57: Layout of FBG based thulium fiber laser

The other end of the resonator was formed by a Fresnel reflection from a flat cleave on a similar, though not photosensitive, section of passive LMA fiber spliced to the other side of the
gain fiber. This splice was also coated in high refractive index epoxy to act as a “pump dump” and “cladding mode stripper” to strip out any unabsorbed pump light and strip off any signal light leaked into the cladding by imperfect splices. Gain was provided by ~5 meters of 0.09NA, 25 µm core, 0.46NA, 400 µm cladding thulium doped fiber (full description of this fiber is given in 2.2.2.8) spliced between the two passive sections. This fiber was wrapped around an ~11 cm diameter water cooled fiber mandrel with round grooves designed to fit the polymer coated fiber outside diameter. The mandrel was water cooled to ~ 14°C as were the “pump dump” and FBG to enhance thermal stability. Pumping was achieved by directly splicing a 400 µm core, 440 µm clad, 0.22NA pump fiber to the photosensitive FBG fiber on the opposite end from the active fiber. The pump fiber was connectorized and could be plugged directly into a 790 nm, 300 W fiber coupled laser diode from LIMO to provide pump light. The entire laser (with the exception of the pump diodes) was packaged into a 20 x 30 x 5 cm box with connectorized pump inputs and outputs.

Testing of this laser was done both at Nufern by Frith where results from such testing can be found in [313] which demonstrated 54% slope efficiency with 109 W of output power (limited by the ~225 W pump then available) and <2.5 nm FWHM linewidth as measured by a monochromator with relatively poor resolution and with M²<1.2. Several years later after having been rebuilt due to some thermal damage, the laser was retested at UCF as part of this dissertation work, with a more thorough investigation of spectral behavior by analysis with an optical spectrum analyzer (OSA) with 50 pm resolution, results of these tests are described below.

As seen in Figure 58, the maximum tested output power was ~70 W with a slope efficiency of ~50% and a threshold of ~10 W of pump power (which is quoted as directly from
the pump diode, losses in splices leading to the active fiber are assumed to be negligible). There is no sign of thermal roll-off, however at this output power, testing was stopped due to catastrophic thermal damage to the laser, most likely resulting from insufficient cooling of the splice between the FBG and active fiber caused by the degradation of the thermally conductive paste used at this point to cool the splice.

Laser beam quality was relatively high, with $M^2<1.2$ and with a far field output beam as seen in Figure 59. It should be noted that the beam does not appear to be completely perfect in terms of shape in the far field. This apparent degradation is due to speckle associated with signal light trapped in the cladding interfering with light from the core. This is due to insufficient stripping of the cladding light by the cladding mode stripper and could be avoided in future lasers by using a longer mode stripper or using non-double-clad fiber for the delivery fiber, which itself would act as a cladding mode stripper due to a high refractive index coating, rather than the low refractive index coating used for double clad fibers. The amount of power in the cladding light is relatively small compared to the power in the light coming from the core and if necessary can be easily filtered by free space spatial filtering techniques, as at a focus this light is on the periphery of the beam. Because the divergence of cladding light is usually larger than that of core light, it is often naturally filtered out by the aperture sizes of turning mirrors or lenses.
The spectral performance of the laser as measured with the high resolution OSA is seen in Figure 60.

As would be expected from gain dynamics of a laser whereby the regions of highest gain and lowest loss (where the HR mirror has its peak reflectivity) lase first and subsequently, as pumping increases, a broader and broader spectrum is able to lase. At low powers, near threshold a near resolution limited linewidth is achieved with <50 pm FWHM, but as power increases the FWHM increases from this sub-50 pm width up to around 300 pm as side lobes begin to also lase. As power is further increased several peaks begin to form, though all of these peaks fall beneath the envelope of the FBG reflectivity spectrum. The peak with the largest power and the
overall “center of mass” of the spectrum also shifts by a few hundred picometers with pump power. This behavior is similar to what might be observed in a free running thulium fiber laser with a broadband HR mirror, random peaks occur at the peak of the gain which shifts around with pump power. At the highest operating powers, a secondary peak begins to come in around 2049 nm while the main peak is between 2051 and 2052 nm. This peak is not present at all high powers, but rather comes in and out as gain favors it. The peak falls outside the design FWHM of the FBG; this may be due to side lobes of reflectivity that can occur in FBGs or may be due to lasing of a higher order mode that would see a slightly different reflectivity of the FBG. Without characterization data for the FBG it is difficult to pinpoint the issue exactly, but the existence of this feature points to a main challenge associated with fabricating FBGs in LMA fiber: dealing with the slightly multimode nature of the fiber. It can be difficult to achieve sufficiently narrow FBGs in LMA fibers as the FBG must be designed to match the propagation constant of a mode and each mode has a different constant [3]. Also due to the larger core diameter, it can be more challenging to fabricate an FBG with accuracy across the core.

As evidenced by the results of this experiment, FBGs can be effective as spectral control devices, as they managed to force lasing in the thulium fiber at ~2050 nm while the free lasing wavelength of the same length of fiber would be closer to between 2010-2020 nm. However, extremely fine and stable spectral control under the envelope of the FBG could not be achieved due to the nature of the relatively broad, flat reflectivity of the FBG and the broadband feedback provided by the Fresnel reflection. Use of a narrower FBG may alleviate some of these problems, but these can be difficult to fabricate as previously discussed. An alternative is to use an OC FBG which is either narrower than the HR FBG (which is easier to achieve as the OC only requires ~15% reflectivity to ensure that it has more feedback than any potential Fresnel
reflection). The narrower OC would tend to force lasing only under its envelope. If a narrower grating could not be fabricated an OC which was slightly detuned in center wavelength compared to the OC could be used so that the reflectivity spectra of the OC and HR FBGs only overlap in a small region, thus forcing narrower linewidth operation. Overall, as evidenced in these results the use of FBGs is an effective spectral control method (as it has been used in many lasers based on Yb at kW levels). It is especially effective for applications where only nominal wavelength stability is required such as applications with broad absorption resonances or transmission windows, or for applications where a stable spectrum is only desired to enable accurate design of AR or HR coatings and spectrally sensitive components such as isolators which only require a few nm of stability. When highly accurate, extremely narrow linewidths are desired from fiber laser oscillators the FBG may not be the method of choice and free-space based alternatives as described in the subsequent sections may be required.

4.1.3 Diffraction Gratings

Though FBGs are the mainstay of commercial lasers when the desired wavelength range is known and usually consistent, lasers for laboratory use, experimental systems or systems for applications requiring very broad tunability may require alternative techniques to achieve spectral control. Use of diffraction gratings is a commonly used, simple technique to provide spectral control of a fiber laser. The following sections outline the basics of spectral control using diffraction gratings and discuss experimental results of moderate power grating tunable thulium fiber lasers.
4.1.3.1 Basic Theory

The basic operating principle of a grating tuned fiber laser involves using the angular dispersion of the grating to feed only a particular wavelength back into the resonator. Fiber lasers are especially easily tuned as only a modest amount of feedback is required to efficiently control the wavelength; this is due to the very low reflectivity of the “output coupler” cleaved fiber end. Since fiber lasers are also relatively tolerant to loss and still able to maintain efficiency, high quality gratings with minimal loss are not absolutely necessary, and inexpensive lower quality gratings with efficiencies in the 70-90% range can be used [3]. The most common configuration for a grating tuned cavity is use of a grating in the Littrow configuration (Figure 61).

Figure 61: Grating in Littrow configuration with blaze facing correct direction. The angle shown is the Littrow angle.

In this configuration, tuning is achieved based on angle of the grating with respect to the incident light, which is reflected back on itself into the cavity. The Littrow angle varies as

\[ \lambda_L = 2\Lambda \sin \theta \]  

where \( \lambda_L \) is the laser wavelength, \( \Lambda \) is the grating line spacing, and \( \theta \) is the angle of the light with respect to the grating. For a typical 600 line/mm grating used around the 1.9 to 2.1 \( \mu \text{m} \) tuning range of thulium angle of incidence will be 35-40 degrees.
An additional benefit caused by laser tuning using a grating is narrowing of laser linewidth, which is caused by the spatial dispersion of the grating. Only a small band of light is fed back into the fiber core and thus linewidth is narrowed. Though laser linewidth of a grating tunable laser at all operating powers cannot be predicted completely (as is the case for any tuned laser) because near threshold and at low powers, the spectrum tends to be narrower and broaden with increased power as the reflectivity bandwidth is filled. Though at any point the linewidth cannot be predicted, an upper limit on its value can be predicted based on the parameters of the fiber laser cavity according to

\[ \Delta \lambda_L \leq \frac{\lambda_L M^2 A \cos \theta}{f \sin^{-1} NA} \]  

(65)

where \( M^2 \) is the well known beam quality parameter (usually close to 1 for a fiber laser), \( f \) is the focal length of the collimating lens, and the other parameters are as defined earlier [3, 99]. Essentially what is being determined by (65) is the width of the spectrum of light which fits within the acceptance NA of the laser fiber based on how it is dispersed by the grating in space. The general trend is, the smaller the fiber core and higher the NA, the narrower the linewidth, since the output beam is more divergent, and hence uses more of the grating and thus sees more dispersion. Any parameter that gives a larger spot on the grating reduces linewidth. Hence, a LMA fiber will have more difficulty keeping a narrow linewidth than a single mode fiber.

There are some limitations and challenges associated with grating tuned lasers. First, since diffraction gratings are not perfectly efficient in reflecting light, the lasers are not as efficient as compared to their free running counterparts based on HR mirrors. Drops in efficiency as large as 25% can occur [1]. This drop in efficiency is due to lower feedback from the grating.
and also losses and absorption associated with gratings. These drops can be combated by using PM fiber and polarized lasers, as typically gratings are significantly more efficient on one linear polarization direction (90% vs. 70% for typical gratings used for thulium). Power scaling in high power oscillators based on gratings also becomes difficult because the inefficiency of metal coatings (the least expensive gratings) is partly due to absorption, and this leads to thermal distortion issues at hundreds of watt level powers. Thermal distortion can be combated by using actively cooled metal substrate gratings or by use of significantly lower loss dielectric gratings, but both techniques increase the cost and complexity of the system. An additional disadvantage of high power operation with gratings is due to the need for LMA fibers to achieve high powers, linewidths of high power tunable lasers can be several nanometers calculations on (65) and demonstrations in [1, 314, 315]. This issue with larger linewidths is one of the main reasons for the use of MOPA based system designs, including the system discussed in 4.2.2.

4.1.3.2 Single Polarization, Single Mode Tunable Thulium Fiber Laser

A tunable thulium fiber laser with single polarization and high beam quality was designed, with the intent to use it as a seed laser for a high power MOPA system. In order to achieve effective seeding, single mode fiber is required; to achieve maximum transmission through an optical isolator, a polarization stable laser is required. To ensure saturation of the amplifier, an output power of up to 10 W is desired with the largest tuning range possible with stable operation to ensure the amplifier is constantly seeded.

In order to achieve these characteristics, a laser based on PM thulium doped single mode double clad fiber is constructed (Figure 62).
Figure 62: Schematic of grating tuned thulium fiber laser.

The gain medium is ~5 m of PM 0.16NA, 10 µm core, 0.46NA, 130 µm clad thulium doped fiber (see section 2.2.2.8). For thermal management this active fiber is wrapped around an ~8 cm diameter fiber mandrel with round bottomed grooves and water cooled to ~14°C. One end of the active fiber is spliced to core and cladding matched passive PM fiber, the opposite end of which is flat cleaved to form the output coupler of the cavity based on Fresnel reflections. A “cladding stripper” is used on the passive fiber to remove unabsorbed pump light and strip out cladding light. Pumping is achieved by a 2+1:1 fiber side combiner (ITF Labs) with a feed through fiber matched to the active fiber and two 0.22NA, 105 µm core, 125 µm clad pump fibers. Transmission of the pump light delivered by two 790 nm, 40 W, 100 µm core, 0.22NA fiber coupled laser diodes through the combiner was >90%. Though the diodes are capable of a total of 80 W of power, and the laser needed to operate at only 10 W, which requires <40 W pump, the combiner is only rated for 25 W per input port, and hence two diodes are used. The opposite end of the combiner feed through fiber is angle cleaved at ~8° and held in a water cooled block. The output from this end is collimated with a 26 mm achromatic triplet lens, then passed through a quarter and half wave plate, a polarizing beam splitter and finally reflected off of the diffraction grating which is placed in the Littrow configuration. Theoretically only a half wave plate is required to orient the polarization from the fast or slow axis of the PM fiber to pass.
through the beam cube and hit the grating with the desired polarization, however addition of the quarter wave plate gives fine adjustability to fine tune the polarization state to account for changes in birefringence as power was increased and also to account for the broad range of wavelengths the laser is used at, as all of the polarization components including the waveplates were designed for 2050 nm, thus down near 1900 nm the extra quarter wave plate helped with stability.

The tuning grating is a copper substrate, gold coated grating blazed for 1.9 µm which had 600 lines/mm. Diffraction efficiency of the grating is >90% for light incident in the s-plane of polarization and <70% for light in the p-plane. The diffraction gratings available for wavelength tuning are only capable of handling in the range of 10 W of power before thermal distortion caused instability in the linewidth and power. To help mitigate these issues and maintain stability, the grating is thermoelectrically cooled to 17°C. According to the analysis in 4.1.3.1 the larger number of lines used on a grating should allow narrower linewidth performance, so use of a collimating lens with a focal length longer than 26 mm (providing an ~6 mm beam) would have been preferred. However the limiting aperture of the polarizing beam splitter cube of ~8 mm precluded the use of a 50 mm focal length lens, which was the next length available.

The maximum output power from the laser system at any wavelength is at 2007 nm with 12.5 W power, a slope efficiency of ~40% and a threshold of 1.5 W (Figure 63).

Figure 63: Slope efficiency of tunable MO at 2007 nm showing ~40% slope efficiency
This efficiency is relatively low compared to that expected from other thulium fiber lasers (easily over 50%) and this power efficiency is due to a combination of losses in the different elements in the free space cavity including ~5-10% loss in the beam cube and ~10% loss from the grating itself. In addition, the PM 2+1:1 combiner has a ~10% transmission loss in each direction for the signal, as it is not intended for intracavity use, but rather as a seed launch in an amplifier. Finally, the fiber length may not be optimal for pump absorption, but due to the use of a pump dump, the exact amount of leaked pump power is unknown.

The laser was tunable over more than 200 nm ranging from 1902 nm to 2106 nm. Power of up to ~10 W was achievable from 1907 nm to 2100 nm with a rapid fall off in achievable power beyond these wavelengths caused by the onset of parasitic lasing. Slope efficiency varied from 33% to 40% with the wavelengths closer to the gain peak having the highest efficiency, but also higher thresholds due to reabsorption losses. Figure 64 shows a plot of slope efficiency, launched pump power laser threshold and highest achievable power versus wavelength.

Figure 64: Maximum laser power, slope efficiency and laser threshold vs. wavelength for the grating tunable laser

Error and the slight point to point variation, rather than a smooth trend in the plots is likely due to differences in laser alignment. At longer wavelengths the efficiency is slightly lower, but thresholds are also lower due to quasi-four level operation with minimal reabsorption (beyond ~19800 nm). However at extremely long wavelengths beyond 2070 nm, background
absorption losses, losses in the bulk cavity components and low emission cross section increase the threshold and reduce efficiency again. The tuning range is limited by a combination of decrease in transmission of the intracavity elements along with incorrect fiber length. A longer fiber would help achieve wavelengths beyond 2100 nm enabling higher gain at these very low emission cross section wavelengths while a shorter fiber would reduce reabsorption losses and allowed for significantly shorter operating wavelengths; the 5 meter length was a reasonable compromise between efficiency and total tuning range [99, 289]. In a similar cavity based on longer LMA fibers during the developmental work for this laser a long wavelength of ~2120 nm was achieved, but at the expense of the shorter wavelengths, limiting them to 1945 nm as seen in 4.2.2.2. With appropriate care, and perhaps additional output coupling reflectivity, the output of thulium can be pushed to as long as 2180 nm as seen in [316], but again at the cost of the shorter wavelengths. In the short wavelength regime, the wavelength might be pushed as short as 1723 nm as seen in [289] which used a ~24 cm long, core pumped fiber and achieved pump power limited 10 W level powers. By combining a two lasers with a dichroic or diffractive element (one with an extremely long cladding pumped fiber for long wavelengths beyond 2100 nm and one with an extremely short, core pumped fiber to cover wavelengths down from 1950 to 1720) a system with an extremely wide tuning range of >400 nm might be realized with 10’s of W in power which might find a use in numerous spectrally sensitive applications. The results still make it clear that knowing the desired wavelength range, a laser can be tailored to cover the range. Use of a slightly larger angle cleave on the intracavity fiber end may have also assisted in reaching a slightly larger tuning range, however such large angle are difficult to achieve consistently without polishing techniques in single mode fibers.
The polarization extinction ratio (PER) of the laser was measured to be >20 dB by taking the ratio of the beam transmitted and reflected by a polarizing beam splitter. The value is only an approximation, as it is likely that the 20 dB PER is the same order of magnitude of the PER of the beam cube itself. However this 100:1 ratio is more than sufficient for the application of transmission through the optical isolator in the amplifier system that this laser is intended to seed. The polarization of the laser needs some small adjustment as power is increased most likely related to changes in the diffraction grating as it heats up, however overall polarization is stable with power and PER can be maintained at a high level regardless of output power.

The beam quality of the laser is excellent, as expected for single mode fiber, with a $M^2<1.1$, likely limited by the aberration in the collimating lens used, rather than the fiber itself. The output beam is extremely clean and mostly free of cladding light (Figure 65).

Figure 65: Diffraction grating tuned single mode laser output beam profile

There is a likely to be a slight degradation in beam quality as shorter wavelengths are approached, because below ~2000 nm the fiber is not strictly single mode based on the $V$ parameter, however due to the relatively tight coiling of the fiber, any higher order modes would still mostly be stripped out.

The laser linewidth was maintained at < ~ 200 pm across the entire tuning range at full operating power. As is typical of fiber lasers, at low operating powers, the linewidth was extremely narrow (resolution limit of the OSA) and broadened out as power increased. However
since only 10 W maximum was used, the linewidth did not fill out the full potential bandwidth given by (65). Figure 66 is an example spectrum at full operating power.

![Example spectrum of the grating tuned laser at full power. 3dB width is < 200 pm.](image)

The line center and width remained stable over time for up to several hours at full power as did all other parameters of the laser system as was required for the laser’s designed application as a seed system for a high power amplifier.

4.1.4 Volume Bragg Gratings

Though traditional diffraction gratings are a useful method for achieving narrow linewidths and a high degree of spectral control, they have difficulty maintaining extremely narrow linewidths without use of long, cumbersome external cavities. Also, unless expensive dielectric gratings are used, they suffer from thermal limitations and relatively low diffraction efficiencies, both adversely affecting laser performance. Volume Bragg gratings (VBG) are a suitable alternative for use as spectral control elements in high power fiber lasers. They are able to maintain narrow spectral widths, achieve tunability and withstand high average powers while keeping relatively simple cavity configurations [317, 318]. They can also be used as combining elements in spectral beam combination schemes and as pulse stretchers and compressors in high power chirped pulse amplification (CPA) systems [319-321], however the focus of their use in
this work is as spectral control elements in laser resonators. VBGs have been used to stabilize most types of bulk lasers and were first used in fiber lasers in [322]. The following sections describe the basic theory of VBGs and discuss their first use in a thulium fiber laser cavity.

### 4.1.4.1 Basic Theory

A VBG is simply a sinusoidal variation of refractive index induced in the bulk volume of a material. Though there are numerous ways to form this structure, the most common, and the method used for the VBGs used in this dissertation is holographic writing in a photo-thermal-refractive (PTR) glass [318]. This is done by forming an interference pattern with a laser beam, exposing the glass, and subsequently thermally developing it to set the refractive index variation structure.

VBGs can be used in both transmissive and reflective regimes, however for this work, only the reflective regime was used. In this regime, light is incident perpendicular to the lines of refractive index variation [317]. If the period between these refractive index layers satisfies the Bragg condition for a given wavelength

\[
\lambda = 2n_{\text{bulk}} \Lambda \cos(\theta_{\text{i,int}})
\]  

(66)

where \(n_{\text{bulk}}\) is the refractive index of the PTR glass, \(\theta_{\text{i,int}}\) is the incident angle from normal (inside the PTR glass as determined from the incident angle on the grating surface and Snell’s law) and \(\Lambda\) is the period of the sinusoidal refractive index variation [317]. Figure 67 shows the expected tuning behavior with angle of a VBG designed in the thulium wavelength regime compared to experimental data. For normal incidence operation \(\theta_{\text{i,int}}\) is 90° and thus the sine term goes to unity. If one defines \(\lambda_B\) as \(2n_{\text{bulk}} \Lambda\), where \(\lambda_B\) is the design wavelength of the VBG and rewrites in
terms of external angle of incidence using Snell’s law, the wavelength of the VBG reflectivity as a function of angle of incidence is

$$\lambda = \lambda_B \cos \left[ \arcsin \left( \frac{1}{n_{bulk}} \sin(\theta_i) \right) \right].$$  \hspace{1cm} (67)

This expression can be used to calculate the expected operating wavelength for a given VBG angle.

Figure 67: Tuning curve of the VBG versus angle of incidence on the VBG surface. The solid line is a plot of the theory based on (67).

In order to determine the way light propagates in a VBG with high precision, the scalar wave equation assuming plane waves should be used, or for more precision, the wave equation should be solved for Gaussian beams [317]. However for reasonable estimates in situations where plane waves can be assumed (collimated beams) and assuming the grating in the bulk is not tilted with respect to the glass surface (a reasonable estimate, though most practical VBGs have <1° tilt to ensure Fresnel reflections do not interfere with operation) approximations can be made yielding simple to understand equations for grating reflectivity and linewidth [317]. The reflectivity of a VBG is given by

$$R = \tanh^2 \frac{\pi t \delta n}{\lambda_B \sin(\theta_{i,\text{int}})} \hspace{1cm} (68)$$
where \( t \) is the VBG thickness, \( \delta n \) is the refractive index step between the modified and unmodified glass, \( \lambda_B \) is the normal incidence design wavelength of the VBG, and \( \theta_{i,\text{int}} \) is again the internal angle of incidence [317]. Figure 68 shows the fall off in reflectivity versus angle of incidence for typical parameters of a VBG, which shows strong dependence on both VBG thickness and refractive index modulation.

![Figure 68: Plot of reflectivity versus internal angle for typical parameters at an operating wavelength of 2 \( \mu m \). The first plot is a variation of refractive index step in parts per million for a constant 5 mm thickness. A typical value achievable is in the 100-200 ppm range [318]. The second plot is varied thickness for constant 100 ppm index step.](image)

This modeling shows that for typical VBG parameters, the VBG can be a useful device to tune laser wavelength by rotating from normal incidence, as reflectivity does fall off somewhat, but not to an enormous extent, which enables efficient laser operation in angle tuning configurations. For instance for the VBG used in later experiments with 5 mm thickness, reflectivity at the full tuned angle might fall off only by 20%.

The linewidth of a VBG is determined (again within approximations) by

\[
\delta \lambda_{\text{HWFZ}} = \frac{\Lambda \lambda_B \left[ \text{arctanh}(\sqrt{R}) \right]^2 + \pi^2}{\pi t}^{1/2}
\]  

where \( \delta \lambda_{\text{HWFZ}} \) is the Half Width at the First Zero of reflectivity of the VBG, and all other variables are as defined earlier [317]. Again the effect of the different VBG parameters should be
noted, especially the thickness since as thickness increases, the VBG linewidth decreases, however it does so asymptotically, dominated by the $1/t$ behavior.

Using these basic principles it is observed that in the fabrication of a VBG, having the longer wavelength is not actually an advantage as it turns out to be for other areas. In both reflectivity and spectral width of the VBG, the longer wavelength of thulium makes it more difficult to fabricate a grating at a given performance level with respect to more typical, shorter wavelengths. This difficulty will manifest itself later in some of the high power experimental results discussed later where the relatively large VBG linewidth is observed, especially compared to similar results at shorter wavelengths. With advancements in fabrication techniques this hurdle can still be overcome and relatively narrow linewidths can be achieved.

4.1.4.2 Simple Experimental Results

A volume Bragg grating based thulium fiber laser oscillator designed for moderate power operation was constructed as a proof of concept for the VBG as a spectral control element on a thulium fiber laser. The PTR glass that the VBG is made from is transparent at thulium wavelengths with minimal background losses due to absorption and scattering, making it a suitable candidate for spectral control [318, 323]. At the time of the experiment, only one other fiber laser had been constructed with VBG feedback [322]. This work, as published in [324, 325] represents the second VBG stabilized laser, the first VBG laser at eye-safe wavelengths, and most likely the first use of a VBG in any thulium based laser.

The VBG used for these experiments was a 5 mm square aperture, 6 mm thick piece of PTR glass with no AR coatings. To avoid interference of Fresnel reflections with the VBG itself, the plane of the refractive index modulation was written at 0.6° angles in the vertical and
horizontal from the place of the PTR glass surface. The center wavelength of the VBG was 
~2052 nm with a 0.55 nm FWHM as specified by the vendor, OptiGrate. However these 
characterizations were done at a second harmonic wavelength, as the vendor did not have a 
thulium source available for testing. With the availability of the OSA and thulium fiber to pump 
and use as an ASE source the VBG was independently characterized. A thulium fiber laser was 
pumped without feedback mirrors, resulting in a few hundred mW of ASE with a bandwidth 
from 1.7 µm to 2.2 µm (though the bandwidth is quoted as ~30 dB down from the spectral peak 
power). The VBG is placed in the ASE beam at normal incidence and the spectrum behind the 
VBG is detected, leaving a notch where the VBG reflects out the ASE. By subtracting this notch 
from the ASE spectrum without the VBG in place, and then subtracting from unity, the 
reflectivity spectrum of the VBG can be determined (Figure 69).

![Figure 69: VBG Reflection Spectrum](image)

This measurement is only qualitative since it was assumed all light blocked by the VBG 
was reflected. Scattering effects (~1-3%), Fresnel reflections (~4% per surface) and absorption 
losses (<1%) are not accounted for so the actual VBG reflectivity is unknown, though by design 
the reflectivity is >95% according to the vendor. The FWHM of the reflectivity spectrum is ~1.2 
Nm, which is slightly larger than that measured by the vendor.
A VBG can also be used to tune a laser by rotating it from normal incidence and using a secondary feedback mirror. As the VBG is rotated, its center reflection wavelength should change according to (67). In order to test this, the VBG was placed in the path of the ASE and its angle recorded along with the wavelength it rejected to produce the plot seen in Figure 67.

The VBG can only be tuned down in wavelength from the design wavelength. The short wavelength range is limited by a combination of lack of sufficient ASE power to make a measurement and running out of VBG aperture as the angle of incidence is beyond 50° since the collimated beam is relatively large (~3mm diameter). VBG tuning range actually extends beyond the reasonable range over which lasing can be achieved due to reabsorption losses at wavelengths below ~1.9 µm. The long wavelength end is limited by VBG design, and if a VBG were to be used for a future tunable laser, a longer design wavelength around 2.1 µm would allow for an increased tuning range overall.

With the VBG appropriately characterized, a laser can be built to test its capabilities as a cavity stabilization element. The gain fiber for this laser was 25 µm core 0.09NA fiber with an octagonal 400 µm, 0.46NA core thulium doped fiber (see section 2.2.2.8) and was spliced to matching passive fibers on both ends. The active fiber was wrapped around an 11 mm diameter water cooled fiber mandrel with the spliced held straight in water cooled “V” grooves. One end of the passive fiber was cleaved at 8° to suppress parasitic lasing on the intracavity side, while the other passive fiber end was flat cleaved to act as the output coupler. Figure 70 shows a schematic of the VBG laser system with the pump being launched by a pair of 100 mm focal length achromatic doublets through a dichroic mirror HR at thulium wavelength and HT at 790 nm onto the flat cleaved fiber end facet.
Pumping is achieved with a 400 µm diameter delivery fiber, 790 nm laser diode capable of providing the ~65 W used for this experiment (of which ~50 W could be launched into the fiber). The opposite end of the cavity was formed by an uncoated, BK7 glass 17 mm focal length aspheric lens to collimate the output from the fiber, followed by the VBG or an HR mirror for comparison purposes. Fiber ends were both held in copper water cooled cooling blocks for further thermal management.

In order to determine if the VBG is a suitable element for cavity stabilization its performance is compared to a cavity formed by an HR mirror. If the VBG is to be a feasible element, the laser performance should suffer minimally compared to the HR mirror laser. Figure 71 is a plot of the power performance of the two lasers.
Clearly the performances are quite similar, with ~19 W achieved in the HR laser and 17 W achieved in the VBG laser, power was likely limited in both cases by instability associated with absorption and subsequent heating of the BK7 collimating lens. Slope efficiency for the VBG laser was ~46% with respect to launched pump power, which is only slightly lower than the 51% efficiency of the HR mirror laser. The laser threshold for both systems was essentially identical at ~8 W of launched pump power. The slightly lower VBG efficiency is due to the losses associated with the lack of AR coating on the VBG combined with internal absorption and scattering losses and less than 100% reflectivity (~95%). These extra ~10% losses contribute to the reduced efficiency of the laser. Overall, the laser efficiency in both cases also suffered from the use of the ~15% loss in the aspheric lens which was replaced by low loss aplanatic triplets in later experiments.

Spectral performance of the two lasers is shown in Figure 72, with the spectrum of the HR mirror laser fluctuating and spreading to an ~12 nm region around 2027 nm while the VBG is locked at its design wavelength of ~2052 nm. The linewidth of the VBG laser at powers up to 17 W was maintained at <50 pm, which is the OSA resolution limit.

Figure 72: Comparison of VBG and HR mirror laser spectra at moderate operating powers

This narrow linewidth is somewhat surprising, as the FWHM of the VBG was >1 nm, but it appears that the gain in the narrow band is sufficiently high to keep other modes lasing until
this power level. Any attempts to move beyond this power level resulted in splitting of the peak into two or more lines (though still under the VBG reflectivity envelope) before the laser was forced into instability by the lossy and high absorption collimating lens.

Beam quality of the laser was, as is typical of the LMA fiber used, quite high at around $M^2 < 1.3$, with no discernable difference between the VBG and HR mirror lasers. Tuning was also achieved by rotating the VBG and using an external feedback mirror. A ~50 nm range from 2052 nm to ~2004 nm while maintaining linewidth at watt level powers was demonstrated; this tuning will be expanded upon in 4.2.1. Overall, it is clear that the VBG is a suitable tuning element for a fiber laser, and with addition of AR coatings and increase of reflectivity, performance is likely to match that of an HR mirror. This proof of concept experiment is further expanded to a tunable laser and to significantly higher powers in 4.2.1.

4.1.5 Guided Mode Resonance Filters

Guided mode resonance filters (GMRF) offer a potentially advantageous alternative spectral selection technique in fiber lasers being in developed for thulium fiber lasers by our group at CREOL in collaboration with Eric Johnson at UNCC. These devices are relatively simple dielectric layer structures designed to produce very narrow reflection resonances at a designed wavelength, first pioneered by Mehta et al for use in stabilizing lasers [326]. The wavelength of the reflection is dependent on the physical dimensions of features in the device. Since they are fabricated by standard thin film and lithographic processes, GMRFs are easy to produce in large quantities with easily variable wavelengths, as nearly 100 filters can be produced on a single 4” standard wafer with varying feature dimensions across the wafer. Most GMRFs consist of only two or three layers, vastly simplifying the fabrication process and
reducing time and hence cost in expensive thin film deposition machines, especially in comparison to a standard Bragg stack with a similarly narrow resonance that might consist of tens to hundreds of layer pairs [327]. Due to their dielectric stack nature such devices should have damage thresholds on the order of what might be seen from dielectric mirrors, making them suitable for stabilization of high power fiber lasers. GMRFs should also be relatively insensitive to temperature, meaning that stable spectral behavior can be achieved at all power levels. Such devices have been demonstrated at modest power levels in Er:Yb fiber lasers [326], and in the following sections their initial use in thulium fiber lasers will be discussed.

4.1.5.1 Basic Theory

The simplest GMRFs are essentially two layer structures (plus a substrate layer) consisting of a one dimensional diffraction grating layer and a waveguide layer [327, 328]. The spacing of the grating is usually designed to be somewhat smaller than the intended wavelength of operation and the thickness of the layers is on the order of $\lambda/4$ [327, 328]. With appropriate care, the structure can be designed such that a diffracted order from the grating couples into the guided mode of the waveguide layer; this mode is subsequently leaked out of the waveguide by the diffraction grating, and at the design wavelength a resonance where constructive interference occurs enables a narrow reflected band of wavelengths [327, 328].

These simple 1D structures are somewhat limited due to their need to change both dimensions and material refractive index to achieve flexibility in wavelength. Therefore, a newer design consisting of a 2D diffraction grating is used which gives an extra degree of freedom in design space, enabling more flexibility without the need to change the refractive index of the materials used [328]. The 2D grating enables excitation of modes in the waveguide layer.
traveling in multiple directions in the waveguide, enabling additional features such as multiple resonances to be built into the device. Due to this enhanced flexibility, these 2D GMRFs based on hexagonal arrays of holes acting as 2D diffraction gratings are the devices used in this work. A schematic of the structure is seen in Figure 73.

![Schematic of GMRF structure](image)

Figure 73: Schematic of GMRF structure showing the SiN layer in blue which is etched down to through the SiO₂ layer in green. Dimensions are as used for 2 µm GMRFs in [328]

By selecting the grating hole pitch, waveguide thickness and grating hole size appropriately, GMRFs for thulium wavelengths can be designed, though this design requires use of numerical analysis via the rigorous coupled wave (RCWA) method or other computational techniques to fully understand the GMRF properties [326, 329]. Using these advanced analysis techniques, the simple two layer structure and 2D grating can be optimized for essentially infinitely many combinations of line spacing, center wavelengths, multiple lines and even polarization sensitive lines by simply varying physical parameters. The following section discusses the use of GMRFs designed at thulium wavelengths for the first time, the performance of the filters and areas for future improvements.

4.1.5.2 Simple Experimental Results

GMRFs have been tested on Er:Yb based fiber lasers to watt level powers as demonstrated in [326]. Recently GMRFs fabricated by the same techniques by Eric Johnson and
his team have been used to spectrally stabilize a thulium fiber laser and to explore their potential as high power stabilization devices in experiments spearheaded by Andrew Sims in collaboration with Tayna Dax, Christina Willis and myself. The GMRFs are fabricated at the University of North Carolina Charlotte (UNCC) and consist of a hexagonal array of holes etched into a SiO$_2$ layer which is deposited over a Silicon Nitride waveguide layer, which is in turn deposited onto a fused silica substrate wafer. Fabricated by standard lithographic processes using a photo-resist, development and subsequent etching, the pitch of the hexagonal array of holes is $\sim$1.5 $\mu$m and the hole diameter is $\sim$1 $\mu$m with small variations around these values to create a variation in resonances. An array of 64 GMRFs is fabricated on a single wafer with a filter size of 0.5 cm square. A single wafer can contain filters with a large number of different reflectivity resonances, simply be varying the pitch of the holes on a photo-mask. This ease of mass production, leading to low per-device cost is one of the main advantages of the GMRF technology over other spectral selection technologies.

The laser setup used to test the GMRFs consisted of a simple linear cavity shown schematically in Figure 74 [330].

![Figure 74: Schematic of the GMRF characterization setup](image)

The cavity contained $\sim$4 m of 25 $\mu$m core LMA thulium doped fiber with 400 $\mu$m cladding diameter (discussed in detail in 2.2.2.8). This fiber was spliced to $\sim$1 m sections of passive fiber
matched to the LMA fiber for the purposes of thermal management. Thermal management was also enhanced by wrapping the fiber around a ~11 cm diameter water cooled aluminum mandrel and the spliced sections were held straight in water cooled V grooves. The output facet of the fiber was perpendicularly cleaved to produce feedback from the 4% Fresnel reflections. Pump light was also injected into this end via a pair of 100 mm focal length achromatic lenses from a 400 μm fiber coupled 790 nm, 40W laser diode. The light was reflected off of a dichroic mirror designed to be HR at 790 nm and HT around thulium’s wavelength band and into the cavity. The opposite end of the resonator was formed by an ~8° angle cleaved fiber facet, followed by a 26 mm focal length AR coated Infrasil aplanatic triplet lens which produced an ~3 mm diameter collimated beam which was set to be incident on the GMRF wafer. The beam size was selected to make the largest possible beam on the GMRF, while still fitting within their 5 x 5 mm aperture. When correctly aligned, a single GMRF was able to create feedback to the laser and induce lasing with narrow, spectrally controlled linewidths. For most experiments, GMRFs were selected to be used slightly away from the natural linewidth of the laser formed by either direct lasing with the angle cleave or by Fresnel induced feedback by the non-AR coated back surface of the fused silica wafer. This natural wavelength was determined experimentally, and fit with calculations as discussed in 4.1.1.

Before making lasers with the GMRF, it is beneficial to characterize them by using the laser setup previously described as an ASE source. To achieve this, the laser is pumped with enough power to produce ASE, but kept below laser threshold. The GMRF is placed in the ASE beam and aligned for optimal rejection of the ASE in its reflectivity band so it can be characterized for reflectivity width, location and magnitude. The reflectivity of one GMRF, as measured by Sims, in particular is seen in Figure 75.
When aligned for optimal rejection (and hence reflectivity) a peak with nearly 8 dB of reflection is achieved with a FWHM of <500 pm. This is performance which is quite near the design of 400 pm. However, when aligned in this configuration the GMRF is slightly misaligned in terms of feedback to the laser cavity; as a result, this high reflectivity characteristic cannot currently be exploited. This issue lies in the design and fabrication process of the GMRF and is currently being studied. When optimized for optimal laser feedback, the GMRF is tested for transmission again (by reducing pump power below laser threshold and using ASE) and a broader, double peaked reflectivity can be seen with only ~2.5 dB of reflectivity and a 1.5 nm FWHM [330]. This may be due to the GMRF reflecting the two different polarizations of ASE differently due to a slight variation in the design from optimal (an optimal design creates a GMRF that has the reflectivity of both polarizations overlapped) [330]. With more detailed study of the material refractive index around thulium wavelengths and further optimization of the design process, this reflectivity can be enhanced, as at 1.5 μm wavelengths, greater than 99% reflectivity has been demonstrated [326]. The issue may lay in the background absorption of these materials at thulium wavelengths having an effect on the design, since absorption implies a complex refractive index, which current models do not necessarily account for. An alternative solution is to make a design where two polarizations are spread far apart, thus making extremely
polarization sensitive GMRFs which could then be used in PM fiber based cavities [330]. Sims is continuing this work in collaboration with Johnsons group at UNCC to develop superior GMRFs.

With the GMRFs characterized, their performance in the laser is studied in collaboration with Sims. Results for a single GMRF are discussed here, but a large number of filters are characterized as part of this work, with a range of wavelengths and laser results, with more details being given in [330]. A maximum power of ~10 W single end output was produced with a slope efficiency of ~34% with respect to launched pump power (Figure 76).

![Figure 76: Slope curve for GMRF based thulium fiber laser](image)

The slope efficiency was relatively low compared to other thulium fiber lasers discussed in the dissertation; however this is likely due to the combination of absorption and scattering losses in the GMRF itself and the relatively low feedback of less than 2.5 dB. This low reflectivity led to a significant amount of output power from the opposite end of the resonator (through the GMRF), which is not included in total output power, as only single ended output is useful for laser performance. The magnitude of this output power can be estimated from an equation stemming from Rigrod analysis of the laser cavity given by
where $P_1$ and $P_2$ are output powers from fiber ends with reflectivity $R_1$ and $R_2$ [3, 325, 331]. Clearly if $R_2$ is not a large number (in this case $<0.4$ since losses in the collimating lens and other intracavity Fresnel reflections must be included as well, with $R_1=0.04$ from Fresnel reflections), a significant amount of power can be emitted from $P_2$. In earlier experiments this equation was also used in reverse to determine the reflectivity $R_2$ from the output powers from each end to confirm the technique for determining GMRF reflectivity currently using the OSA. Improved GMRF feedback will vastly improve laser performance, though the 34% efficiency is still quite high considering the large amount of losses in the cavity. Maximum laser power was limited by parasitic lasing caused by unwanted feedback from Fresnel reflections off of the back surface of the fused silica substrate wafer. Future wafers might be used with wedged surfaces or AR coatings to avoid this issue. In addition, the limitation on power was cause by splitting of the linewidth of the laser into two due to the reflectivity spectrum seen in Figure 75.

The spectrum of the GMRF laser also varied with increase in output power, however the linewidth was maintained well below the 1.5 nm FWHM reflectivity up to the 10 W of power tested. Linewidth varied from $<180$ pm at 1 W of power up to 700 pm at 10 W. Below 1 W, linewidths could be $<50$ pm, which is the resolution limit of the OSA, but have been measured by Fabry-Perot techniques to be as low as 10-30 pm at these low operating powers [325]. Using this narrow linewidth stabilization ability, sub-Watt GMRF lasers have been used to seed power amplifiers to create high power beams used in the spectral beam combination section discussed later section 6.1. This variation in spectral width is expected due to the inhomogeneous
broadening nature of the thulium fiber laser as discussed in 4.1.1. The linewidth will broaden under the reflectivity envelope until it reaches the edges of feedback reflectivity. Under this envelope the linewidths are free to take any shape, as is seen especially in Figure 77 for the 10 W level, where the spectrum begins to split into two lines, both under the envelope of the GMRF.

![Figure 77: Spectral evolution of GMRF laser with output power increase](image)

The center wavelength also shifts as determined by the gain dynamics of the laser, the shift simply occurs as the laser lases where it is most favorable in terms of gain. In future GMRF lasers with filters having higher reflectivities and much narrower linewidths (as achieved for 1.5 μm in [326]) the spectral performance will be significantly more stable.

As the optimization of fabrication techniques to produce the highest performing filters at 2 μm wavelengths is still in progress at UNCC, the results of the thulium lasers produced are not optimal, but still show promise in terms of the potential of such GMRF devices. Their power handling in a laser resonator has been shown to exceed 10 W and in addition, testing of GMRFs
by illuminating them with an external 50W Tm fiber laser while running in a cavity shows that they are likely capable of 50 W or more operation [330]. Since these are simply dielectric structures, one might speculate much higher potential powers since HR mirrors, also dielectric structures, can handle significant power levels. However in order to achieve such levels, the reflectivity, bandwidth and losses of GMRFs must be significantly improved in the thulium spectral regime. When this is achieved, these devices will likely be able to compete with VBGs and other spectral control components due to their low cost, ease of volume production, ability to be fabricated for any wavelength in the thulium spectrum on a single wafer with a single mask and likely higher thermal stability (when optimized) compared to the other spectral control techniques discussed in this chapter.

4.1.6 Comparison of Spectral Control Techniques

A variety of spectral control techniques for thulium fiber lasers have been discussed and experimentally demonstrated. Each technique has its advantages and disadvantages, and as will become clear, each technique has its place in the realm of spectral control of fiber laser systems depending on the application. If taking advantage of the inherent stability of an all-fiber spliced system is the driving motivation behind the construction of a fiber laser system and only a modest degree of spectral control is required, the FBG based system is the obvious choice, as it is the only option which enables truly all-fiber construction. As discussed earlier, FBGs have their limitations in terms of potential operating linewidths, especially in LMA fibers where the slightly multi-mode nature leads to issues. However, even these problems can be circumvented with appropriate systems design. Single mode thulium fiber systems are capable of achieving output power levels of up to ~70-100 W without out fear of damage [305], and in a single mode
fiber, fabrication of a narrow linewidth FBG pair is far more achievable. If a system with even higher power is required to be all fiber and narrow linewidth, there is still the potential of an LMA fiber based MOPA type system seeded by a moderate power single mode fiber laser. If the system stability requirements are somewhat more relaxed, VBG and GMRF based components are also potentially suitable, as they could be packaged in highly stable, compact devices that could be essentially fiber pigtailed and thus act like an all fiber component. In terms of stability, the grating is by far the worst choice as it requires long cavities and large spot sizes to enable narrow linewidth operation.

If the driving factor behind the laser system is tunability, however, the grating becomes the element of choice when the largest tuning range is required. They are simple to implement, and can be relatively inexpensive if system stability, size, efficiency and power handling is not a great concern. However, if this tunability is required at high output powers, the grating based systems may suffer due to thermal effects on all but the most costly gratings. As a consequence, tunable VBG based systems offer the next best tuning ranges with proven high power handling capabilities. If only small ranges are required, FBGs can also function as tuning elements. In addition any of these systems can be relatively easily scaled in MOPA based configurations.

The GMRF and FBG may both prove to be excellent solutions for producing a low cost system, since for single mode fiber applications mass production of these components can be quite simple. When cost and linewidth are the driving factors the GMRF is the best choice. Conversely, if only a low degree of control is required, the FBG is likely the best alternative due to the simpler implementation into a laser, with no requirement of free space alignment.

If there is a demand for extremely high power oscillators there may be difficulties associated with thermal damage effects in FBGs or even (in pulsed systems especially) optical
damage due to high intensities, especially those in LMA fibers where it can be difficult to fabricate FBGs. As a result, the use of external spectral control components with a larger aperture and hence lower intensity such as the VBG or GMRF may be required. Both techniques are capable of producing narrow linewidths and the VBG has proven power handling capabilities, but may be susceptible to thermal lensing effects, especially at 2 \( \mu \)m wavelengths where material transmission is no longer perfect. This leads to the potential of GMRFs as a high power, external cavity stabilization element if their reflectivity and linewidth can be improved and their power handling capabilities proven.

Because of the long lengths of fiber lasers, and hence close spacing of longitudinal modes, none of these components are capable of producing single frequency fiber lasers, which are of interest for a number of applications. When the demand for this degree of spectral performance is required, the ultimate solution is a DFB fiber laser or diode seeded MOPA, which significantly increases the cost and complexity due to the very low available seed powers and hence the need for a number of preamplifiers before power amplifications is achievable [147].

Overall, the specific demands of a laser system drive the choice of the spectral selection mechanism. Consideration must be given to desired linewidth, cost, stability, tunability, system complexity and power performance and the importance of each weighed to make a suitable choice of spectral control component for a thulium fiber laser system.

4.2 High Power Spectrally Controlled Laser System Demonstrations

Numerous applications are driving the power scaling of spectrally controlled fiber lasers. These applications, including spectral beam combining for power scaling, atmospheric propagation for sensing and directed energy require both narrow laser spectra controlled stably
This section covers two laser systems used to demonstrate the power scaling capabilities of thulium fiber lasers. First, the use of a VBG shows the potential for direct power scaling of narrow line oscillators and second a tunable system designed for atmospheric propagation with flexible linewidth is discussed. These tunable systems also enables the exploration of the abilities of thulium fiber lasers to amplify across a broad region of their available bandwidth.

4.2.1 High Power Volume Bragg Grating System

The use of a direct oscillator to produce high powers with narrow spectra offers the advantage of system simplicity, compactness and cost compared to a MOPA system. However, in order to increase power levels, while maintaining spectral control in LMA fiber, devices other than FBGs are required, as FBGs struggle to keep sub-nanometer spectral widths. Tunability can be achieved with other methods, including diffraction gratings, however at high powers the lasers can suffer in terms of efficiency and can have issues with linewidth, as the bulk tuning gratings used are subject to relatively broadband feedback unless extremely long cavities are used [315]. As seen earlier in this dissertation, the spectral control of thulium fiber lasers with VBGs has been demonstrated [324], however in this section the scaling of powers and spectral tunability at high powers will be demonstrated. High power VBG demonstrations have been made in both Er:Yb and Yb systems with tunability [314, 332], however this current demonstration (owing in part to the inherently large spectral bandwidth in thulium) represents the highest reported power and widest tuning range from a VBG controlled fiber laser to-date [333].
4.2.1.1 System Layout and Design

The layout of the tunable and high power VBG thulium fiber laser systems are based on an expansion to the HR mirror based system discussed in 4.1.1.2. The active fiber used was a ~5 m section of 25 μm core, 400 μm clad, non-PM thulium doped fiber discussed in more detail in 2.2.2.8. The fiber is wrapped around an 11 cm diameter, aluminum water cooled mandrel with splices to ~1.5 m long passive, matched LMA fiber held straight in water cooled V-grooves. The ends of these fibers are also held in water cooled copper V-grooves to provide thermal management of the fiber polymer which can be damaged by un-launched pump light. Pumping is bidirectional based on 790 nm pump light deliverable to each end from 400 μm fiber coupled laser diodes collimated and focused with a pair of achromatic doublets either through or off of appropriate dichroic mirrors. Total pump power available directly from the diodes was 300 W per diode, but with losses in the collimating and focusing optics and due to losses stemming from aberrations in the focused beam causing a larger than 400 μm pump spot, coupled pump power was reduced to between 200 and 220 W per end. For laser stability, the pump optics were water cooled to avoid changes in alignment associated with stray pump light being absorbed in the optomechanical mounts and in the lenses themselves. The output fiber end is perpendicularly cleaved to provide the ~4% Fresnel reflection and the intracavity end of the fiber is angle cleaved at ~8° to ensure parasitic lasing does not occur. As shown schematically in Figure 78, the output from the angle cleaved fiber end was collimated by a 26 mm focal length AR coated Infrasil achromatic triplet after which the feedback mechanism took one of two configurations.
Figure 78: Two configurations of the High Power VBG Laser. The high power configuration uses the VBG in normal incidence for the maximum efficiency and the tunable configuration uses an angled VBG and external feedback mirror. In both schematics AC and FC are a angle and perpendicular cleaves; UDF and TDF are passive fiber and active thulium doped fiber; M1 is a mirror HR at ~790 nm and HT from 1.85-2.1 µm; M2 is a broadband mirror HR from 1.85 - 2.1 µm and HT at ~790 nm; L1 is a 26 mm FL AR coated Infrasil aplanatic triplet; L2 is a 5 cm diameter, 100 mm FL NIR achromatic lens; LD1 is a 300 W, 400 µm fiber coupled diode; L3 is an output collimating lens.

The high power laser configuration uses direct feedback from the VBG at its design wavelength of 2053 nm to produce the highest possible efficiency and hence highest power operation. The tunable configuration uses the VBG at an angle, which reflects light onto an HR mirror used for external feedback to the cavity. In both cases, the VBG used is the same VBG that is described and characterized in 4.1.4.2 which is a 5 mm square aperture, 6 mm thick uncoated grating centered at ~2053 nm, having ~1.2 nm FWHM, 90 - 95% reflectivity and with the VBG structure written 0.6° with respect to the polished face. For stability, the VBG was mounted in an aluminum block which was actively thermoelectrically cooled to ~17°C to avoid any issues associated with thermal distortion. In all cases, the laser was aligned for maximum
output power at ~1 W levels before being increased in power, with no realignment made at high powers.

4.2.1.2 High Power VBG System Performance

When aligned in the high power configuration, the VBG laser was able to produce a maximum of 159 W of output power stabilized at ~2052 nm where the VBG is designed. This power level was limited by parasitic lasing at around 1970 nm caused by the fiber itself lasing and ASE feedback from the uncoated VBG surfaces (this region is where lasing would be expected for a free running laser with one 4% feedback end and one angle cleaved extremely low feedback end as discussed in 4.1.1). The slope efficiency of the laser was ~54% with respect to the launched pump power, which clearly shows that there is significant cross relaxation occurring, as the laser efficiency is well above the 39% quantum defect limit. In order to understand the effect of using the VBG in the cavity in terms of induced losses, the laser was also configured to run with a simple HR mirror as feedback, as described in 4.1.1.2. The results from this comparison are shown in Figure 79.

Figure 79: Slope efficiency of High Power VBG laser and HR mirror comparison. Slope of VBG laser is 54% and HR laser slope is 60%
In this configuration, at up to the same pumping power as the VBG laser, 185 W was achieved with 60% slope efficiency, however the laser in this configuration ran spectrally uncontrolled between 2020 and 2040 nm. The reasoning behind the slight differences in slope efficiency between the VBG laser and the HR laser can be explained by inherent losses in the VBG similar to the discussion in 4.1.4.2. The VBG was not AR coated, which induced an extra 4% loss into the cavity, plus there was a 1-2% loss contribution from both scattering and material absorption not experienced by the HR mirror laser. In addition, since the VBG was not 100% reflective, but likely closer to 90-95% some power was also emitted through the VBG according to equation (70). There is also a slightly larger quantum defect from pump to signal at the VBG wavelength compared to the free-lasing wavelength since they differ by more than 20 nm. There is also a lower emission cross section at the longer wavelengths. The sum of these losses and deficiencies caused the 6% reduction in slope efficiency. This drop in efficiency would likely be eliminated with optimized VBG design for reflectivity and with AR coatings, as other high power VBG based lasers using coated VBGs were able to achieve nearly identical slope efficiencies compared to their HR mirror counterparts [314, 332]. The slight roll off in slope in both HR and VBG systems seen in Figure 79 is due to the pump diodes drifting off from an optimal absorption wavelength at high powers. If the chiller for the diodes could be run colder than the 10°C they are currently used at, the roll-off could be avoided, however the dew point of the lab precludes colder operation without condensation. In future systems more spectrally optimal laser diodes could be used to alleviate this issue.

The VBG laser was successful in locking laser wavelength to its design wavelength and holding it stable underneath the VBG reflectivity envelope. Figure 80 shows a comparison of the spectral performance of the VBG laser to that of the high power HR mirror laser as taken from
the laser output on an OSA, showing a significant increase in spectral brightness and spectral stability.

Figure 80: Comparison of OSA spectrum of VBG and HR mirror laser operating spectra at full power

The spectrum of the VBG stabilized laser, as well as its output power is observed to be stable over time with no thermally induced drift. This is due to thermoelectric temperature stabilization of the VBG.

The detailed spectral behavior of the VBG laser at a variety of operating powers is shown in Figure 81.

Figure 81: VBG spectral performance at a variety of output powers
The spectrum is observed to shift around within the ~1.2 nm VBG reflectivity envelope, as would be expected from the inhomogeneous gain saturation experienced by the thulium gain medium. This tends to drive the linewidth wider and move the spectrum to where gain is most favorable under the VBG envelope (seen in Figure 69). Center wavelength remains within a 0.3 nm range with the only drift being attributed to the gain competition processes and not thermal drift in the actively cooled VBG. This is because the drift is observed not to have a systematic direction with increase in power (wavelength moves both longer-to-shorter and shorter-to-longer as power increases). The spectral width can vary significantly with the narrowest linewidths not necessarily being at the lowest powers, due to the gain competition process. Since often multiple peaks make it difficult to determine a value for FWHM (3 dB width) the linewidths at 10 dB down from peak are compared and found to be in the range of 0.3 nm up to ~1.5 nm from 40 W to 159 W. Below 20 W the output linewidth was quite narrow, measured as 50 pm FWHM limited by the OSA resolution, similar to the result discussed in 4.1.4.2. However this spectral performance and instability is only related to the VBG width itself. Since the VBG used for this experiment is an early prototype (likely among the first designed for operation at 2 μm, with the fabricator not having a 2 μm source or detector to use for characterization) the spectral reflectivity is not optimal. It is likely with further development that linewidth can be narrowed below 0.2 nm FWHM, and thus the laser linewidth will also be locked within this 0.2 nm window. Such parameters have been demonstrated in VBGs at more friendly-to-work-with wavelengths at 1 and 1.5 μm [314, 332].
4.2.1.3 Widely Tunable VBG System Performance

With a slight change in laser configuration (Figure 78), the VBG laser setup is changed into a tunable configuration. Tuning is achieved by changing the angle of incidence on the VBG as seen by the VBG characterization curve in Figure 67. The tuning range achieved spanned more than 100 nm from 1947 nm to the center wavelength of the VBG at 2053 nm (VBGs can only be tuned down in wavelength). Powers of up to 48 W were achieved with more than 30 W achievable across the entire tuning range as made clear in Figure 82.

![Figure 82: Tuning performance of the VBG laser in power and slope efficiency](image)

The limitation on the short end of the tuning range stemmed from a combination of running out of VBG aperture (the 3 mm diameter beam began to be clipped by the angled 5 mm diameter aperture VBG) and the long length of the active fiber causing too much reabsorption for laser threshold to be reached without parasitic lasing. The short wavelength range is similar to that found for a diffraction grating tunable laser in a similar length of LMA fiber, so it is likely that the fiber length played the largest role in limiting the tuning range. The range could be extended by using shorter fiber for shorter wavelengths or by using a VBG with a longer center wavelength to begin with, enabling a larger overall tuning range.
The slope efficiencies of the laser ranged from 47% to 54% with longer wavelengths having high slopes due to being closer to normal incidence and hence experiencing lower Fresnel reflections from the uncoated VBG surface, and shorter wavelengths experiencing better slopes since they were closer to the ASE peak in the fiber, and also due to the lower quantum defect. The generally lower slope efficiencies in this configuration versus the high power direct feedback configuration are due to the combination of larger Fresnel reflection losses on the angled VBG surfaces, lower reflectivity of the VBG, as VBG reflectivity is a function of angle (discussed in 4.1.4.1) and because the beam must reflect from the VBG twice. This double reflection occurs due to the external mirror feedback and thus doubles the effect of imperfect VBG reflectivity.

Laser threshold tended to increase for shorter wavelengths due to the higher reabsorption losses experienced in the relatively long 5 m active fiber. Below 1980 nm only 30 W of power could be achieved before the onset of parasitic lasing, which limited the tuning range of the laser at every wavelength in general. This parasitic lasing threshold could be increased with use of a larger angle cleave on the intracavity fiber facet and better AR coatings on the VBG. The linewidths of the tuned wavelengths remained well under the 1.2 nm FWHM VBG envelope, but were observed to still undergo similar fluctuations under this envelope as seen in the high power configuration.

4.2.1.4 Discussion

Beam quality of the laser in all operating configurations was high, having $M^2<1.2$ at all power levels and independent of feedback element being either a VBG or HR mirror. With the current VBG laser configuration, no thermally induced drift in wavelength was observed,
however temperature control was used to stabilize the VBG. Future experiments with narrower spectrally performing VBGs would enable a more systematic study of thermal tuning of VBGs the effects of high power operation on laser wavelength. The current tuning range of this system is limited by the finite size of the VBG and the fiber length, however with an appropriately designed cavity or VBG it is likely the tuning range can be extended to 200 nm with multi-hundred-watt operating powers if appropriate care is take in VBG design, coating and fabrication. In sum, the VBG is proven as an effective mechanism for scaling thulium fiber lasers to high average powers with a reasonably high degree of spectral control. In addition the VBG is an excellent technique for laser tuning when a diffraction grating cannot provide sufficiently narrow spectrum or cannot handle the high demands on operating powers. Future improvements to VBG technology at 2 μm wavelengths enabled by the increasing availability of sources and diagnostics in the region will enable further expansion of power scaling and spectral brightness of VBG based thulium fiber lasers. But even in its current state, the VBG stabilized oscillator offers a useful technique for scaling to tunable hundred watt power levels without the need for a complex, expensive and larger MOPA based system.

4.2.2 High Power Widely Tunable Master Oscillator Power Amplifier

Applications requiring spectral control of high power thulium fiber lasers which are currently in their developmental stage often require some degree of testing to determine optimal wavelengths, linewidths and power levels. Though many such applications exist, one particular application, atmospheric propagation, has laid out a particular set of demands for a system to investigate the potential use of thulium fiber lasers in numerous applications which require atmospheric propagation. Since this system is a testing-level system, it does not have to be quite
as robust and stable as a system designed for a “hands off” field application, and would actually benefit from the flexibility of the largest possible tuning range, the design parameters of the system allow for use of a diffraction grating to achieve spectral selection. However the system also demands 200 W level powers and relatively narrow linewidths to accurately test different atmospheric windows. As a consequence, a simple oscillator design cannot be used, because, as discussed in 4.1.3, when used with LMA fibers at high powers thermal effects can cause degradation of performance and linewidths cannot be maintained at very narrow levels. The solution is to construct a tunable master oscillator with the ability to achieve the narrow linewidths and stable seed powers required, and subsequently amplify the output with a suitable power amplifier. Other demands on the system include highly stable operation for the ability to make longer duration tests, as well as to facilitate use on a day to day basis with a minimum of realignment. High beam quality is also critical, but is inherent with the use of the appropriate LMA fiber. Finally, the system must be portable, to enable it to be moved from the lab to facilities outfitted to test atmospheric transmission. This means that the system must be breadboard mounted, and mechanically stable enough to survive shipment to other locations and require relatively minimal realignment upon arrival.

The following sections outline the construction and performance of this system including discussion of some instructive iterative steps towards final system design. Though several small steps were taken towards improvement of the system, three major steps in system layout were taken to reach the final fully functioning system. These steps mainly involved the configuration of the master oscillator and the way it was coupled into the power amplifier. The actual power amplifier itself required only small changes to its configuration to achieve the desired
performance. Subsequent sections will outline the layout and performance of the three main iterations of the MOPA system

4.2.2.1 Initial System Version

The construction of the earliest version of the system was mainly driven by components available at the time, and performance was limited by some of the compromises that were made as a result.

4.2.2.1.1 System layout and design

The layout of the initial iteration of this MOPA system is seen in Figure 83, showing a master oscillator and power amplifier both made from LMA fiber with 25 μm core and 400 μm cladding as described in 2.2.2.8.

![Figure 83: Layout of first system design](image)

The master oscillator consisted of ~5 m of LMA fiber which was wrapped around a water cooled 11 cm diameter mandrel in the same thermal management scheme discussed on several occasions with ~1.5 m passive, matched LMA fibers spliced for additional thermal management. The output end of the fiber was perpendicularly cleaved and held in water cooled copper V-
grooves. The intracavity end of the fiber was angle cleaved at ~8° to suppress parasitic lasing and was followed by a 50 mm focal length near IR achromatic collimating lens. It should be noted that this lens was not optimal for use at thulium wavelengths and had 15% transmission losses. Following the lens was a 600 l/mm, 1.9 μm blazed diffraction grating in the Littrow configuration to enable tunable operation. The laser was pumped through the flat fiber end through a dichroic mirror which was HT at the 790 nm pump wavelength and HR from 1.85 to 2.2 μm. Pump light was supplied by a 40 W, 400 μm 0.22NA fiber coupled laser diode bar which was relayed through two 100 mm focal length, 50 mm diameter achromatic lenses and focused on the fiber tip with a total coupling efficiency of ~70%. The output from the master oscillator was collimated by a 60 mm focal length singlet lens, before passing through a 2:1 telescope based on a 500 mm and 250 mm singlet to reduce the beam diameter such that it is able to pass through the 1.25 cm diameter best form singlet used to launch into the power amplifier.

The layout of the power amplifier was essentially identical to the layout used for the high power oscillator in 4.1.1.2, which was the test bed for the power amplifier used here. As discussed in 4.1.1.2, the oscillator was capable of long term stable operation, indicating that the mechanical and thermal management systems discussed earlier were capable of handling the stability and power demands. This knowledge effectively decoupled any problems with the MOPA system with problems in the thermal and mechanical management of the power amplifier. Pump optics were water cooled to enable stable operation when launching the 300 W, 400 μm 0.22NA pump light from the fiber coupled diodes. The active fiber was ~6 m in length, wrapped around a water cooled 11 cm diameter mandrel and spliced to ~1.5 m sections of passive fiber, with the splices held in water cooled V-grooves and the entire fiber coated in thermally conductive paste to further enhance cooling. The only variations from the layout
discussed in 4.1.1.2, was that the output facet of the fiber was cleaved at a 10° angle to suppress parasitic lasing in the amplifier, while the input end was perpendicularly cleaved. This configuration is not optimal for an amplifier, since it does not allow as high a level of hold-off from parasitic lasing as having both ends angle cleaved, however due to the lack of an optical isolator to protect the MO from feedback, the single angle cleave was used to direct any parasitic lasing or ASE away from the MO based on the implications from equation (70), this concept has been used in other thulium fiber lasers, due to the common problem of poor availability of optical isolators [287]. The lens used to couple signal light into the fiber was a 25 mm focal length AR coated, fused silica best form singlet.

4.2.2.1.2 System performance

The performance of the LMA based MO included a maximum output power of 7 W (though useful long term stability could only be attained at under 4 W) and a tuning range of 70 nm from ~1980 nm to ~2050 nm. This performance was severely limited by the losses inherent in the intracavity collimating lens used and in the output collimating lens used, which also induced ~15% loss. Because there was also no polarization stability, the diffraction grating feedback was also relatively low (~70%). Overall the effect was a laser with <35% slope efficiency. The low output power limited the performance of the MOPA system, as sufficient pump power to saturate the amplifier and to ensure operation without parasitic lasing could not be assured. The LMA nature of the fiber also did not allow for particularly narrow linewidths according to equation (65).

The second deficiency with the system design lay in the seed launch scheme. This deficiency was twofold, involving issues with the LMA nature of the master oscillator and with
the nature of the relay optics themselves. The multimode nature of the LMA fiber MO lead to a somewhat multimode beam which had to be matched in mode field diameter to the same LMA mode field diameter in the LMA fiber power amplifier. In theory, this is possible by using a simple 1:1 imaging scheme, however in practice the process is significantly more difficult. Aberrations in lenses (especially the relatively poor quality collimating lens used) lead to distortion of the launched signal beam and thus can lead to relatively poor coupling efficiency into the power amplifier. This is further complicated by thermal distortions in the MO collimating lens initiated by the absorbing nature of its optical cement and BK7 glass. Overall this leads to a spread of the seed beam and a greater than 1:1 imaging ratio, leading to relatively low coupling efficiency of <50%, which compounds the problem of insufficient seed power. Further compounding the problem, the seed light that does not get launched into the core can be launched as cladding light or into the fiber pedestal. Cladding or pedestal modes can both have some portion of their field in the core and thus steal gain from the actual signal. In addition these cladding modes can create interference “hot spots” in the fiber as they receive gain and cause catastrophic damage to the active fiber at arbitrary points along its length, leading to fiber breakage, and self-destruction of the amplifier.

With these issues, compounded by parasitic lasing issues associated with the insufficient seed power and insufficient hold-off created by the cleaving scheme on the power amplifier, the performance of this system was severely limited to around 70 W of output power at only a relatively small region of the tuning range where amplifier gain and seed power were at their maximum. In addition, system level thermal instabilities lead to highly unstable operation with amplifier self-destruction occurring regularly.
4.2.2.2 Version 2.0 with Improved MO and Coupling Scheme

With the lessons learned from the first iteration of the system, changes were made to the pump coupling scheme and master oscillator to enable improved performance and reach 100 W, stable operating powers.

4.2.2.2.1 System layout and design

The basic layout of the system was quite similar to that described in the previous section with two major changes. The largest change was in the master oscillator itself, as seen in Figure 84.

![Figure 84: Second version of MO, including MFA](image)

The layout of the cavity remained similar, but instead included a change in pump direction to accommodate the MFA discussed later. The lossy 50 mm intracavity achromatic lens is still used as the intracavity collimating lens, however the pump was upgraded to have a higher available power for slightly more signal power and, most critically, a mode field adaptor was introduced into the cavity to improve the beam quality, and allow for better signal coupling to the power amplifier. The mode field adaptor was fabricated on a Vytran GPX-3400 by matching the mode field diameter of 0.1NA 25 μm core passive LMA fiber to that of 9.5 μm core 0.15 NA active fiber by tapering the LMA fiber down and splicing it to the single mode fiber.
The calculation of the required MFD of the LMA fiber and thus the taper ratio required is determined by calculations based on analysis done in 2.2.1.2. This taper had <0.5 dB loss in the direction from the single mode fiber to the multimode fiber, and likely slightly higher loss in the opposite direction, as higher order modes in the LMA fiber are likely stripped out, leading to slightly mode loss. The MFA was spliced to the passive LMA output fiber of the MO such that the laser output was from the flat cleaved facet of the 9.5 μm, 0.15NA core single mode fiber end of the MFA. A cladding mode stripper using high index epoxy to strip out any cladding light launched into the single mode fiber by the MFA was also incorporated to ensure high beam quality output.

The second change in configuration was the replacement of the poor quality collimating lens and telescope scheme used in the previous experiment with an AR coated Infrasil aplanatic triplet with 26 m focal length. This lead to a signal coupling optical train which is a telescope which magnifies the light from the 9.5 μm 0.15 NA single mode fiber with ~12.5 μm mode field diameter by a factor of two to launch into the ~23 μm mode field diameter of the LMA amplifier fiber. By making small adjustments to the separation of lenses in the telescope, a near perfect match in mode field diameter could be achieved, thus greatly enhancing coupling efficiency. Because of the room for error (alignment and induced by aberrations) in the telescope system given by the launch of a smaller mode field diameter into a larger MFD, a significantly higher pump launch scheme is possible.

This improvement can be seen in a fiber coupling analysis carried out in the physical optics propagation model in ZEMAX software (an example of which is seen later in Figure 87). The two aplanatic triplet lenses were modeled, as well as the collimating lens from the previous experimental setup and the two signal coupling schemes were analyzed (taking into account the
fiber dimensions). The resulting optimized efficiencies were <50% coupling for the case of LMA to LMA fiber with poor coupling optics (not including additional losses due to lack of AR coatings on elements) and ~94% for the single mode fiber to multimode fiber using the updated setup (not including losses in lenses), clearly a vast improvement. The ZEMAX model is not perfect, and thus the coupling efficiencies it estimates are slightly higher than experimental realities due to additional small misalignments that are not included in the ZEMAX model; however, qualitatively the importance of correct launch optics and matching mode field diameters is clear.

4.2.2.2 System performance

The performance of the MO with the incorporated MFA is seen in Figure 85 with a tuning range of 161 nm and a maximum power of 6 W, and a range of 100 nm over which more than ~4 W of seed was available.

![Figure 85: Tuning range at maximum achievable power for MO](image)

The specification of 4 W of seed is necessary, as it was experimentally found to be the minimum power required to be able to reach stable operation at high powers. The MFA has only a minimal effect on performance of the MO, with the long wavelength edge being limited by reflectivity of
components and losses in the cavity and the short wavelength end of the tuning curve limited by reabsorption in the long length of active fiber as suggested by results in 4.1.1. The maximum output power was limited by available pump and the relatively low slope efficiency of the laser in the 25-45% range caused by residual losses in the system on both the diffraction grating and in the intracavity lenses. The important improvement is in the single mode nature of the output beam and the ability to match this beam effectively to the power amplifier.

The performance of the power amplifier is seen in Figure 86 showing up to 120W of output power with slope efficiencies in the 50-60% range and a tuning range of more than 100 nm.

![Figure 86: Version 2.0 laser amplifier performance. The longest wavelength points also include two extrapolated points (empty squares) indicating the power level achievable if instability had not set in.](image)

The power on the long wavelength end of the spectrum beyond 2050 nm was limited by parasitic lasing in the amplifier, caused by insufficient seed power to deplete the amplifier gain, combined with a lack of sufficient feedback hold-off to keep the amplifier from parasitically oscillating at the peak of its gain above output powers of ~75 W. Performance on the short wavelength end of the tuning curve was simply limited by the amount of available seed power to sufficiently saturate the amplifier and deplete the gain. The stability of the system at 100 W power was good and there is no sign of spectral broadening of the output beyond the input linewidth of the master
oscillator. However at high operating powers there are also likely issues with feedback to the oscillator from the amplifier, causing the oscillator power to fluctuate, endangering the amplifier, which if subjected to a rapid drop in seed power while running would almost certainly self-destruct due to a large spike in power due to the onset of parasitic lasing. Looking at the maximum gain achievable before the onset of instability it appears that the limit for the amplifier system configuration is around 13-14 dB with respect to the output power from the MO (actual gain is somewhat higher due to coupling efficiency and other losses), meaning that at least 8 W of seed is required to reach the 200 W output power goal of the amplifier system. Achieving this requires the final round of improvements to the MOPA system.

4.2.2.3 Final System Version

A final round of improvements were made to the MOPA system to reach the required performance characteristics, again mainly to the MO and signal launch scheme. New parts and components required for these improvements became commercially available and thus enabled the completion of this final stage of improvements and thus achievement of the full systems capabilities.

4.2.2.3.1 System layout and design

The MO was reconfigured with PM single mode fiber and an all-fiber pump scheme with up to 50 W of available pump power and is described in layout in 4.1.3.2. The single mode fiber gave a slight improvement in beam quality over the MFA design, as there was less cladding light present, and more importantly, output power was improved, based on a combination of slightly
better slope (though losses in the pump combiner, polarization optics and tuning configuration still kept the efficiency relatively low), more effective launch of pump power (>90% compared to 75%) and significantly lower laser threshold owing to the single mode gain fiber (~2 W compared to ~8 W launched). The use of an AR coated 26 mm aplanatic lens as an intracavity collimating lens rather than the lossy 50 mm achromatic lens also improved performance, and was required to enable the collimated beam to pass through the 8 mm aperture beam splitter cube used for polarization maintenance. The shorter focal length had minimal effect on linewidth performance compared to the previous LMA based MO systems because, though the collimating lens was shorter, the larger NA and smaller core of the single mode fiber compensated as seen in equation (65). The lower threshold of 2-4 W enabled more pump power to be used for creating output rather than reaching the nearly 10 W threshold in the LMA fiber. This difference in threshold is explained by the lower background losses associated with single mode fiber as seen in analysis done in 4.1.1.1.

The second critical improvement was in the use of an optical isolator designed for the 2 μm wavelength regime with up to 30 dB of isolation. However in order to accommodate the isolator, several changes were made to the system including use of an 11 mm aspheric lens as a collimating lens for the MO rather than the 26 mm aplanatic lens, due to the need for a collimated beam diameter capable of fitting through the <4 mm clear aperture of the isolator. The beam diameter of the 26 mm aplanatic lens collimated single mode fiber output was 5 mm and hence output would have been clipped by the isolator. In order to accommodate this in the launch scheme and maintain the ~2x magnification in the imaging telescope, the 50 mm aplanatic lens used for signal launch in the amplifier was replaced with the 26 mm aplanatic triplet to achieve a potential coupling efficiency according to a ZEMAX model of >92% and an actual coupling
efficiency of ~90% (not including Fresnel and other reflection losses in launch optics and isolator) as measured by launch into an undoped fiber. Figure 87 is a schematic of the ZEMAX model for the new pump launch configuration (not including isolator effects, but including effect of launching through an angled dichroic mirror).

Figure 87: ZEMAX layout and calculations for the 11 mm focal length aspheric lens launching light from a 9.5 μm core single mode fiber to a 25 μm core LMA fiber through an aplanatic triplet and angled dichroic mirror at a distance of 1 meter between the systems.

In addition, the MO was required to be made from PM fiber and oscillate on a single polarization in order to optimize transmission through the isolator. This was achieved as is described in 4.1.3.2. In addition, in order to allow for the greatest transmission through the isolator, a zero order quarter and half waveplate were used to make fine adjustments to the polarization and optimize transmission through the isolator. The half wave plate enabled rotation in polarization, and the quarter wave plate allowed for small adjustments in polarization required to help compensate for incomplete rotation caused as the signal wavelength strayed from the
2050 nm design wavelength of the waveplates in order to maximize transmission through the isolator.

The final difference in the system lay in the power amplifier, which was reconfigured to have angle cleaves on both ends, with the input end having an \(~8^\circ\) cleave and the output end having a \(~10^\circ\) cleave. The differential in cleaves still tends to help a majority of power form ASE or parasitic lasing exit from the output end, away from the MO, however, the use of the isolator reduced the concern about feedback overall, so the larger cleave angle on the input end was able to be used, thus increasing the threshold for parasitic lasing of the power amplifier significantly.

The final layout of the system is seen in Figure 88 with a photo of the entire system packed onto a single 6’ x 2’ breadboard (with the exception of chillers and power supplies) is shown in Figure 89.

Figure 88: Schematic of finalized system layout

Figure 89: Photo of final system layout on a 6’ x 2’ breadboard
4.2.2.3.2 System performance

The performance of the MO can be found in 4.1.3.2 with up to 13 W of power being stably produced. However for consistency of the experiment, ~8.5 W was launched in all cases, as this was the highest available power across the entire desired testing tuning range. The overall coupling efficiency of the power through the collimating lens, optical isolator and into the fiber was found to be ~75% meaning that ~6.3 W was launched at maximum. One important note was that there is a significant thermal lens in the isolator due to absorption in the isolator material and possibly the Glan laser polarizers in the isolator. This causes issues with amplifier alignment as the output from the MO is increased. As a result, alignment at low powers from the MO is done, the power is subsequently increased and the alignment is fine tuned before amplification takes place. The thermal lens effect is clear, as the main adjustment needed is a change in the distances between the collimating and focusing lenses in the signal launch telescope.

With this seed, the performance of the amplifier was able to reach its 200 W goal with long term operating stability. Summarized in Figure 90, the power performance across the tuning range is seen with the maximum power being ~219 W at 1967 nm and the range over which ~200 W could be achieved is ~170 nm from 1927 nm to 2097 nm. The slope efficiency also stayed above 50% with a maximum of 64%. The decrease in slope at longer wavelengths is due to lower gain at these wavelengths, and the requirement of more seed power to reach sufficient saturation to achieve the highest efficiency operation. In addition, the quantum defect contributed to a several percent drop in efficiency from the short wavelength to the long wavelength end of the spectrum.
The tuning range was limited on the long wavelength end by the stability in the MO. At wavelengths above 2100 nm the MO operating stability and power were not sufficient to seed the amplifier. In addition, the transmission and isolation of the optical isolator was not as high as closer to its design wavelength of 2050 nm. On the short wavelength end, though the MO could produce wavelength down to 1900 nm, the amplifier was unable to provide sufficient gain at wavelength below 1927 nm due to the extremely high reabsorption losses caused by the long fiber length in the PA, coupled with issues with stability in the MO and relatively poor isolation, since the optical isolator was being operated almost 150 nm from its design wavelength. A shorter PA fiber and more appropriate isolator would enable amplification to the 200 W level at these shorter wavelengths. However, since the longer wavelength regime >2020 nm is the spectral region of interest for atmospheric propagation experiments this system was designed for, the performance at the shorter wavelength is sacrificed.

The slope of the laser was found to be extremely linear, showing no signs of saturation or roll off (shown in Figure 91), with the exception of the small drift at the highest pump powers due to the pump diodes walking off from the optimal absorption wavelength in the fiber. Performance was limited by the amount of pump power that could be launched based on
limitations in the pump diodes and based on limitations to the thermal management scheme for long term stable operation without damage.

![Graph](image)

Figure 91: Example slope efficiency at 1967 nm showing 64% slope efficiency up to 220 W output power

The spectrum of the laser showed no signs of broadening in the seed laser linewidths which were in the 100-200 pm range depending on the particular wavelength and alignment of the seed. Figure 92 shows example spectra taken at full power operation across the tuning range of the MOPA. There is no sign of ASE, parasitic lasing or any other signal within the 30 dB of signal to noise on the OSA measurements, and no signs of spectral broadening. Temporal stability of the operating spectrum is also found to excellent, with no signs of drift in the wavelength of the MO over time, thus suggesting high isolation between the MO and PA.

![Spectra](image)

Figure 92: Spectra at ~1927 nm, ~2017 nm and ~2097 nm at full output power levels around 200 W in both full 200 nm range and close in showing no signs of ASE or spectral broadening
Beam quality of the laser was measured at up to 150 W and found to be $M^2<1.2$ with the limitations in measurement powers being caused by a thermal distortion in the wedges used to sample the beam (as the camera used for these measurements required only mW of power). Since the wedges were made from low grade fused silica or quartz, they absorbed a significant portion of the 2 μm light transmitting though them and hence their surfaces were distorted by the beam as they heated and expanded, causing thermal distortion effects which threw off $M^2$ measurements at any higher power levels, and likely even affected the measurements at the 100+ W levels. In addition, most collimating lenses used also suffered from thermal distortions, further throwing off measurements, though the best results came from using an AR coated Infrasil triplet which likely suffered minimal thermal effects. Regardless of these effects, it is observed that operating power had minimal effect on $M^2$ up to the final measured value, so it is likely that this high beam quality will be maintained. The fiber being used has inherently high beam quality due to its low V parameter and has produced excellent $M^2$ values which were able to be measured in other experiments [147]. Figure 93 is a sample of $M^2$ data taken at 20 W and also an image of the beam quality in the far field at high power.

Figure 93: Measurement of $M^2$ using 1 m focal length focusing lens and 50 mm focal length output collimating lens and image of high power beam in far field (pixilation from 124 x124 element camera is smoothed using external plotting software).
Overall, all of the required performance specifications of this system were met in terms of operating stability, power, tuning range and portability. There is still room for further improvement in the system as it relates to improving the pump launch efficiency by changing pump optic schemes or using “all-fiber” pump combiners. This would enable more effective use of the available pump power and also contribute to an even higher stability system.

4.2.3 Comparison of Direct Power Scaling and MOPA Power Scaling

In the previous sections, two distinct systems for spectrally controlled, high power thulium fiber lasers have been discussed. The systems are both based on the same LMA thulium doped fiber but with significantly different architectures; thus differences in terms of performance and appropriate uses exist. Depending on the desired end application, one technique may be more appropriate than the other for the final system design.

High power oscillator systems similar to those based on the VBG offer the simplest implementation in terms of system size, number of components and complexity per watt of performance power. However, they suffer the disadvantage of the potential for change in spectrum as power is increased, seen in Figure 77 for the VBG laser. Applications requiring operation at a variety of power levels may therefore be adversely affected by these spectral variations and uncertainties, because direct oscillators will always be subject to gain dynamics and thus linewidths will start out narrow and will expand as power increases, until they fill the envelope of the spectral feedback element. This can lead to difficulties in applications which require highly specific control of spectrum. In addition, gain dynamics can lead to somewhat noisier output in the temporal domain, as any perturbation to the laser can induce relaxation oscillations and hence potentially unwanted spikes in output. The ability to tune to very long and
very short wavelengths may also be limited by the onset of parasitic lasing and will be limited by
the tuning range of spectrally selective element which must perform at very high powers.

MOPA systems like the system described earlier, based on either low power laser
oscillator seeds or on direct semiconductor laser seeds offer the greatest level of control over
laser output spectrum because the seed system is usually only designed to work at one power,
therefore, providing a more consistent source to the amplifier. The power amplifier has minimal
effect on the seed due to use of effective isolation and thus no impact on spectral performance
(provided any nonlinear effects are avoided). The amplifier will also tend to be less sensitive to
the tuning range of the seed, thus allowing for simpler tuning whether achieved by a single
tunable oscillator or perhaps an array of diode based seeds, multiplexed in a WDM to provide a
number of potential operating channels within a single amplifier architecture. Downfalls of the
amplifier scheme are of course in cost, complexity and space required for the system. Several
stages of amplification are needed and hence there can be difficulties when cost efficiencies and
also power efficiencies are an issue. Manufacture time is also impacted, further increasing cost.
The extra components also open up the potential for more problems, because as the complexity
of a system increases, so does the number of components which can undergo a potential failure.

Overall, spectrally controlled oscillators are best used in any application with less strict
spectral control requirements and those where cost, space and efficiency are sufficiently large
issues to justify lower spectral performance requirements. The use of the MOPA configuration is
best used where a higher degree of stability in the output signal is required or where a larger
degree of spectral control (either in terms of tunability or linewidth) is required.
4.3 A Theoretical Steady State Model for MOPA System Performance

When designing MOPA systems like the one previously described, it is helpful to have a basic understanding of what is expected in terms of performance and what system limitations might be. As part of this dissertation a model based on modifications to a version by Phillip Wilcox and William Tourellas [273]. In order to achieve this, the rate equations of the thulium energy level system can be solved in the steady state configuration to determine the approximate performance and estimate maximum potential system efficiency in a given laser configuration. In addition, by breaking the solutions of the rate equations into discrete spectral channels, the ASE performance and limitations in a laser can also be determined. The growth of the laser signal can be tracked as it propagates along the fiber, showing how the signal might react due to different pump schemes and fiber lengths. There is no substitute for experimentation, but this model can act as a guide for design of high power thulium MOPA systems across their potential operating spectrum in terms of selecting the ideal core dimensions, pump powers and fiber lengths required. The details of the model, based on a similar model described in [273], a comparison of model findings to the experimental results from the MOPA constructed as part of this dissertation and a selection of interesting calculations are discussed in the following sections.

4.3.1 Outline of Model Theory

The premise for this model is the use of the rate equations for the populations of the major thulium energy levels which play a role in achieving amplification in the 1.8-2.1 μm wavelength regime, including the role of beneficial cross relaxation processes. The detrimental cross-relaxation processes producing upconversion are ignored here for simplification, as they
are much less probable, but should be included in more rigorous treatments [74, 281, 282]. The rate equations for each level can be deduced from the energy level diagram, seen in Figure 28, in terms of the radiative and non-radiative processes causing excitation and de-excitation of energy levels. Such processes include cross relaxation, pump absorption, stimulated emission, radiative emission and non-radiative (multi-phonon) emission and are given in [273, 281, 282] and seen below.

\[
\frac{dN_3}{dt} = \frac{\sigma^p_{i} N_0 (P_p^+ + P_p^-)}{h \nu_p A_{\text{clad}}} \frac{A_{\text{core}}}{A_{\text{clad}}} - \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{31}} - \frac{N_3}{\tau_{30}} - \Gamma_3 N_3 - k_1 N_3 N_0
\]  

(71)

\[
\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} + \Gamma_3 N_3 - \frac{N_2}{\tau_{21}} - \frac{N_2}{\tau_{20}} - \Gamma_2 N_2
\]  

(72)

\[
\frac{dN_1}{dt} = \frac{N_3}{\tau_{31}} + \frac{N_2}{\tau_{21}} + \Gamma_2 N_2 + 2k_1 N_3 N_0 - \frac{N_1}{\tau_{10}}, - \Gamma_1 N_1 - \frac{\sigma^p_{i} (\lambda) N_0 (P_p^+ (\lambda) + P_p^- (\lambda))}{h \nu_l A_{\text{eff}}} \frac{A_{\text{eff}}}{A_{\text{core}}}
\]  

\[+ \frac{\sigma^a_{i} (\lambda) N_0 (P_p^+ (\lambda) + P_p^- (\lambda))}{h \nu_l A_{\text{eff}}} \frac{A_{\text{eff}}}{A_{\text{core}}}\]

(73)

\[
\frac{dN_0}{dt} = \frac{N_3}{\tau_{30}} + \frac{N_2}{\tau_{20}} + \frac{N_1}{\tau_{10}} + \Gamma_1 N_1 + \frac{\sigma^a_{i} (\lambda) N_0 (P_p^+ (\lambda) + P_p^- (\lambda))}{h \nu_l A_{\text{eff}}} \frac{A_{\text{eff}}}{A_{\text{core}}} - k_1 N_3 N_0
\]  

\[+ \frac{\sigma^a_{i} (\lambda) N_0 (P_p^+ (\lambda) + P_p^- (\lambda))}{h \nu_l A_{\text{eff}}} \frac{A_{\text{eff}}}{A_{\text{core}}} - \frac{\sigma^p_{i} N_0 (P_p^+ + P_p^-)}{h \nu_p A_{\text{clad}}} \frac{A_{\text{core}}}{A_{\text{clad}}}\]

(74)

where \( N_i \) is the population of the \( i^{th} \) energy level, \( P_p^+/- \) is the power of the pump or laser signal in either the forward or backward direction in the fiber (these can be a function of time), \( h \) is Planck’s constant, \( A_i \) is the area of the core, clad or the effective area given by the mode field diameter, \( \nu_{l,p} \) are signal and pump frequencies, including for ASE channels, \( \sigma_{a,e}^{p,l} \) are the absorption and emission cross sections of the pump or laser as a function of wavelength, \( \tau_{ij} \) is the spontaneous radiative decay constant from the \( i^{th} \) to the \( j^{th} \) level, \( \Gamma_i \) is the non-radiative decay constant from the \( i^{th} \) level, and \( k_1 \) is the cross relaxation constant for the cross relaxation transition of interest. It should be noted that ASE treatment is accomplished by splitting the
spectral power into channels as discussed later. Each ASE and signal channel have a separate set of four rate equations from above. In essence, these above rate equations are also a function of wavelength. Solving the rate equations in the time domain can give transient laser behavior or pulsed laser or amplifier behavior, however in the current situation, the concern is only for CW amplifiers, and thus the rate equations above can be collapsed into simpler expressions by assuming steady state conditions and thus letting the derivatives go to zero.

With a good deal of algebraic manipulation the information contained in (71)-(74) can be expressed in a far simpler form for the steady state following the analysis done by Phillip Wilcox and William Tourellas in [273], by first writing the population of the three highest levels in terms of the ground state as seen below

\[ N_3 = \frac{\alpha N_0}{1 + \beta N_0} \quad (75) \]
\[ N_2 = \frac{\alpha \gamma N_0}{1 + \beta N_0} \quad (76) \]
\[ N_1 = \frac{\alpha N_0 + BN_0^2}{1 + \beta N_0} \quad (77) \]

where

\[ \alpha = \frac{\sigma_p^p A_{core} (P_p^- + P_p^+)}{h \nu_p A_{clad}^2 \left( \frac{1}{\tau_{32}} + \frac{1}{\tau_{31}} + \frac{1}{\tau_{30}} + \Gamma_3 \right)} \quad (78) \]
\[ \beta = \frac{k_1}{\frac{1}{\tau_{32}} + \frac{1}{\tau_{31}} + \frac{1}{\tau_{30}} + \Gamma_3} \quad (79) \]
\[ \gamma = \frac{1}{\frac{1}{\tau_{32}} + \Gamma_3} \quad (80) \]
and the symbols are all defined as previously. The summations in the above equations are done over the entire wavelength range of interest in the laser, which in the case of thulium is ~1.7 \( \mu \text{m} \) to 2.16 \( \mu \text{m} \) (limited by the available cross section data) usually in discreet step sizes depending on the number of ASE channels being considered. With these equations simplified, following the analysis in [273], the population of the ground state can be written in terms of the total number of ions in the fiber and the populations of the other energy levels under the assumption that the four levels are the only levels with population. Thus, \( N_{\text{total}} \) can be written as

\[
N_0 = N_{\text{total}} - N_3 - N_2 - N_1
\]  

and by inserting (75)-(77) and using a bit more algebra, including the well known quadratic formula on the quadratic expression in \( N_0 \), the ground state population can be written as

\[
N_0 = \frac{(\beta N_{\text{total}} - 1 - A - \alpha(\gamma + 1)) + \sqrt{(\beta N_{\text{total}} - 1 - A - \alpha(\gamma + 1))^2 + 4(\beta + B)N_{\text{total}}}}{2(\beta + B)}
\]  

where the variables \( A, B, \alpha, \beta, \) and \( \gamma \) are as defined in (78)-(82). The value of the populations at steady state take into account population and depopulation effects due to the contribution of all wavelengths in the thulium emission band due to the summations in (81) and (82). These
populations are functions of wavelength, pump power and signal power when included in the power equations discussed below.

With knowledge of the steady state population of the ground state and all excited states via (75)-(77) and (84) as a function of wavelength, pump power and signal power, the rate equations governing the growth and decay of the pump and laser signal in both directions along the fiber length can be implemented. This is possible because they depend on the gain in the fiber, which is directly related to these populations and the difference between them. These equations are discussed in numerous sources on modeling of fiber lasers including [3, 273, 281, 282, 304]. For thulium amplifiers of interest here the pump evolution equations along the fiber length are

\[
\frac{dP_p^+}{dz} = -\frac{A_{core}}{A_{clad}} \sigma_a^p N_0 P_p^+ \quad (85)
\]

\[
\frac{dP_p^-}{dz} = \frac{A_{core}}{A_{clad}} \sigma_a^p N_0 P_p^- \quad (86)
\]

for the two potential directions of the pump along the length \((z)\) of the fiber. The ratio of the core to cladding area is included to account for the double clad pumping scheme, reducing the effective absorption cross section. If core pumping were being modeled, this ratio would be the overlap of the pump mode to the doped core mode. The equations for the propagation of the laser signal or ASE are also well discussed in literature [3, 273, 281, 282, 304] and are given by

\[
\frac{dP_l^+}{dz} = \frac{A_{eff}}{A_{core}} \sigma_e^l(\lambda) N_l P_l^+ - \frac{A_{eff}}{A_{core}} \sigma_a^l(\lambda) N_0 P_l^+ + \frac{2 \sigma_e^l(\lambda) N_l \frac{hc^2}{\lambda^3} \Delta \lambda}{\alpha_{background}(\lambda) P_l^+} \quad (87)
\]
where most terms are defined as previously and $\alpha_{\text{background}}(\lambda)$ is the silica fiber background loss which can become significant at long wavelengths and $\Delta \lambda$ is the bandwidth of either the ASE channels or laser signal. The term containing $\Delta \lambda$ in (87) and (88) is the term that supplies the spontaneous emission seed and based on discussion in [281] there is no scaling factor in front of this term, however if the fiber were multimode a factor equal to the number of total modes would be used to scale this term. In the LMA fibers used here, the loss on the second order mode induced by coiling likely removes the need to consider its contribution to ASE, so ignoring of this scaling factor is justified.

The system of differential equations given by (85)-(88) thus consists of two equations for the pumping of the system and $2m$ equations for signal and ASE where the signal and ASE are broken up into $m$ spectral channels of bandwidth $\Delta \lambda$ covering the entire spectrum with one particular channel being given the seed power initial condition. The system of differential equations can be solved with appropriate selection of initial conditions for the forward and reverse pump $P_p^+(z=0)$ and $P_p^-(z=L)$ (where $L$ is fiber length) and for the forward and reverse signal $P_i^+(z=0)$ and $P_i^-(z=L)$. The ASE channels have initial power equal to zero, and are only seeded by the background spontaneous emission term.

It is also important to note that this model is also able to be used for modeling the power in a laser resonator by selecting boundary conditions for the signal which are based on the signal power times the reflectivity of the HR mirror and output coupler. Such a configuration is not
discussed further here, but the equations are exactly the same with the exception of boundary conditions. However, since the model is solved for steady state populations, the interesting laser dynamics of relaxation oscillations, gain switching or Q-switching will be ignored. But for laser oscillators, usually a time dependent model is more interesting for system analysis and hence the model described here is insufficient. More advanced models such as those in [281, 282] can be used to solve for dynamic behavior.

In addition, this model is described for 790 nm pumping of the $^3H_6$ to the $^3H_4$ levels as seen in Figure 28, however by writing the appropriate rate equations for other energy levels such as in band pumping $^3H_6$ to the upper levels of $^3F_4$ or pumping $^3H_6$ to the $^3H_5$ band can also be modeled. The equations above also assume cladding pumped schemes, modeled by the core-to-cladding ratios present in equations (85) and (86). The equations can be simply converted to the core-pumped configuration by considering the overlap of the pump mode to the doped core rather than the cladding modes to the core. Nonlinear effects can also be accounted for by adding appropriate terms to the equations for signal propagation along the fiber length. However at the power levels used in these models, nonlinear effects are not significant.

Solutions of the model as described, with appropriate parameters and boundary conditions, can effectively determine the amplification performance of thulium fiber amplifiers with ASE included across the entire lasing spectrum. The model can be used to predict the desired fiber length beyond which reabsorption becomes a factor, the effect of different doping concentrations on efficiency, the slope efficiency of an amplifier, and the ASE background at any signal wavelength among other possibilities.

It should be noted that, though the equations make it capable of calculating backwards ASE and signal propagation, the state of the model currently is not optimized for this calculation.
Thus the calculation proves too intensive for the available computer in reasonable amounts of time and hence it is not used in the calculations discussed in subsequent sections. This can be included in future versions of the code by optimizing the efficiency of the code operation. It should also be noted that to further speed evaluation times, backwards propagating pump is given its initial condition at length equals zero in the code. This means that its initial condition is a guess as to the amount of backwards leaked pump power. The initial condition is then adjusted to make the pump power level at the “$z = L$” end of the fiber evaluate to the correct level. This need may be removed in future versions of the code by further optimization, however the results predicted using the current method are acceptable and do make reasonable predictions. All calculations in the following sections are completed with Mathematica software [334].

4.3.2 Comparison of Model Results to Experimental MOPA System

The model described in the previous sections is used to analyze the results from the MOPA system discussed in 4.2.2. The program is set up identically to the experimental system using the system parameters seen in Table 8 which stem from [272, 273, 335-337] and are the values used everywhere unless otherwise noted.
Table 8: Input parameters for Tm fiber amplifier code [272, 273, 335-337]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cladding Diameter</td>
<td>400 μm</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>25 μm</td>
</tr>
<tr>
<td>Mode Field Diameter</td>
<td>23 μm</td>
</tr>
<tr>
<td>Doping Concentration</td>
<td>$3 \times 10^{26}$ Ions/m³</td>
</tr>
<tr>
<td>Fiber Length</td>
<td>5 m</td>
</tr>
<tr>
<td>Pump Wavelength</td>
<td>793 nm</td>
</tr>
<tr>
<td>Seed Power</td>
<td>6 W</td>
</tr>
<tr>
<td>Number of ASE Channels</td>
<td>50</td>
</tr>
<tr>
<td>ASE Range</td>
<td>1750 nm to 2160 nm</td>
</tr>
<tr>
<td>Spontaneous Radiative Relaxation</td>
<td></td>
</tr>
<tr>
<td>Decay Constants (1/s, defined as 1/τᵢⱼ)</td>
<td></td>
</tr>
<tr>
<td>$A_{10}$</td>
<td>160.69</td>
</tr>
<tr>
<td>$A_{21}$</td>
<td>3.89</td>
</tr>
<tr>
<td>$A_{30}$</td>
<td>181.23</td>
</tr>
<tr>
<td>$A_{31}$</td>
<td>14.61</td>
</tr>
<tr>
<td>$A_{32}$</td>
<td>58.71</td>
</tr>
<tr>
<td>$A_{33}$</td>
<td>716.90</td>
</tr>
<tr>
<td>Non-radiative Decay Constants (1/s)</td>
<td></td>
</tr>
<tr>
<td>$Γ₁$</td>
<td>2592.88</td>
</tr>
<tr>
<td>$Γ₂$</td>
<td>$2.92755 \times 10⁷$</td>
</tr>
<tr>
<td>$Γ₃$</td>
<td>80594.3</td>
</tr>
<tr>
<td>Cross Relaxation Constant</td>
<td>$1.8 \times 10^{-47}$ x Doping Concentration</td>
</tr>
</tbody>
</table>

The emission and absorption cross section data used is from Figure 29. Seed input power is based on the estimated input power after losses from launch efficiency. In order to produce a comparison to experimental results, the model is run several times at a given seed wavelength for various pump input powers. The resultant output is able to be plotted as a slope efficiency versus wavelength and maximum achievable power at a given pump level versus wavelength.

Before comparing the results over the entire spectrum, results from a single wavelength are compared as seen in Figure 94.

![Figure 94: Slope efficiency prediction by the model and actual slope efficiency data from MOPA at 1967 nm. The triangles connected by the line are the model results and the squares are the actual data](image-url)
As is clear from the figure above, the slope efficiency predicted is nearly identical to that modeled, with the model predicting ~63% slope efficiency while the experimental results demonstrated 64% slope efficiency. This small discrepancy is well within the experimental error in terms of power meter calibration, and within discrepancies between the model and the experiment in terms of launched pump power, systems parameters like cross section, lifetime and others which are not exactly known for the preform that is used to fabricate the fiber used in experiment.

When looking at slope efficiency versus wavelength over the entire range that the MOPA is tested over, the model also makes quite reasonable predictions over most of the range. This is seen in Figure 95.

![Figure 95: Plot of wavelength versus slope efficiency and maximum power for experimental MOPA system and model. Experiment is indicated by triangles and connected by a line; experimental data is indicated by squares](image)

It is clear that over the majority of the range of wavelength, the prediction between model and experiment is quite close. The experimental data is somewhat less consistent in terms of a trend, but this is likely because of alignment issues and test to test variations in the experiment which are not accounted for in the model. The final achieved output power for the experiment is also somewhat low because the experiment, as is seen in 4.2.2.3.2, shows roll off in power at the high end due to diode wavelength shift. The model does not experience this, as it is assumed that
pumping wavelength is kept constant for simplicity. This leads to the relatively consistent over-prediction of the results in terms of power. In addition, the model assumes a constant MFD for all wavelengths, when in reality, the MFD is function of wavelength and thus may vary by some amount, which can affect laser efficiency and power as is discussed in a later section. However, in terms of slope efficiency, with the exception of a few outliers the results are quite close. This is somewhat surprising, as the parameters used in the model including fiber dopant concentration, cross section and lifetimes are only approximate values, not known precisely for the thulium fiber used in the experiment.

The largest difference between the experiment and the model is the predicted total tuning range. In the experiment, the tuning range is limited to between 1927 nm and 2100 nm while the model predicts reasonable performance out towards 2150 nm and down to 1907 nm. This discrepancy is due to the inability of the model to account for the onset of parasitic lasing. The model does include ASE in its calculations, which explains why the achievable power drops off when it does (ASE begins to steal all the gain and the output power form the system is actually 100’s of W of ASE according to the model). However, at ASE power levels of around 0.5 W or even less, the laser begins to parasitically oscillate as the small amounts of feedback from the fiber facets are able to experience sufficient gain to overcome threshold. The model cannot account for parasitic oscillation; however it can accurately predict ASE levels, and using these, the model can be used to estimate the point for parasitic lasing. Experimentally by using the MOPA as an ASE source, the output ASE level when parasitic lasing begins is ~0.1 - 0.5 W of ASE. When ASE is beyond this level, the gain at the peak of the ASE is sufficient to enable parasitic lasing. This point is seen in Figure 96, which is a plot of total ASE power from the amplifier at full pump power versus wavelength as predicted by the model (assuming single
directional ASE propagation). Backwards ASE is neglected in this case; it is likely that total ASE power would remain relatively constant, but with ASE power split between bidirectional outputs.

![ASE power versus wavelength at full pump power](image)

Figure 96: ASE power versus wavelength at full pump power, the horizontal line indicates the 0.5 W cutoff for onset of parasitic lasing instability

Going by the 0.5 W experimentally observed cutoff, the onset of parasitic lasing in the modeled MOPA should be somewhere in the range between 1910-1930 nm for this given amplifier length and parameters. This is in agreement with the onset of instability observed experimentally which is at between 1927 and 1917 nm. However this does not explain the instability of the MOPA system in the longer wavelength regime beyond 2100 nm. This instability is actually inherent in the MO wavelength instability regime. Based on the prediction of the model, a future experiment with an improved MO, having longer output wavelength stability and an appropriate isolator, might allow 200 W level amplification well beyond 2100 nm with a theoretical cutoff around 2140 nm. Of course because of the larger quantum defect and much smaller emission cross section, the efficiency in this region would suffer compared to other regimes, however based on the model predictions the result should be possible.

Overall, the model compares to the experimental results quite well with deviations due to unknown materials properties, inability of the model to take into account parasitic lasing or other experimental considerations like alignment variations and MO seed instabilities. The model does
predict the general trends in efficiency versus wavelength and can be a useful tool for system
design, for a known set of input parameters. If a known wavelength range and power level is
desired, the fiber length can be estimated and required seed level determined to achieve the
results with the desired stability and level of ASE.

4.3.3 Instructive Calculations

With the previous section proving the code’s ability to reasonably predict the output of an
actual system, it can be instructive to take a brief look into the different fiber parameters and
their effects on results. This section, though by no means covering all the potential combinations
and their interactions with each other, covers some of the most commonly varied system
parameters.

The first parameter to be investigated is the dependence of cross relaxation (and hence
laser slope efficiency) on doping concentration. To test this, the model is set up using most of the
same material parameters used in the previous section, however with the noted difference that
wavelength is fixed at 2000 nm and pumping is unidirectional, with the pump and 2.5 W signal
copropagating. Approximately 225 W of pump power is used in this calculation. The internal
slope efficiency (slope with respect to absorbed pump power rather than launched power) is used
due to the variation in concentration having an effect on pump absorption and the desire to keep
fiber length as constant as possible (though for extremely low concentrations length had to be
increased to enable sufficient pump absorption). Figure 97 is a plot of slope efficiency of the
laser with respect to absorbed pump power as compared to the weight percent doping
concentrations for a range of concentrations up to levels that are extremely high (higher than can
be realistically fabricated).
A clear trend showing a rapid increase in efficiency as concentration approaches and surpasses ~2-3 wt % is seen with potential efficiencies beginning to level off beyond this point, with only a ~3% increase in slope efficiency for an increase in doping from 3 to 30 wt. %. This shows that once the concentration is able to be brought to a critical level, the efficiency gains in thulium are no longer reasonable for the amount of effort put into increasing concentration, and a gain in efficiency towards the theoretical limit must be sought in other places. It should be noted that especially for the highest concentrations, this model may not be making the absolutely correct predictions, as it uses a relatively simplistic model for the cross relaxation constant (discussed in 4.3.1) and does not include energy transfer upconversion (essentially the reverse of the CR process). A future improvement to the model taking this effect into account may affect the prediction of the required concentration for achievement of efficiency. It should also be noted that for the lowest concentrations, the efficiency trend may be under-predicted as the efficiency begins to be significantly be affected by the background losses associated with the long fiber length. Overall, however the importance of optimal fiber concentration is clear, levels of in the range of 2-3 wt. % are necessary to achieve optimal fiber performance, though this optimal concentration may vary from fiber design to fiber design and with pump levels. It should also be
noted that in actual fiber used in the majority of experiment in this dissertation, concentration is ~4 wt. %, making it safely in the regime where efficiency is possible.

A second area of parameter space investigated is the fiber core design itself. Because the fiber operates in the nearly single mode regime, the mode field diameter of the fundamental mode carries the majority of the power in the fiber. If this mode does not strongly overlap the pumped, doped core region, some percentage of the pump power will be wasted, and overall laser efficiency will suffer. The model can be used to predict this trend, as it has terms for both MFD of the fundamental mode and the doped core size. The same 225 W co-pumped configuration of a 2.5 W seeded 2000 nm thulium fiber amplifier is used as the test bed for these calculations. By keeping a constant core size and varying the core to clad ratio, a plot showing the dependence of slope efficiency on pumped core-mode overlap can be seen (Figure 98).

![Figure 98: Internal (absorbed pump power) slope efficiency versus MFD to doped core ratio](image)

Clearly, as the overlap of the core and MFD increase, the slope of the laser is significantly improved. At the actual value of fibers used in experiments of 23 μm MFD and 25 μm doped core, the efficiency is ~60% while if overlap can be increased, the efficiency can be increased by more than 10% to ~71% overall. This phenomenon is the result of the increased extraction of the gain in the core region, as when overlap is incomplete, some pump power is wasted. It should be noted that the predictions here are somewhat qualitative, as the model only determines the effect
of overlap by including the ratio of the MFD and core diameter very simply. This results in over-prediction in efficiency when the MFD actually becomes larger than the core. In addition, this model assumes a constant MFD along the fiber, which is likely not true as fiber coiling causes the MFD to become deformed and “squeeze” towards the wall of the fiber, thus changing the overlap beyond the prediction capabilities of this model. Use of a more sophisticated calculation which varies MFD with fiber length and takes coiling into effect may allow better prediction of actual efficiencies which depend on MFD overlap. However, the trend is clear, improvements in MFD overlap by cleaver design of the NA, and perhaps by only doping a portion of the core region to be sure the MFD closely overlaps the doped core, can contribute significantly to improvements in performance, however before such changes in core design are put into practice, the influence of bending on mode shape and hence efficiency should be more thoroughly investigated.

Another important factor in laser design is the length of the fiber, especially in the case of a thulium fiber where three-level laser effects like re-absorption can become significant. To illustrate the effects of length versus wavelength for a thulium fiber amplifier similar to that used in previous examples (co-pumped with 225 W and 2.5 W seed) is changed to more extreme wavelengths (1908 nm and 2137 nm) to show long and short wavelength behavior of such systems as a function of length.

When wavelength is on the short end of what a given system should be capable of, ASE and reabsorption can become a major factor is selecting the fiber length, and in fact, the optimal fiber length may not be where internal efficiency is highest, but is a compromise between internal efficiency and fiber length. Figure 99 shows the results of plotting length versus efficiency in terms of both absorbed pump power and launched pump power.
Clearly an optimal length for the fiber amplifier of ~4.5-5 m is seen for this particular pumping configuration though it is likely that the optimal point will actually vary with the pump directions, power levels and certainly if the fiber is used as an oscillator or amplifier. The trend is still clear, though efficiency increases with respect to absorbed pump power with a reduction in fiber length due to decreased reabsorption losses, the launched power efficiency actually dies off somewhat due to reduction in pump power absorption. In the same regard, if fiber length is made too long, in order to improve pump absorption, ASE begins to become a factor and steals efficiency from the amplification. By balancing fiber length and the potential for parasitic lasing and ASE the length of an amplifier can be determined for any particular wavelength.

When the wavelength is at the long end of the spectrum, the trend is slightly different, as there are minimal reabsorption losses but some background silica glass losses. This means that in terms of absorbed pump power, the efficiency as a function of length is relatively flat and fiber length can be selected to produce the optimal power in terms of optimizing absorbed pump power. As seen in Figure 100 below, the optimal length is actually closer to 6-6.5 m rather than the 4.5-5 m at the shorter 1908 nm length.

Figure 99: Slope efficiency with respect to absorbed and launched pump power versus fiber length for a 1908 nm co-pumped amplifier.
As parameters like core diameter, doping concentration, background loss, seed power and pumping direction vary, the exact optimal length for any given wavelength will vary, however with a given set of parameters, each wavelength will have an optimal length and achieving a system with optimized efficiency requires appropriate attention to fiber length.

Seed power also can affect the performance of an amplifier system as is seen by the plot in Figure 101.

The configuration of the laser is similar to those used earlier with a wavelength of 2000 nm and pumping up to 225 W total (distributed evenly in the case of bidirectional pumping). It is clear
from the figure that the amount of ASE power is lower for the co-propagating direction of pump and this advantage grows as the amount of seed power is reduced, leading to the conclusion that in the case of lower power seeding, the co-propagating direction is more advantageous. This is due to the gain being highest where seed power is lowest, letting the seed grow quickly and enabling it to reach levels above the ASE background at an earlier point along the fiber. In the co-propagating case, the ASE and seed both see similar gain along the early length of the fiber as there is minimal gain in the fiber until the last few meters due to lower pump levels. This is seen in the resulting output plots from the actual model in Figure 102. The plots from left to right show first the power in each channel including the various ASE channels. The second plot is the maximum power at the output fiber end as a function of wavelength and the final plot is output power versus length including the total ASE power rather than per channel.

Figure 102: Actual output from model for three different pumping configurations for a very low power seed to illustrate the difference in how signal and ASE grow with length
In the co-pumping scheme, the ASE grows quickly, but is reabsorbed strongly along the length while the seed is still able to grow, and since the amplifier is not pumped strongly at the output end (due to low residual pump power) the ASE is significantly reduced. But also because the far end is not pumped strongly, the signal cannot pull out enough power to continue experiencing gain, and hence the growth begins to roll off. In the counter-pumping scheme, ASE and signal both grow slowly at the beginning, but since both are on similar orders of magnitude they take equal gain until the re-absorption losses begin to cut ASE and the signal can grow. Because the pump absorption is strongest at the signal output end, the signal grows more and more quickly. The bidirectional pumping is a combination of both and shows a closer to linear growth of the seed, and is often the “happy medium” required to enable maximum pump power by using both fiber ends. Regardless of seed levels, these trends are the same, and only the amount of ASE varies.

The lower ASE powers from the co-pumping scheme come at a slight cost in terms of slope efficiency, as seen in Figure 103.

![Figure 103: Seed power versus laser efficiency for three pumping configurations](image)

Clearly efficiency is affected by both seed power and pump configuration. The higher the seed power the better the operating efficiency, however the benefit is relatively small, and the
bigger benefit from using a high power seed comes in the form of reduced ASE and hence the potential for parasitic lasing. However the different pump schemes do show consistent trends of a few percent efficiency differences among them. This is a result of the level of the signal during amplification with respect to the pump power. In the co-propagating scheme, the signal power is highest where the pump is lowest, and hence a majority of the gain is put to increasing signal from low levels, and the signal is unable to hugely saturate the amplifier and extract pump effectively in this region (though reabsorption of ASE seems to contribute to some extent to increased efficiency). On the contrary, in the case of counter pumping, the signal is largest where pump is highest, so where the amplifier is saturated is where gain is largest and able to effectively use pump. Bi-directional pumping of course lies in the middle.

There are a few caveats to these results stemming from the nature of the model. First, because the model only uses forward ASE, the results may be slightly skewed. The co-propagating scheme may be more adversely effected by backwards ASE, reducing its efficiency somewhat compared to what is seen in the results above. In addition, the idea that an amplifier could be seeded with only a few hundred microwatts to reach hundred watt level output powers is not practical. Though the model predicts it is possible, parasitic lasing, which is not included in the model, would likely reach the point of onset for seeding less than a few hundred mW. Of course performance of the lasers described here is also a function of the other laser parameters, fiber dimensions and seed powers which all conspire to give final system performance. Further optimization of the code by including bidirectional ASE and reflected signal power will enable more accurate prediction of results that better match reality, since currently the model does not predict the low seed power performance of the amplifier in a realistic way, though it does give reasonable results for high power seeding.
Overall, despite imperfections and some need for future improvement, the simple model used here is able to predict interesting trends in fiber laser performance that can help guide the design of thulium fiber lasers in terms of pump configurations, seed levels and fiber designs to suit the needs of any amplifier system.

4.3.4 Future Extensions to Model

There are a few improvements and extensions that could be made to the model to bring its results to a level where extremely accurate predictions of performance can be made. Some improvements including use of ETU effects in the energy level scheme to better model CR efficiency, bending effects and backwards propagating ASE and signal have already been suggested, however another important area is in the use of a full time domain model. As discussed in [281], by making the power time dependent and including the population rate equations in the time domain, the results can also be made useful for prediction of the results of pulsed amplifier systems or to predict the dynamic behavior of a laser system. Such an improvement is relatively simple to implement, but becomes extremely intensive in terms of processor use, especially to enable sufficiently small time steps. As a result it may not make the best tool for designing a system to first order, but for fine tuning it may prove to be useful. This model could be extended even further by including nonlinear effects such as SRS into the power equations to help predict the outputs in the high peak power pulsed regime.

In general, extending the model described in the previous sections to oscillators is relatively simple, and can be done by choosing the appropriate boundary conditions, assuming the model can be optimized for signal and ASE propagating in both directions. Even using the steady state conditions, the model should be useful for predicting laser behavior.
Finally, the model could be extended to cover pumping in other wavelength regimes by including pumping terms to other energy levels and re-deriving the equations discussed earlier for the steady state rate equations. This would make the design of short length lasers or low doping concentration lasers which may be useful for some applications possible, making the model even more useful in terms of having additional degrees of freedom in the design space.
5 POWER SCALING OF PULSED THULIUM FIBER LASER SYSTEMS

In addition to the need for control of laser spectrum, there are numerous applications that require high peak powers that can only be attained in pulsed laser systems. In order to achieve these powers, the temporal performance of thulium fiber lasers must be controlled to produce pulses of the required durations. Applications such as LIDAR, LIBS and other remote sensing require high energy, short duration nanosecond pulses to enable long range, effective operation with high resolutions. Materials processing for waveguide and other induced feature fabrication or low heat effect cutting require high repetition moderate energy ultrashort pulses to achieve desired effects. Depending on the particular nonlinear process to be exploited, frequency conversion may require a number of pulse durations to produce a desired wavelength range.

Clearly, depending on desired application, discussed in more detail in 1.3, these durations may need to be in the nanosecond, picosecond or femtosecond regime. Because of the relative youth of thulium technology, the ability to not only amplify such sort pulses, but in fact even generate the pulses is limited, with only a relatively small number of published results concerning such systems in existence. As a result this chapter will focus on the generation and to some degree, amplification of pulses in thulium fiber laser systems, as what may be a building block for future expansion in pulse energy via use of high average power amplifications techniques and very large mode area fibers discussed in previous chapters. The following
sections outline techniques for generation of both nanosecond and picosecond duration pulses and also discusses briefly the performance of thulium fiber lasers with no temporal controls.

5.1 Uncontrolled Thulium Fiber Laser Temporal Performance

One interesting and potentially detrimental characteristic of thulium doped fiber lasers is their behavior when there is not temporal control, for instance when they are intended to be run in CW operation. In this regime at laser start up, as is well understood and predicted by laser dynamics [9, 10, 160], the rapid rise in pump power at laser turn-on initiates oscillations in laser output power that theoretically damp out over time. This is caused by the pump introducing excess inversion before intracavity photons have time to deplete this inversion, resulting in a large laser pulse. As the inversion settles to a constant level, the spiking behavior damps out and true CW lasing is initiated. This process can be modeled by solving the rate equations in (87), (88) and (71)-(74) with inclusion of a time dependent derivative in terms of power and with the output power as a function of time (87) (88). However because of the need to solve for fibers in terms of both distance and time, as well as over several channels of wavelength as described in 4.3, the modeling to achieve this is more in-depth and complicated. Simplifications of the equations by collapsing population equations to a single equation in terms of population inversion and assuming single directional operation and time domain only solutions (essentially assuming gain is uniform over the entire fiber length which is not a particularly good approximation) can be achieved, but in the case of fibers because of the long length and distributed, non-uniform gain along the length, the solutions only give a qualitative picture of what can occur. By solving such coupled differential equations (found in the simplified form in [9]) a simple picture of the RO spiking behavior at laser turn on can be made. Figure 104 shows
the result of such a calculation of a hypothetical thulium-like system with similar parameters in
terms of cavity length, lifetime and cross section to a real thulium laser but with the output
population inversion and power normalized, as the results of the simulation are not likely to be
realistic anyway.

![Plot of population inversion and power output for a hypothetical thulium fiber laser free running at pump turn on](image)

Figure 104: Plot of population inversion and power output for a hypothetical thulium fiber laser free running at pump turn on

The slow buildup to laser threshold is seen before the onset of laser power, which
exhibits the spiking behavior before relaxing to a CW steady state, as there are no further
perturbations to the cavity. The process could theoretically be repeated by additional
perturbations to the cavity after reaching inversion.

This dynamic cannot be ignored in many cases, as often it is important for a laser to have
an extremely stable CW output. In addition, information carried in clean oscillations can yield
important information about the laser gain medium and laser cavity including round trip loss and
emission cross section, as the period of the oscillations is tied to pump threshold, round trip loss
and cross section while the decay rate of the oscillations is also tied to photon lifetime and upper
state lifetime [9, 10, 160]. In fact such oscillations are used to determine the Tm emission and
absorption cross sections in [268].
These relaxation oscillations (RO), however are not only initiated by pump fluctuations, but also by loss fluctuations in a laser cavity [9, 10, 160]. As a result, any mechanisms that induce changes in loss can initiate dramatic pulsing of a laser, again a fact that is used to an advantage in laser Q-switching discussed in 5.2.1.1. However, when the loss mechanism is unwanted, the resulting chaotic laser behavior can affect performance.

Thulium fiber lasers exhibit such unwanted modulations in their output which has been observed in a number of instances [99, 101, 338, 339]. The suggested mechanism for such modulations is a saturable absorption effect caused by upconversion in the thulium energy level scheme (seen in 2.3.3.1). These upconversion effects, occur as a result of two excited laser electrons in the $^3F_4$ level interacting to produce an excited $^3H_4$ electron which is able to decay to the ground state $^3H_6$, thus emitting a photon in the ~1.5-1.6 $\mu$m wavelength regime [338]. Because the thulium fibers used are highly doped, this effect is relatively strong, as the probability of the transition is related to the proximity of adjacent ions, as is the case with cross relaxation. The upconversion nonradiatively causes a decrease in population inversion, which at low pump levels can cause inversion to drop below laser threshold [338]. When the inversion is reduced like this, the upconversion process is no longer as strong; the laser is able to recover, until upconversion again depletes the upper laser level, hence driving the inversion into the oscillatory behavior that subsequently causes the emission of laser pulses [338]. This process is essentially a saturable absorber process, as the “absorber” is the upconversion that saturates when inversion drops too low. It should also be noted that as the pumping level is increased, inversion is replaced faster and the dips in inversion thus occur more frequently but with lower modulation and eventually they no longer drive the laser inversion below threshold and hence the oscillations damp out with an increase in laser pump power [338].
Theoretically, based on modeling in [338], the oscillations should be relatively clean, however the modeling does not account for the random, free running wavelengths that occur in thulium fiber lasers that are not spectrally controlled and they also do not account for multimode operation in either longitudinal or transverse modes that can influence the clean behavior of RO spiking. The overall result for a free running laser is an apparently randomized output with a number of different repetition frequencies [338], though as observed in [246] use of spectral control techniques can simplify the output self pulsation and in [99, 338] these oscillations are also observed to depend strongly on wavelength, as the ratio of absorption and emission cross section influences the entire process [338].

These types of oscillations are also observed in thulium lasers constructed for this dissertation. For illustrative purposes the output behavior from a simple linear thulium fiber laser cavity which is free running with HR mirror feedback (like the laser described in 4.1.1) is shown in Figure 105 for three pump levels: near threshold, twice threshold and three times above threshold.

![Figure 105: Temporal behavior of “CW” thulium fiber laser at various pumping levels](image)

The randomized self-pulsing behavior resulting from the saturable absorption effect described in [338] is clearly seen in the figure above. The repetition rate of the pulses increases as pump power is increased. In addition, the pulses eventually do not drop to zero as the increase
in pump power reduces the influence of the saturable absorption effect. At levels of laser operation well above threshold, as is the case in the 200 W CW laser described in 4.1.1 or the tunable laser in 4.1.3.2 where single mode fiber enabled very low threshold, these oscillations are almost completely damped out and relatively stable time domain operation is possible.

It is also interesting to note that these saturable absorber effects can also initiate modelocking if the conditions in the laser are arranged correctly as is reported in [339]. Fortuitous alignment on occasions in systems used for this dissertation also produced such self-modelocked effects, often with reasonably stabilities, though with long pulse durations.

Overall, it is important to be aware that even in CW lasers there is the potential for temporal domain fluctuations, particularly in thulium fiber lasers. Removal of such characteristics by either operating well above laser threshold or by other spectral and temporal control techniques may be critical to applications sensitive to fast-time-scale pulsing of CW lasers. In addition, the dynamics are critical to understand, as they are the driving factor behind the nanosecond pulse generation techniques described in the following sections.

5.2 Thulium Lasers in the Nanosecond Regime

The nanosecond regime of operation is perhaps the most common regime of operation for pulsed lasers in general, as achieving pulses in the range of a few hundred nanoseconds is relatively straightforward by simple Q-switching techniques. In addition, this regime is also potentially the most commonly used regime of pulsed operation due to the myriad applications that directly benefit from its use, including remote sensing, LIDAR, LIBS, materials processing (particularly marking) and nonlinear frequency conversion. However, depending on the exact application, a high degree of control on pulse duration is usually required, and particular
applications often make demands on pulse characteristics that require special attention to thulium fiber laser design. This section covers two techniques for creation of nanosecond pulses and in addition discusses other potential techniques for achieving these pulses in future thulium laser systems.

5.2.1 Q-Switched Oscillator Experiments

The simplest and most well known technique for achieving nanosecond duration pulses in a laser system is basic Q-switching. This technique involves essentially modulating the loss in a laser resonator by any method. Most commonly this is achieved in fiber lasers by use of an acousto-optic modulator (AOM), however it can even be achieved by techniques as simple as a rotating prism mirror or chopper wheel [9]. As a simple side experiment with an available rotating prism, this experiment on a basic thulium fiber laser as used elsewhere in this dissertation is shown to produce ~500 ns pulses at a ~200 Hz repetition rate with 50 μJ of pulse energy. Figure 106 shows a pulse from such a laser.

![Figure 106: Pulse output from 200 Hz rotating prism Q-switched thulium laser](image)

Of course, because of the highly unstable mechanical nature of a rotating prism and the limitation in repetition frequency, the pulses are not particularly stable in repetition rate; however
the simple experiment shows that simple methods can be used to produce clean pulses from a
fiber laser. However for a higher degree of control and for shorter pulse durations, a device such
as an AOM must be used. The next sections outline the basic theory behind AOM based Q-
switching and briefly discuss results of a thulium fiber laser system using this configuration.

5.2.1.1 Basic Q-Switching Concept

The Q of a laser cavity is also known as its “quality factor.” It contains information about
the cavity losses. A higher the Q indicates lower intracavity loss. Q-switching means that a laser
configuration is switched rapidly from low to high Q to create a short duration pulse. The
underlying principle to Q-switching of a laser is to configure a laser resonator such that the
losses in the resonator are extremely high (low-Q), precluding any potential for lasing [9, 10].
The laser gain medium in the cavity is pumped, so that energy is stored; however, the laser can
never reach threshold because the loss is too high. When the desired amount of energy is stored
in the gain medium (or at some given repetition frequency for CW pumping), a Q switch is
triggered, causing the laser resonator losses to very quickly decrease far below laser threshold.
The stored energy will begin to build up a pulse in the laser cavity, because the population
inversion, and hence gain will be extremely high [9, 10]. The power in that pulse builds up
extremely rapidly because of the high gain, and a pulse of light is emitted. The pulse builds up so
quickly that it completely (or nearly completely) depletes the inversion, so the laser is no longer
able to oscillate. The switch is then closed again, allowing time for the pump to build up more
inversion before another pulse is emitted. This process is driven by the same laser dynamics that
drive the RO spiking process already discussed and the gain switching process discussed later,
with the only difference between the those processes and Q-switching is what is being modulated (gain or cavity Q).

A simple model of the process can be achieved by incorporating a time dependent loss into the same simplified rate equations discussed in 5.1. The results of solving these equations for parameters similar to thulium fiber lasers but without accounting for fiber nature are seen in Figure 107.

![Theoretical plot of the output from a thulium-like fiber laser based on simple solutions to the laser rate equations with thulium laser parameters in the Q-switched regime](image)

The population inversion is assumed to be already existent in this case and the resulting pulse clearly shows the typical Q-switched properties of a faster leading edge and slower trailing edge (though it is not pronounced dramatically in this case because the assumed pump power is not bringing the inversion to a level where efficient extraction is occurring). As the Q-switch is fired, the population begins to decrease and the pulse builds up, as inversion begins to shrink, a point is reached where the pulse can no longer grow and it begins to dissipate.

Because many cavity round trips are required to extract the gain, the length of the cavity influences the speed at which the pulse can build up. The longer the cavity, the longer it takes to build up the pulse, and hence the longer the pulse will ultimately be [10]. This is a significant issue in terms of creating short pulses in thulium fiber lasers, as the cavity length is usually quite
significant on the order of tens of nanoseconds, so achieving extremely short pulses can be difficult.

The Q-switching method used for most fiber lasers involves the use of an acousto-optic modulator (AOM). The device operates on the basic premise that an acoustic wave traveling in a material creates a grating structure inside material bulk due to density dependent refractive index [9, 10]. If the acoustic wave has a period correctly matched to the desired laser wavelength, the grating will diffract an incident beam to some extent (the amount of power diffracted depends on the power of the acoustic wave). The drive source for the acoustic wave is a piezoelectric material driven by an RF generator, and if the RF is switched off the grating dissipates. AOMs can typically diffract on the order of 70-80% of light into a single higher diffracted order. In the case of solid state lasers, the addition of a 70% loss is enough to kill any lasing and thus result in an effective Q switch. However in the case of a fiber laser, the gain is so high that lasing through the 70% loss in the AOM is easily possible, and hence an alternative orientation must be used where the laser feedback is located at the diffracted order of the AOM, thus when the AOM is off, there is no alignment at all and hence very high hold off. The consequence is the higher loss inherent at all times in the cavity due to the imperfect diffraction efficiency. The following section uses the basic concepts of Q-switching discussed here to produce a nanosecond pulsed thulium fiber laser.

5.2.1.2 AOM Q-Switched Thulium Fiber Laser

In order to investigate the high average power and pulse energy limitations of a Q-switched thulium fiber laser system, a basic AOM Q-switched laser resonator is constructed in collaboration with Larry Shah who is the principle experimentor on the work and Christina
Willis. The resonator is similar to most other systems discussed in this dissertation, with the addition of an AOM to the cavity (from NEOS). A schematic of the system is seen in Figure 108.

The active fiber in the cavity is ~4 m of PM thulium doped 25 μm core, LMA fiber as described in 2.2.2.8, with ~50 cm long matched passive fiber spliced to enable thermal management, but keep the cavity length sufficiently short to enable shortest possible round trip time and hence shortest duration pulses. The counter-pumping scheme is similar to others described earlier with 300 W of 400 μm fiber coupled 790 nm pump light launched with ~70% efficiency into the fiber. The intracavity fiber end is angle cleaved at ~8° to reduce the potential for parasitic lasing and the output end is flat cleaved to act as an output coupler. A 26 mm aplanatic triplet lens is used for intracavity collimation and the light is passed through a dichroic mirror to strip out residual pump light before passing through a half wave plate, the AR coated AOM designed for 2 μm operation with 70% diffraction efficiency, a Glan laser polarizer and finally a feedback element which can be either a VBG, HR mirror or diffraction grating depending on the degree of spectral control desired. It should be noted that the laser is aligned to lase off of the first diffracted order of the AOM, so when the AOM is not diffracting, the laser cannot lase. This is done to optimize the laser hold-off as discussed earlier, and it typical of most fiber lasers due to their high gain. Thermal management of the system is the same as other
systems described earlier, including a water cooled fiber mandrel and cooled blocks for the fiber tips.

With the laser appropriately aligned, stable, high power Q-switching is obtained at a number of repetition frequencies from 20-100 kHz, however since 20 kHz is the intended operating frequency for the majority of applications this particular laser is designed for (LIBS and materials processing applications) the majority of the data collected at this operating frequency. Before being operated in the Q-switched regime, the laser is operated as a CW system to investigate the effects of the various elements in the cavity on efficiency. In this regime the laser operates with ~44% efficiency up to a power of 10 W, though this power is only limited for the comparison to Q-switched operation at 20 kHz which becomes unstable above these pump levels. The actual CW power is tested at up to ~40 W levels. The slope efficiency here is slightly lower than most lasers discussed in this dissertation, which is attributed to a combination of effects from losses in the various intracavity elements, each bringing ~5-10% loss, and with a total of 4 elements this means loss is 20-40%, a value which is higher than that in most other lasers tested. In addition, the fiber length of 4 meters is not sufficiently long to effectively absorb all of the pump power. Since slope is given with respect to launched power, the large amount of leaked pump means that slope is likely 5-10% higher with respect to absorbed pump power.

In the Q-switched regime (in this case at 20 kHz) the operating efficiency declines significantly; this is most likely due to the additional loss introduced by the AOM operating in the first diffracted order, which is only 70% diffraction efficient. This leads to an additional 30% loss to the cavity. In order to briefly investigate spectral control of the fiber laser, the laser is tested using three feedback elements in this regime including a VBG, diffraction grating and HR mirror. Because the actual applications being tested (LIBS and materials processing) do not
require an extreme degree of control, the majority of data is taken in the standard HR configuration, with the spectral control data available as a proof of concept for future systems which require the higher degree of spectral control. However a future intended application in the area of frequency conversion demands pulse energy with spectral control, and hence the VBG or grating tuned systems are critical to investigate.

Performance at 20 kHz is summarized in Figure 109, showing performance of the laser with the three spectral feedback components and in the CW regime. Maximum powers of the HR, grating and VBG based systems correspond to 7.2 W, 6.5 W and 4.5 W respectively before the onset of limitations either by spectral instability or approaching potential facet damage pulse energy levels.

![Figure 109: Performance of the Q-Switched laser setup with various feedback mechanisms at 20 kHz operating frequency](image)

The slope efficiency of the HR Q-switched laser is the highest at ~33%, while the grating and VBG laser are slightly lower at 28% and 24% respectively. The overall decline in efficiency is due to the increased loss of 30% as discussed earlier. The reduction in slope efficiency of the grating based system compared to the HR based system is due to the inherently higher losses of the grating with only ~80-90% reflectivity for incident polarized light compared to essentially 100% for the HR mirror, thus explaining the decline in laser efficiency. Operating with the VBG has the lowest efficiency overall, which is slightly unexpected, as it is observed in 4.2.1 in the
CW regime that only a ~6% drop in efficiency is expected due to lack of AR coatings and lower reflectivity. There is an additional contributing factor with is likely due to the relatively short active fiber length. At the 2050 nm wavelength of the VBG, the gain is relatively low compared to that of the 1992 nm tuned diffraction grating or ~1980 nm free-running HR laser (due to short fiber length). It requires a longer fiber length (>5m) in order to operate efficiently. Since the length is a full meter shorter, it is likely that the VBG efficiency suffers due to the lower gain. Since the sources for the reduction in efficiency are understood, it is possible to improve the feedback mechanisms, especially the VBG, to produce lower losses. Achievement of operating efficiencies on par with HR feedback is possible, thus enabling short pulsed spectrally controlled systems for a number of future applications.

The efficiency performance of the laser is also investigated using the HR mirror at 100 kHz and found to be similar to the 20 kHz performance, though slightly more efficient, as might be expected due to the higher repetition rate, with ~40% slope achievable compared to the 33% slope at 20 kHz. This leads to a final reason for the reduced efficiencies in the Q-switched regime, which is that CW pumping is used. If repetition rate is not high enough, there can be loss of stored energy due to fluorescence between pulses. This is because the time between pulses is becoming closer to the upper state lifetime of the thulium laser transition, and hence energy is beginning to be dissipated between pulses. Lowering repetition rate further, and approaching the inverse of the fluorescence lifetime would enable the maximum potential pulse energy to be extracted from the fiber, however the average power will begin to severely suffer as repetition rate is further decreased [10]. Conversely there is minimal benefit in terms of efficiency by increasing repetition rate much above 100 kHz, as the efficiency gains begin to roll off, though often the higher repetition rates enable more average power at a given pulse energy which is

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desirable for some applications. The performance slope efficiencies at 20 and 100 kHz are seen in Figure 110.

![Figure 110: Comparison of slopes at 20 kHz and 100 kHz](image)

Figure 110: Comparison of slopes at 20 kHz and 100 kHz, the 100 kHz power level is significantly higher because the pulse energy per pulse is lower. The cutoff in increasing power is based on pulse energy being no higher than \(~300 \mu J\) and thus the 100 kHz laser can operate significantly higher in average power.

One additional important note is that PER of the laser is measured and found to be >10 dB regardless of operating power levels due to the intracavity polarizing elements and PM fiber. This is especially useful in frequency conversion applications, as often such processes can be polarization sensitive.

In terms of the behavior of the actual laser pulses, durations as short as 115 ns are achieved at the 20 kHz repetition rate. This is expected in a Q-switched laser, because as the pump power, and hence output pulse energy increases, the pulse duration decreases, since photon flux is higher and thus able to more quickly deplete the gain. The pulse duration versus pump power is seen in Figure 111.

![Figure 111: Pulse duration and pulse energy for 20 kHz and 100 kHz lasers versus launched pump power](image)

Figure 111: Pulse duration and pulse energy for 20 kHz and 100 kHz lasers versus launched pump power. Similar trend and performance is observed
It is important to note that though laser action occurred down to a threshold of ~10W launched pump power, pulse durations and energies are only given in regimes where actual pulsing at the correct repetition rate is occurring. In the case of the 100 kHz laser especially, the onset of true 100 kHz operation does not occur until ~60 W of pump power. This is because below this level, often only every other pulse or every fourth pulse is emitted (or every other pulse has lower energy) because there is insufficient pump power and hence recovery time between pulses at 100 kHz to bring gain to a sufficient level for clean pulses operation. The lower per-pulse energy in the 100 kHz pulses lead to longer duration pulses, again as would be expected from Q-switching theory [10]. These pulse durations and energies correspond to peak powers on the order of 2.5 kW. The limiting factor in terms of further increasing pulse energy is the potential for fiber facet damage induced by the high peak powers, and hence the pulse energies are capped at the 350 μJ level for the ~100 ns duration pulses. By incorporating an external output coupler and end capped fiber, the powers most likely can be scales to significantly higher levels approaching mJ energies.

The largest area for improvement in this system is a desire to increase peak powers by reducing pulse energies. Many applications call for sub-50 ns or even sub-20 ns pulses and hence to make such lasers useful, techniques for decreasing pulse durations must be investigated. The difficulty with Q-switched fiber lasers is their inherently long length, and hence long round trip times, leading to inherently longer pulses as seen in the theory section earlier. In order to reduce pulse durations, the cavity length must be decreased. However using the current fiber this is not practical, because insufficient pump absorption will be achieved. An alternative is to use a higher core to cladding ratio fiber to achieve the absorption, but this still leads to lengths of up to 2-3
meters. Another alternative is to utilize a different pump band, such as in-band, core pumping by 1550 nm erbium fiber lasers or 1.9 μm thulium fiber lasers to make cavity lengths extremely short (on the order of <0.5 m) which still being capable of reasonably high power levels. These shorter lengths will enable significantly shorter pulse durations, however the shorter fiber lengths will limit the long wavelength (>2.01 μm) operating capabilities of thulium. As discussed earlier, use of an external output coupler will also enable the integration of fiber end caps, thus allowing higher pulse energy operation.

Overall, the direct Q-switched operation regime provides a simple and effective way for the generation of well controlled ~100 ns duration pulses with reasonably high average powers and energies that can be useful for a number of applications. However, as the demand for higher pulse energies increases in conjunction with shorter pulse durations, the more optimal system architecture begins to shift towards amplifier based systems as discussed in the following section.

5.2.2 Gain Switched MOPA System

First demonstrated in a thulium fiber laser in [340], gain switching is a potential alternative technique to Q-switching that can be utilized simple to create pulses in the Er wavelength regime with reasonably long durations and translate them to very short pulses in the thulium regime by core pumping very short length thulium fiber lasers. Use of a MOPA architecture enables simple scaling of thulium output powers to similar levels of a Q-switched oscillator, but with significantly shorter potential pulse durations.

As part of this dissertation work, in collaboration with Gavin Frith of Nufern Incorporated at a summer internship, a gain switched thulium fiber MOPA system was
developed [135, 341]. In Q-switched fiber oscillators, it is difficult to attain short duration nanosecond pulses due to the gain dynamics of the thulium fiber laser system, based on theory outlined in 5.2.1.1. As seen in the previous Q-switched laser section, the pulse duration of a Q-switched laser is tied to the cavity length and AOM switching speed. Because of the need for bulk AOMs to achieve Q-switching in current thulium fiber lasers, cavity lengths may be too long to produce sufficiently short pulses, even for core pumped, short length systems. In addition sufficiently fast AOMs in the thulium wavelength range are not currently available on the market.

As a consequence, when pulses with durations shorter than ~50 ns are desired in thulium fiber lasers, other means must be taken to generate them. Gain switching enables short pulse durations at reasonable power levels, thus reducing the need for multiple pre-amplification stages which would be needed in a direct diode laser seeded system as described in 5.2.3.

The motivation for the construction of the gain switched system discussed here is for its future use in frequency doubling to wavelengths in the 9xx nm region. This means operation at a slightly shorter wavelength regime than the laser described in [340]. Consequentially, the performance will be slightly different because of the higher reabsorption and three level nature of the thulium transition at these wavelengths.

The system seen in Figure 112 is based on high dopant concentration, PM single mode thulium doped fibers with a MOPA architecture consisting of a gain switched seed and a power amplifier both made from a similar type of fiber. The next sections discuss the performance of the gain switched oscillator and power amplifier used to achieve the pulsed output.
5.2.2.1 Gain Switched MO

The most critical component of the laser system is the gain switched oscillator, without this seed, the system is similar to and generic amplifier chain used for CW or pulsed lasers. As such, the design and layout of the oscillator is critical to achieving the pulse durations realized in the system. Before a review of the MO design and performance is given, the concept of gain switching is reviewed.

5.2.2.1.1 Basic Concepts of Gain Switching

Q-switching is the workhorse method in the realm of generation of short pulses in lasers because it enables short pulses to be generated by storing large amounts of energy in a gain medium over relatively long periods of time before that energy is released by allowing cavity loss to drop [9, 10]. A similar alternative technique that becomes useful in the realm of fiber lasers with short duration pump sources readily available (as is the case with thulium, due to its pump bands in the region of Er fiber lasers) is known as gain switching. This technique involves turning the gain of a cavity on and off quickly by modulating the pumping scheme. As discussed in 5.1, it is well known that if pump power in a laser cavity is turned on or perturbed severely, the laser can be thrown into pulsations, based on dynamic interactions between population
inversion and photons in the cavity; photons over-deplete the inversion and bring it below laser threshold before pump recovers the inversion and the process can begin again. If the pump pulse is short enough so that after the initial pulse emitted from the signal laser, the inversion is not able to recover (as it does in RO spiking behavior), a single short pulse can be emitted [9, 10]. The shorter the pump pulse and the higher its energy, the more quickly and efficiently the laser signal pulse is able to extract gain, and thus the shorter, higher energy pulses can be achieved. In simplest terms the pump is turned off before the second RO spike is able to be emitted. The duration of the pulse emitted is usually on the order of, though somewhat shorter than, the pump pulse.

Because of its similarity to RO spiking behavior, a simple model of gain switching based on the simplified rate equations discussed in 5.1 can be made by including a term for a pulsed pump source that is short in duration. The results of a simulation with similar parameters to a thulium laser is seen in Figure 113 (though power levels and inversion levels are all scaled to arbitrary units because the model is not optimized to be particularly reliable for fiber lasers in terms of accuracy in power).

![Figure 113: Population inversion, signal and pump power versus time for a gain switched thulium-like laser for 100 and 200 ns pump pulses, showing the emission of a second pulse due to too long of a pump pulse.](image-url)
Gain switching behavior can be seen clearly from the figure, an incident short pump pulse rapidly increases inversion well above laser threshold before the pulse has time to begin to build up. The strong inversion enables the energy stored to be extracted in a rapid spike. Before the next RO pulse has a chance to form, the pump pulse has turned off and the inversion is left below threshold. Running this simulation for several conditions, it is observed that for higher pumping energies and shorter pump pulses, the inversion level is decreased more dramatically, while less energetic pulses result in a longer signal pulse build up time and longer durations. The large inversion level is seen by comparing to Figure 104 for an RO spiking laser where the pump does not drive the inversion as high before the first pulse, resulting in smaller fluctuations in inversion. If the pump duration is made too long a secondary pulse can be emitted as seen in the second image in Figure 113.

The higher the pump energy, the shorter the pulse, so in the case of a change in repetition rate of a Q-switched pump laser which keeps its average power relatively constant (as is the case with the Er:Yb pump laser used here), pulse energy increases and hence gain switched pulse durations should decrease. The duration of the pulses is also strongly tied to cavity round trip time, because the longer pulse takes to make the necessary number of passes through the gain medium to sufficiently build up, the longer the pulse will be in duration [9, 10].

Because gain switching does not enable the storage of energy over long times, but rather relies on all the needed energy being deposited in a single short pulse, it is usually not the method of choice for creating laser pulses [9, 10]. Logically, if you have a laser that can produce higher energies and short pulses, there is not usually much point in using it to create another laser. However, in the case of thulium fibers pumped by Q-switched fiber lasers, the reasonably
short Q-switched pulses can be converted to very short pulses in the wavelength regime desired because the gain switched fiber can be kept short with no need for external pulsing components.

5.2.2.1.2 Performance of MO

In order to minimize fiber length and thus ensure short pulse durations, the gain switched seed of the system is made from high concentration thulium doped fiber which is core pumped by a Q-switched Er:Yb fiber laser emitting at 1550 nm. The Er:Yb fiber laser consists of a simple AOM-modulated, FBG stabilized cavity which is capable of 10’s of μJ power levels (corresponding to a maximum of 1.3 W average output powers). This pump laser is actually the limiting factor on gain switched laser performance, as the pump power limitations are set by the inherent instability that occurs in the Er:Yb laser at lower repetition rates and by the available pump power for the laser at higher repetition rates. The pump pulses from the laser are on the order of 80-120 ns depending on the operating power level and repetition frequency as determined by gain dynamics. It is interesting to note that due to the gain dynamics of thulium, a pump pulse from the Er:Yb pump laser does not need to be particularly short (~100 of ns) to create sub-30 ns pulses [9].

The thulium fiber used to construct the oscillator was 10 μm diameter, 0.15NA core, 130 μm diameter cladding PM fiber with ~2 wt% thulium doping as discussed in 2.2.2.8. Other fiber concentrations were tested, however it was found that pump absorption occurred in too short of a length to be practical and there was difficulty in achieving lasing around 1908 nm. The resonator is formed by a non-PM HR FBG centered around 1908 nm in undoped, core and cladding matched fiber spliced to ~20 cm of the thulium doped fiber followed by an non-PM output coupler FBG with ~15% reflectivity at 1908 nm. The fiber length is determined by a cut-back
measurement where the power is observed for a long fiber (37 cm) and as the fiber is shortened, the point of optimal power performance is found to be ~20 cm length which showed a near 50% improvement in performance over the long piece of fiber, demonstrating the strong reabsorption effects at the 1908 nm wavelength. The wavelength is selected to enable the desired application of frequency doubling into the 9xx nm regime where there is a lack of high power, high brightness diffraction-limited beam quality sources.

It should be noted that the FBGs are cleaved and spliced as close as possible to the actual grating to remove any residual fiber from the cavity and hence keep cavity length at a minimum (~25 cm total). Early experiments with the system kept the ~1 m length of fiber on the FBGs, making the total resonator length on the order of 2 m total. Such long lengths lead to pulses hundreds of nanoseconds in duration, which fits with the theory of gain switching, stating that minimal cavity length enables minimal pulse durations. The use of the output coupler is also critical. The system did work without the output coupler, but pulse durations were slightly longer, and output pulse stability was significantly lower. The output coupling lowers the laser threshold, enabling it to more effectively use the available pump power.

The output from the Q-switched oscillator is spliced directly to the HR FBG and thus launched into the active fiber core where it was mostly absorbed (>90%). Slope efficiency of the gain switched oscillator is seen in Figure 114 for three different repetition frequencies.

![Figure 114: Slope efficiency of the gain switched laser at a variety of repetition rates](image)

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The maximum achieved power of \( \sim 0.33 \) W is constant for all operating frequencies above 50 kHz, with a slight drop to 0.29 W at 30 kHz due to lower available Q-switched laser pump power. These average powers correspond to between 3 and 9 \( \mu \)J of pulse energy and between 60 and 450 W of peak power when pulse durations discussed in the next section are applied.

The slope is \( \sim 35\% \) with respect to lunched pump power for all repetition rates, which is slightly lower than would be expected with the relatively small quantum defect. However, pump absorption is not 100\% the efficiency will be expected to be somewhat lower than the quantum defect. In addition, reabsorption losses at 1908 nm and the higher reflectivity of the OC grating also conspire to lower output powers and hence have an effect on slope efficiency. The laser threshold is in agreement (and actually slightly lower due to the OC) with that observed in [340] for a similar fiber, but there the reported slope is \( \sim 54\% \). The difference can be explained by the lack of an OC and their use of longer operating wavelengths around 1990-2010 nm.

Operation within the range of the Q-switched seed laser (30-100 kHz) is investigated and pulse duration is determined to depend on the repletion rate of the pump laser. This is due to the dependence of the gain switching process on the inversion provided by a single pulse. At higher repetition rates, but constant average powers, the pulse energies are smaller, leading to longer pulse durations as is predicted by gain switching dynamics. The pulse duration versus repetition frequency is measured at full pump power. Figure 115 is a plot of pulse duration as a function of repetition rate.
The pulse shape takes a form that is typical for a gain switched laser, which is much more Gaussian in shape, rather than the very fast leading edge and slow decay of a Q-switched laser. In a Q-switched laser, inversion is high immediately on release of the switch, so photon flux increases very rapidly, hence causing a fast leading edge. However in the gain switched laser, the process is slower due to the pump pulse itself acting as the gate, thus the somewhat slower leading edge seen in Figure 116.

The pulse train is relatively regular with a slight fluctuation in pulse energy on every other pulse, which is actually caused by the variation inherent in the pump pulse of the Q-switched laser and not by the gain-switched dynamics.

Beam quality is essentially perfect, as would be expected from a single mode fiber and which is confirmed by the extremely clean beam seen in Figure 117.
The laser output is not polarized despite the use of PM active fiber, due to the non-PM nature of the FBGs and also due to the lack of any element in the cavity to force polarization. PM FBGs are not available, and thus polarization stability of the laser cannot be kept constant and is elliptical in nature, with some degree of time variance as perturbations to the fiber from vibrations or temperature fluctuations cause a variation in natural birefringence in the FBG fiber and lead to polarization drift. The state is still nearly circular (with components in two linear directions, and thus when launched through a polarizing optical isolator, there is an inherent \(~50\%\) signal loss.

Overall, the performance of the gain switched oscillator is reasonable, and more than sufficient to launch into an amplifier system. However, it is likely that an improved pump laser would enable significantly shorter output pulse durations, as the laser showed no sign roll off in slope. As pump power is increased, the pulse duration should decrease, as determined by gain switched dynamics. In addition, if lower pump repetition rates could be used, the higher per-pulse energies would also enable shorter gain switched pulses. It is likely that \(<10\) ns pulses are well within the realm of this system.

As an additional extension, the gain switching scheme could actually be applied to a single frequency laser by pumping a DFB thulium fiber with the Q-switched source, thus creating single frequency (and likely single polarization with correct DFB design) operation with reasonably high pulse energies in the 3-9 \(\mu\)J range as achieved in this system.
5.2.2.2 Amplification and Results

With the key component of the system, the gain switched oscillator, working stably it is a relatively simple matter to amplify the pulse to more useful levels. In order to achieve this, a power amplifier is built up and is seeded by the gain switched pulse as described.

Seen in Figure 112, the output from the gain switched laser is collimated using a 26 mm focal length aplanatic triplet, yielding a beam diameter of ~5 mm. The beam is then launched through free-space through an optical isolator. Due to the available lenses and the aperture size of the isolator, the collimated beam could not be launched perfectly through the <4 mm clear aperture isolator and a relay lens system consisting of a pair 250 mm focal length spherical lenses are used to produce an intermediate waist to allow the beam to fit through the isolator without clipping.

After the isolator and relay lens system, the beam is focused into the amplifier input fiber by another 26 mm focal length aplanatic triplet. Total maximum launched power into the amplifier is ~75 mW, representing 25% launch efficiency overall. The low efficiency is caused by losses in the isolator, including 50% loss due to the beam being unpolarized, and 10-20% transmission loss through the isolator assembly. The rest of the loss is due to imperfect alignment to the PA input fiber caused by lack of sufficiently precise alignment stages.

Figure 112 shows that the PA is formed by a 2+1:1 PM fiber combiner coupling up to 36 W of pump into a 3.5 m length of 10 μm core, single mode, ~4 wt% Tm, PM thulium doped fiber (discussed in 2.2.2.8) in a counter-propagating pump scheme. Both the input and output fiber of the PA are angle cleaved at ~8° to ensure hold off from parasitic lasing.
For the ~75 mW seed coupled into the PA at 100 kHz repetition rate, the power performance of the PA is seen in Figure 118.

![Graph showing power performance of the PA](image)

Figure 118: Power performance of the PA at 100 kHz seed of 75 mW

The slope efficiency is ~35% which is essentially constant at all seed repetition rates tested. This somewhat lower than expected slope is attributed to the relatively low seed power being below the saturation power, causing lower efficiency. In addition, the pump power is not fully absorbed (~20% leak) in the only 3.5 m long power amplifier, leading to a further reduction in efficiency. Finally, the inherently slightly lower efficiency at the very short wavelength of 1908 nm results in a lower system efficiency.

The maximum power achievable with respect to repetition rate ranges from ~3.3 W to 5.7 W with complete maintenance of seeded pulse duration and no signs of ASE buildup. The maximum pulse energy, average power, peak power and minimum pulse duration for the various repetition rates is shown in Figure 119.
Figure 119: Average power, pulse energy, minimum pulse duration and peak power versus repetition rate for the amplifier system up to the onset of instability

As seen in the figure, the peak powers range from \(~1\text{-}4.5\text{ kW}\) with pulse energies from \(50\text{-}110\text{ μJ}\). It should be noted that pulse durations in this amplifier test are slightly longer than those as measured from the MO individually. This is attributed to day-to-day variations and potentially a slight degradation in the pump powers in the Er:Yb Q-switched laser pump diode over time, and not to effects in the amplifier itself.

Beyond the listed power levels or energies, the output power of the system becomes unstable and is limited by ASE and parasitic lasing in the amplifier attributed to insufficient available seed power to fully saturate the amplifier and hold off lasing at higher gain wavelengths in the power amplifier. No nonlinear effects are seen in the single mode thulium doped fiber. This is due to the inherently higher nonlinear thresholds at \(2\text{ μm}\) caused by the potential wavelength dependence of these nonlinear effects and the larger mode field diameter for single mode operation as discussed in 2.1. Beam quality of the system is still excellent, as the fiber is still essentially single mode (the V parameter is slightly above actual single mode operation, but any higher order modes are likely stripped by coiling). Figure 120 is an image of
the beam in the far field, showing the high quality. It is estimated that $M^2$ is less than 1.1, limited by delivery optics and not fiber performance. The slight distortions are due to a small amount of un-stripped cladding light that propagates in the delivery fiber.

Figure 120: Beam quality from amplifier

Polarization is reasonably stable, but slightly elliptical, likely due to a splice in the system being sub-optimal. The likely culprit splice is that between the passive seed input fiber and the passive fiber leading to the PA. This splice is between dissimilar fibers due to the unavailability of appropriately matched connectorized fibers. The slight splice mismatch leads to polarization distortion of the beam and hence the elliptical polarization of the PA. The polarization issue leads to incomplete use of the maximum power in later frequency doubling experiments, but will be resolved in the future with use of correct fibers as they become available.

With improvements to the seed and pump laser discussed earlier, the system as a whole would be significantly improved in performance. The gain switched system which is developed here is a far simpler system than other potential MOPA system options discussed later. It is capable of generating 25-60 ns pulses at power levels up to ~5.7 W average power at 100 kHz in purely single mode fiber or ~3 W at 20 kHz, (peak powers of 1-4.5 kW) with only one stage of amplification. The all-single-mode fiber nature makes further power scaling easily possible by subsequently including one or more additional LMA amplifier stages. Use of the standard 25/400 thulium doped fiber employed elsewhere in this dissertation, with appropriate fiber end caps,
should enable amplifications of pulses to mJ levels at 10’s to 100’s of kHz repetition rates. Further scaling beyond even this level is achievable with 40-70 μm core diameter thulium doped fibers which have yet to be developed, but could easily be fabricated and be arranged to maintain near single mode beam quality. Inclusion of pump combiners and all-fiber optical isolators which are becoming available would enable such a system to be extremely tightly packaged and made highly portable for applications such as LIBS or LIDAR. Such a system might be able to reach multi-mJ energies, using conventional fiber with excellent beam quality, a result that would likely not be possible at other wavelengths owing to the inherent advantage of working with thulium at long wavelengths. Overall, the system proves to be a viable option for generation of high peak power pulses in the 2 μm wavelength range. The system is frequency doubled in PPLN and generated ~1W 954 nm light with up to 60% conversion efficiency as is discussed in detail in 6.2.

5.2.3 Other Potential Nanosecond System Designs and Future Potentials

Though the gain switched system in the previous section is able to produce quite short pulses at a variety of wavelengths, it does suffer from one distinct advantage: the fixed pulse shape. As the saturation energy of fiber amplifiers is reached with further stages of amplification, the amplifier itself can begin to gain-shape the pulse, since its leading edge will use up most of the gain in the amplifier and thus cause pulse shape distortion. A potential remedy to this issue is to replace the seed with a narrow linewidth diode seed that is driven at very short pulse durations by an electronic driver. This technique, known as direct diode modulation, provides excellent flexibility and control of laser linewidth, pulse duration, repetition rate and pulse shape because these parameters can be set by the electronic driver signal to an arbitrary level or by selection of
an appropriate seed diode as is demonstrated at Yb wavelengths in [56, 183]. However, laser diodes at thulium fiber laser wavelengths are available with only mW of CW power and running them at kHz duty cycles in the pulsed regime results in only microwatts of average power. This means that several stages of amplification are necessary to reach even reasonable power levels, making such systems costly to implement and significantly more complex. In addition the systems may run into ASE issues in the lowest stages of amplification as the pulsed signal is pulled from the noise. This means the requirement for the incorporation of further complexity via ASE filters and other techniques for cleaning up the pulse. A potential alternative technique may be “pulse carving” where a CW laser at a higher power, perhaps the hundreds of mW to watt level which could be single frequency or otherwise spectrally controlled, is externally modulated at a very fast rate by an electro optic modulator or other technique. By applying appropriate signal, there still may be some degree of pulse shape control. The pulse peak powers would be slightly higher, likely meaning that fewer stages of pre-amplification would be required.

Regardless of the technique for seeding, there is certainly a huge further potential for thulium based nanosecond systems as the inherent advantages of thulium in terms of immunity to nonlinear effects and larger mode field diameters achievable before the onset of beam quality degradation. With the development of mJ level systems that are robust, compact and portable numerous applications in the sensing field open up. In addition, the higher energies open up avenues to the materials processing arena as well as a number of extremely interesting nonlinear regimes where the high pulse energy and high average powers achievable will enable more useful results from frequency conversion with significantly higher average power levels.
5.3 Modelocked Thulium Fiber Lasers

Many applications, such as nonlinear materials processing, long range, high sensitivity LIDAR, LIBS, medical and nonlinear frequency conversion techniques benefit from the high peak powers and short pulse durations that can only be generated in modelocked laser systems. Modelocking of Yb and especially Er based fiber lasers to produce ultrashort pulses (USPs) is well understood; systems with extremely short pulse durations and high pulse energies have been demonstrated on numerous occasions. However, research on thulium based modelocked fiber lasers has been relatively limited, despite the benefits in terms of broad bandwidth (hence short pulses) and potentially lower nonlinear effects. Modelocking of thulium fiber lasers has been reported using a variety of methods including saturable absorbers (based on carbon nanotubes or semiconductor saturable absorber mirrors), additive pulse modelocking and nonlinear polarization rotation as far back as 1995 and resulting pulse durations are from the picosecond range down to 100’s of femtoseconds with energies for the pJ to low nJ regime [69, 70, 342-345]. However these low pulse energies are not completely relevant for applications, as most applications call for pulses at least 10’s of nJ to µJ energies. Since most oscillators are not capable of such powers, thulium fiber amplifiers must be employed to boost pulse energies into the useful power regime. Use of such amplification techniques at 2 µm wavelengths has only been reported once, and that system used a Raman shifted modelocked Er fiber laser based seed, rather than a direct thulium based oscillator [346]. As a result, the area of thulium fiber amplified ultrashort pulses requires significant further investigation to understand any potential benefits that may be inherent in thulium and to begin producing robust systems suitable for applications. In order to begin this process as part of this dissertation, a modelocked thulium fiber laser oscillator and amplifier system is constructed. The following sections outline the theory of the
modelocking technique used to achieve the laser, the experimental results of the system and comments on potential future systems and their performance.

5.3.1 Single Walled Carbon Nanotube Modelocked Oscillator

The first and most critical portion of an amplified USP MOPA system is of course the oscillator. As evidenced by the techniques used in [69, 70, 342-345] for modelocking thulium fiber lasers, there are myriad ways to achieve the short pulses desired. However for this first round of experiments, the simplest technique for achieving the desired pulses would likely be the most useful in terms of forming a beginning understanding of thulium based USP MOPA systems. As a result, the carbon nanotube modelocking technique is employed, because it allows for simple, inexpensive and potentially “all-fiber” modelocked systems. Though it may not enable the absolute shortest or highest energy pulses, this technique is reliable and simple to implement with no special equipment and is proven to produce stable pulses in the picosecond or hundreds of femtosecond regimes. The following sections outline the basics of implementation of carbon nanotubes as a modelocking technique, the basics of modelocking theory as it pertains to carbon nanotubes and experimental results for a carbon nanotube modelocked laser.

5.3.1.1 Single Walled Carbon Nanotubes

Carbon nanotubes (CNT) are a relatively new material, discovered only in 1991 consisting of graphene or several layers of graphite (an individual layer of graphite is known as graphene) rolled into a tube-like structure [347]. They are fabricated by various techniques including laser ablation or arc discharge in appropriate gaseous environments and subsequently
purified by centrifugation to produce high purity, uniform batches of tubes with particular properties [348, 349]. They are well known for their material properties as pertains to their extremely high strength to weight ratio, high thermal conductivity along the tube direction but high insulation properties perpendicular to the tube axis and excellent electrical conduction and/or semiconductor properties as well as their chemical properties in terms of being sensitized or activated with functional groups for particular applications [348, 349], however they may be less known for their uses in optics stemming from unique optical properties. CNTs can have numerous structures, however most interesting to the optical properties useful for this work, are Single Walled CNTs (SWCNTs) which are single sheets of graphene rolled into a tube, furthermore the particular type of SWCNT of interest are those that are semiconducting [350]. The density of states in such nanotubes is essentially 1D (a “quantum line”) and this leads to a number of spikes in the density of states which, though not quite as discrete as in a 0D “quantum dot”, are very sharp [350, 351]. Optical transitions between the various spikes in the density of states leads to the optical absorption properties of SWCNTs being relatively narrow and having peaks [350]. Since the spacing between the peaks in the density of states are tied to the nanotube structure (especially the tube diameter) the optical absorption spectrum of such tubes is determined by tube outside diameter [350]. Based on the energy spacing between the spikes in density of states in semiconductor type SWCNTs for absorption peaks around thulium wavelengths, the required tube diameter is in the range of 1.5 nm (as compared to 0.8 or 1.0 nm for 1 and 1.5 μm wavelengths respectively) [350]. Nanotubes cannot be fabricated perfectly uniformly in terms of diameter, so usually one speaks about mean diameter in a grouping of SWCNTs, and the use of this average tends to spread out the absorption spectrum slightly [350].
Having optical absorption properties alone does not make SWCNTs suitable for laser modelocking, that absorption must also be saturable to enable use as a saturable absorber modelocker (the process of which is described in the following section). At the absorption resonances possessed by the SWCNT, there is a large degree of saturable absorption as determined by the particularities of the structure of the lattice of carbon atoms within the nanotubes as discussed in detail in [350, 352, 353]. The resulting structural properties give rise to $\chi^{(3)}$ nonlinearities, and of course absorbing materials with third order nonlinearity have intensity dependent absorption, which is also known as saturable absorption [146, 350, 352, 353]. This effect is also quite fast, on the order of 0.5-1 ps, as measured by researchers interested in SWCNT applications as ultrafast switches in telecommunications [354, 355]. The fast switching time in combination with the saturable absorption make them extremely suitable for application as modelocking devices as first demonstrated in [356], and as discussed in the following sections as pertaining to thulium fiber lasers.

5.3.1.2 Overview of Saturable Absorber Modelocking Theory

The basic concept underlying any type of laser modelocking is the desire to control the laser in such a way that the large number of longitudinal modes that can oscillate within a laser’s gain bandwidth can be arranged such that they all oscillate in phase with each other. When this occurs, the laser spectrum becomes very broad, as each longitudinal mode is at a slightly different wavelength, and thus Fourier transforms dictate that a broad spectrum must result in a narrow temporal output, assuming the modes stay locked together. Detailed discussion of modelocking can be found in sources including [9, 10, 160, 357]. This locking of modes in phase
can be achieved in numerous ways, but the discussion here is limited to a particular technique known as saturable absorption modelocking.

The qualitative description of passive modelocking is, as the modes in a laser compete and interact with no fixed phase relationship, there are some number of modes that may end up in phase, producing a spike of power in time. When a saturable absorber, a device with absorption that is lower for higher intensities, is inside a laser cavity it causes the high intensity random spikes to experience higher net gain than lower intensities, which are more significantly absorbed by the saturable absorber [9, 10, 160, 357]. This means in a subsequent round trip the initial spike can grow more as it has even higher intensity; as the process continues more modes become locked together as the duration of the spike shortens, since the lower intensity spike wings are reduced cut by the saturable absorber with each pass [9, 10, 160, 357]. Eventually the pulse will either get so short that its bandwidth is beyond the gain of the laser or so that some other mechanism like dispersion begins to attempt to pull it apart [9, 10, 160, 357]. Once the pulse reaches balance, the laser is able to operate in a stably modelocked regime [9, 10, 160, 357].

Within this qualitative picture, a number of effects in the fiber cavity including self phase modulation and dispersion, as well as the gain in the fiber all contribute to creating a modelocked pulse. The propagation of the pulse itself in time and space within a fiber is modeled by the appropriate form of the nonlinear Schrödinger equation. This equation is

$$\frac{\partial A}{\partial z} + \frac{i}{2} (\beta_2 + i g_c T_2^2) \frac{\partial^2 A}{\partial t^2} = i \left( \gamma + \frac{i}{2} \alpha_2 \right) |A|^2 A + \frac{1}{2} (g_c - \alpha) A$$  \hspace{1cm} (89)
where $T_2$ is the inverse of the frequency gain bandwidth of the laser, $\alpha_2$ is two photon absorption (usually neglected in fiber), $\alpha$ is any other loss (including saturable loss as will be discussed later), $\beta_2$ is the dispersion, $\gamma$ is the self phase modulation coefficient discussed in (9) defined as $2\pi n_2/\lambda A_{eff}$ where those parameters are as defined earlier, $z$ is the propagation along the fiber, $t$ is time, $A$ is the amplitude of the pulse field and $g_c$ is the gain averaged over the cavity length [357].

In the case of a saturable absorber modelocked laser, $\alpha$ is replaced by

$$\alpha \equiv \alpha_{cavity} + \alpha_0 (1 + \frac{|A|^2}{P_{sat}})^{-1}$$  \hspace{1cm} (90)

where $\alpha_{cavity}$ is the lumped cavity losses from such things as background absorption, splice loss etc., $\alpha_0$ is the unsaturated loss of the saturable absorber and $P_{sat}$ is the saturation power of the absorber [357].

If (90) is substituted into (89), after analysis and in the case where the saturable absorber is fast enough to respond in the time of the pulse (as with SWCNTs), a solution for the intensity ($A^2$) of the rough form

$$P(t) = P_0 \text{sech}^2 \left( \frac{t}{T_s} \right)$$  \hspace{1cm} (91)

where $T_s$ is the soliton width which corresponds to $1.7627* T_0$ the pulse FWHM and $P_0$ is the soliton power, given by

$$P_0 = \frac{N|\beta_2|}{\gamma T_s^2}$$  \hspace{1cm} (92)
where all parameters are as previously defined and \( N \) is the soliton order (usually 1) [357]. This form is rough because there are some particulars of the saturable absorber modelocking technique that give a more complex and detailed solution which includes chirp and several other parameters as described in [357]. A final important relation for the understanding of soliton modelocking is the soliton period \( z_0 \) which is given by

\[
z_0 = \frac{\pi T_s^2}{2\beta_2} \approx \frac{T_0^2}{2\beta_2}
\]

where all parameters are as previously defined. This parameter is important because as the cavity length of the modelocked laser approaches and surpasses this value, the stability of modelocking is lost and the soliton can become higher order and break up into multiple pulses whose shape change along the fiber length [358]. This is observed in the case of the thulium laser described in the next section for long cavity lengths.

Equation (92) states that a particular laser with an output peak power (or pulse energy) of a given level must have a duration given by the relationship it makes for given dispersion and nonlinearity. For any given dispersion and nonlinearity, the larger the energy, the shorter the pulse. However, the limiting factor is that as the pulse being generated decreases in length it becomes more susceptible to effects associated with the soliton period in (93). If the soliton duration achieved surpasses the soliton period, stable modelocking can no longer be obtained, however larger pulse energies can be obtained by increasing the cavity dispersion at the cost of increased pulse duration. To obtain the shortest pulses, optimized cavity design calculated from the more detailed equations in [357] and eventually experimental optimization must be done, but this is beyond the scope of the work done here.
5.3.1.3 Picosecond System Results

The saturable absorber modelocking method of choice for this particular laser is the SWCNT, as it is an inexpensive, simple to implement and effective technique for producing picosecond pulses in fiber lasers [350, 356, 359-361]. To fabricate the absorber, single walled carbon nanotubes (SWCNT) are dispersed in ethanol via ultrasonication for ~1-2 hours. The tubes are 1.5 μm in diameter giving them an appropriate absorption resonance at thulium wavelengths. The technique for fabricating the saturable absorber from the nanotubes is known as the optically driven deposition method, described in detail in [359]. An FC/APC connectorized section of SMF-28 fiber is dipped into the prepared solution of nanotubes. The opposite end of the fiber is spliced to a ~10 mW thulium fiber laser source which enables optical power to be emitted from the FC/APC connectorized end, while in the nanotube suspension. The optical power causes preferential deposition of SWCNTs on the core of the fiber as discussed in [359] due to a number of potential effects, including thermophoresis and the “optical tweezers” effect. After 30 seconds of exposure, the fiber is removed from the solution and the loss is calculated (loss being caused by deposited nanotubes). If loss is ~50% the absorber is complete, if not the process is repeated until ~50% loss is achieved, usually taking 2-3 attempts. When the desired absorption is reached, the FC/APC connector is connected to a second FC/APC via a mating sleeve to complete what is now a transmissive saturable absorber (SA). Figure 121 is an image of a fiber core with nanotubes deposited by this technique.
With an appropriate saturable absorber formed, a ring resonator is created as shown in Figure 122.

The gain medium in the “all-fiber” modelocked thulium ring laser is based on a ~15 cm length of PM single mode, 10 µm core, ~4 wt% thulium doped fiber (as discussed in 2.2.2.8). One end of this fiber is spliced to a PM WDM which couples up to 1.5 W of 1550 nm pump power from an FBG based Er:Yb fiber laser into the thulium doped fiber core. The other end of the thulium doped fiber is spliced to the FC/APC connectorized SMF-28 pigtail which is part of the SWCNT SA discussed previously. The opposite end of the SA is spliced to a 90/10 tap coupler for output coupling. The 90% port of the tap coupler is then spliced to the appropriate port of the WDM to complete a ring resonator.
It should be noted that the length of the ring resonator is critical to achieving clean modelocked pulses. In earlier versions a low concentration active fiber of ~5 m in length was used in conjunction with longer passive sections on each part of the laser. These long lengths allowed stable modelocking, but caused severe pulse breakup due to the large amount of dispersion (as thulium wavelengths are well into the anomalous dispersion regime in SMF-28) and potential for nonlinearities in the single mode fibers and being well beyond the soliton length. Reconstructing the cavity in the current configuration reduces these effects, but the 4 m length may still be a limiting factor as discussed later.

Laser performance is investigated by increasing pump power on the Er:Yb laser, with laser threshold occurring at ~190 mW of 1550 nm power delivered to the thulium fiber. As pump power is increased, the laser quickly transitions from a brief CW regime to a self-starting modelocked regime. The laser usually starts in a multi-pulsing regime and pump power must be reduced from the level causing initial onset of modelocking to achieve single pulse operation. When this is done, stable, ~46 MHz (corresponding to the ~4.3 m ring cavity length) pulses are observed with some small deviations from pulse to pulse as seen in Figure 123.

![Figure 123: Pulse train of SWCNT modelocked laser](image)

The modulation on the pulses is attributed to environmental instabilities and polarization effects caused by the non-PM SMF-28 saturable absorber splices to the rest of the cavity which is based on PM fiber. These mismatched fibers cause the laser to be quite sensitive to any
mechanical, vibrational or thermal perturbations. The technique for addressing this issue is discussed later.

Modelocking is typically achieved at ~240 mW pump power, while laser threshold is ~190 mW. When stable operation is achieved, the laser emits ~1.5 mW per output port, corresponding to 32 pJ of energy and ~6.5 W peak power. Power increase is linear as would be expected, with the linearity being maintained as power is increased beyond the stable single pulse regime and into the multi-pulsing and eventually completely CW regime. Per-output port power is used because the ring resonator operates bidirectionally due to the lack of an appropriate intracavity optical isolator.

As seen in Figure 124, the laser spectrum is centered at ~1918 nm with a FWHM of ~1 nm. There is very minimal sign of any distortion to the spectrum, however it should be noted that the center wavelength of the spectrum and shape of the spectrum is subject to environmental conditions. In the current laser the fiber must be slightly adjusted in position to optimize modelocking, again pointing to issues with cavity stability attributed to the fiber mismatch mentioned earlier.

![Figure 124: Output spectrum of the SWCNT modelocked laser](image)

The FWHM of this spectrum agrees with an intensity autocorrelation taken with a collinear Michelson interferometer based autocorrelator using a silicon photodiode, exploiting two-photon absorption as the nonlinear element required for autocorrelation. Because of the very
small power of the laser, lock-in amplification techniques are required to view the signal produced from the photodiode. Using these techniques produces an autocorrelation spectrum as seen in Figure 125.

![Autocorrelation Spectrum](image.png)

Figure 125: Autocorrelation of the modelocked SWCNT laser

Note that the autocorrelation shows the correct 3:1 ratio of signal to background in the non-background-free configuration used for autocorrelation.

A final important note is that despite the slight instability to modelocking instituted by the polarization mismatch discussed earlier, the single pulse modelocking is able to be maintaining over long term operation of several hours, as long as there are no environmental perturbations to the laser. In order to overcome the instabilities in future versions of this system, a new type of SWCNT SA is being implemented, known as the evanescent field SA. This is based on an absorber used in [342], where a section of fiber is tapered to 5-7 μm outside diameter, causing the evanescent field of the light in the fiber to be exposed area outside the fiber. The fiber is then coated in a polymer matrix containing SWCNTs which act as a SA distributed over the length of the taper. The advantage of this technique is that there are no tubes directly on the core, thus there is not the potential for peak power damage that can occur in the optically deposited SA. In addition, the taper technique enables any type of fiber to be used, thus
the taper fabricated for this laser will incorporate matching PM fiber to remove the associated polarization issues.

As will be discussed later, the average power and pulse duration of the oscillator will also need to be improved to increase peak powers and enable more stable amplification. Average power and most likely pulse duration can be improved by increasing the output coupling of the cavity, perhaps be replacing the 90/10 tap with a 50/50 or lower ratio tap. Reduction of cavity length will also contribute to decreased pulse duration by removing excess dispersion, though this will come at a cost in terms of pulse energy, as repetition rate will increase. The tap and WDM used for this laser are also not optimally designed, as they are intended for narrow line use at 2040 nm. Correctly designed WDM and taps for broadband operation at the desired wavelength range should also improve laser operation. Addition of a fiber coupled intracavity optical isolator will also enable unidirectional operation and most likely enhance stability and performance if such a component becomes available at thulium wavelengths. The improvements will enable a more robust and useful laser that can ultimately be packaged into a very small container, due to the all-fiber nature. However, the work currently demonstrated shows the future potential of SWCNT modelocked lasers.

5.3.2 Amplification of the Modelocked SWCNT Laser

The relatively low average power (1.5 mW) and pulse energy (32 pJ) and thus peak power (6.5 W) of the SWCNT modelocked laser described in the previous section means that it cannot provide much usefulness in the way of applications. This is typical of most reported thulium modelocked lasers with the exception of [344, 345]. In order to reach power levels of greater utility, amplification must be investigated, however in the area of thulium fiber lasers,
only one amplifier system has been demonstrated [346], and this system did not generate its pulses using a thulium fiber laser, but rather a more complicated Raman shifted Er fiber laser system. The results in the following section discuss the first direct amplification of a thulium modelocked system at the time of this dissertation’s completion.

The output from one tap port of the modelocked laser described in the previous section is used as the seed pulse, while other port outputs are monitored to ensure stable operation is maintained. The output fiber from the tap port used as the seed is spliced to an FC/APC connectorized SMF-28 pigtail which is mounted in front of an 11 mm AR coated glass aspheric lens. The output is launched through a 4 mm diameter optical isolator designed for 2050 nm (similar to the isolator used in 4.2.2) and is coupled into a second connectorized SMF-28 pigtail by a matching 11 mm asphere (Fig. 2). The isolator is not optimal for the seed laser wavelength and this will be a problem as seen later. The entire coupling process can be avoided in future systems, as commercially available fiber coupled isolators in the 2 μm regime are becoming available, and thus a truly “all-fiber” system can be realized.

The layout of the seed launch and remainder of the amplifier scheme is seen in Figure 126.

![Figure 126: Schematic layout of the MOPA system](image)
The SMF-28 section coming from the isolator is spliced to a mode field adaptor which matches the \( \sim 12 \, \mu \text{m} \) SMF-28 MFD to the \( \sim 22 \, \mu \text{m} \) MFD of a section of passive LMA, 0.1NA, 25 \( \mu \text{m} \) core, 250 \( \mu \text{m} \) clad fiber.

The total transmission of the seed up to this point is \( \sim 25\% \). The contributing losses include the losses associated with the unpolarized seed beam in the polarizing isolator (\( \sim 50\% \)), absorption and reflection losses in the lenses (12\% total for two lenses), from free space fiber tips (\( \sim 5\% \) total), isolator (\( \sim 20\% \) due to AR coating not at the required wavelength) and losses in the MFA (\( \sim 15\% \)). This means of the original 1.5 mW seed average power, only \( \sim 0.4 \, \text{mW} \) is available for amplification. A cladding mode and residual pump stripper is included along the length of the passive LMA fiber before it is spliced to a \( \sim 1.5 \, \text{m} \) section of 25 \( \mu \text{m} \), 0.1NA, core, 250 \( \mu \text{m} \), 0.46NA clad thulium doped fiber (discussed in 2.2.2.8). The doped fiber is wrapped on a water cooled \( \sim 6 \, \text{cm} \) diameter mandrel cooled to 14°C. The fiber is counter-pumped by a 40 W, 100 \( \mu \text{m} \) fiber coupled, 790 nm laser diode. The counter pumping scheme is not ideal for the extremely small seed power; it was used to minimize backwards ASE which tends to destabilize the mode locking because of the insufficient isolation provided by the optical isolator. The pump is launched using a \( 2+1:1 \) pump combiner, but the pump fiber itself is not spliced directly to the combiner. Pump power is launched through free space into one of the combiner’s input ports with \( >80\% \) efficiency. This allows the insertion of dichroic mirrors between the combiner and pump in order to protect the pump diode from any amplified signal that leaks into the cladding and possibly backwards into the pump fibers. This can be avoided in the future through the use of a laser diode pump with integral dichroic filters, enabling direct splicing and thus a truly “all-fiber” system. The output end of the amplifier (the feed-through port of the pump combiner) is cleaved at a \( \sim 10^\circ \) angle to suppress parasitic lasing and feedback.
For a seed power of 1.5 mW (32 pJ energy) from the master oscillator, it is estimated that 25% (~0.4 mW or ~9 pJ) is coupled into the amplifier. Amplifier performance is seen in Figure 127.

Figure 127: Amplification slope of modelocked laser output

Pumping the amplifier with up to 27 W power allows a maximum average power of ~0.6 W (13 nJ) at the full repetition rate of the modelocked laser. This corresponds to ~2.6 kW of peak power. (It is interesting to note that peak power level is on par with the powers in the nanosecond lasers in section 5.2 which have pulses of 10000 times higher energies, demonstrating the potentials of extremely high peak powers for future ultrashort pulse based systems). Though more pump power is available, power cannot be increased further because feedback into the oscillator becomes a problem. This feedback is a consequence of either amplifier ASE or back-propagating amplified signal leaking through the relatively poor isolator (<15 dB isolation at ~1918 nm), which is actually intended for use at 2050 nm. However, the onset of instability is still expected around this amount of gain, as practical considerations limit the maximum gain before the onset of instability in a fiber amplifier to the order of 30-40 dB [3]. The gain in this system is just over 30 dB, so it is approaching the range where a higher seed power would be preferred. The exponential growth of the output from the amplifier is expected in this regime of operation with the input seed power far below saturation. As a point of
comparison, to be sure the amplifier is working properly, the performance of the amplifier for a similar powered CW seed is tested and found to perform with a similar slope and exponential trend.

An ~10% slope efficiency for the pulsed amplifier with respect to launched pump power occurs when growth begins to become linear. This slope is still lower than expected due to a combination of operation well below saturation power and a large amount of leaked pump power through the only ~1.5 m active fiber, which has an estimated 5-7 dB absorption. The fiber is required to be short to avoid the onset of any nonlinear effects. More careful optimization of pump laser wavelength will improve amplifier absorption efficiency, however the current pump cooling scheme cannot be temperature controlled and hence there is not the potential for temperature tuning. Leaked pump power could not be measured directly due to the use of a pump dump to strip leaked pump power, so the slope is given with respect to launched power.

No signs of nonlinear effects, ASE or parasitic lasing are observed in the output spectrum of the amplifier up to the operating power level where feedback-induced instability occurs. Beam quality is not directly measured, but it is expected to be quite the active fiber, and the relatively low NA of the LMA amplifier fiber.

The most critical improvement that can be made to the amplifier system is an increase in the average power (pulse energy) of the seed laser by various techniques discussed in the previous section. If output power from the seed cannot be significantly increased, the use of pre-amplification in single mode fiber will also be required; this would most likely would be the best potential solution to push seed power levels to the hundreds of mW levels needed to achieve sufficient saturation of the LMA fiber amplifier. With higher seed powers, the efficiency of the
amplifier should improve dramatically, potentially approaching the 50-60% efficiencies achieved in other systems described in this dissertation.

Use of a more appropriate optical isolator (or multiple isolators) as well as improvements in the operating stability of the oscillator by removing the non-PM fiber should also enable allowing significantly higher amplified average powers to be achieved as the stronger operation of the laser seed which would make it far less susceptible to feedback issues.

There is also an interest in achieving higher pulse energies without needing to scale to extremely high average power, as pulses in the 100’s of kHz to MHz regime are sufficiently fast to ensure efficient amplification without fluorescence losses. This can be achieved by use of a pulse down-counter before seeding the amplifier. In the MHz or 100’s of kHz repetition rates regime, μJ level pulses are far more achievable from the system at reasonably low average powers. Pulses of such energies are useful for numerous materials processing and nonlinear optical applications. Testing of the amplifier in this μJ energy level regime (once sufficient seed power is available) will reveal the point at which the onset of any nonlinear limitations which may occur. Results of such testing will perhaps reveal the higher potential pulse energies that thulium fiber laser should be capable of as a result of the inherent benefits of longer operating wavelength as discussed at many points in this dissertation. Because of the relatively short length of the amplifier and relatively long pulse durations, it is likely that dispersion played little role in the amplifier, and pulse duration is likely minimally effected by propagation in the amplifier. The current system can easily be configured to a fully “all-fiber” laser that could be readily packaged with very small footprint, making it highly useful for future applications.
5.3.3 Challenges and Benefits of Thulium in USP Regimes

The benefits of working with thulium in the ultrashort pulse regime lies in the inherent ability to use larger mode field diameters and hence have reduced nonlinear effects, which themselves may be reduced by thulium’s longer wavelength. However, as pulses are pushed towards the femtosecond regime, a further advantage of thulium surfaces, its ultra-wide gain bandwidth of 300+ nm. This bandwidth enables the amplification and generation of USPs with sub 50-fs durations (and perhaps with extreme care sub-20 fs durations, as a full 300 nm of bandwidth at 2 μm corresponds to ~15 fs pulses). The difficulty lies in the generation of such pulses using thulium; it presents a challenge as pulse durations get shorter in terms of the large amount of material dispersion inherent in the thulium wavelength regime in fused silica glass. This leads to the need to generate the short pulses in some other medium before amplifying using thulium, or perhaps by using nonlinear effects to stretch the bandwidth and recompress to produce the desired pulse. However these techniques make the use of thulium more complex, and as a result there is a need to potentially seek out materials with low dispersion at thulium wavelengths to achieve higher performance in thulium based oscillators. The large dispersion in thulium does not lead to as many problems in amplification, as in the chirped pulse amplification regime, the pulse enters the fiber already stretched, however the high dispersion could still cause distortion to the pulses to some extent. There may be some inherent advantages to the strong dispersion as is suggested in [346], because a pulse can be stretched and subsequently recompressed in the amplifier fiber; therefore, reaching minimal durations just at the end of the fiber and enabling short pulses to be emitted directly from the amplifier with no recompression.

Overall, the most important consideration for the further scaling of thulium fiber lasers and amplifiers is the control of dispersion to enable the maintenance of clean, high peak power
ultrashort pulses. A great deal of further investigation into materials with appropriate dispersions (normal dispersion) to compensate the large amounts of anomalous dispersion in silica at thulium wavelengths must be found. This may involve bulk materials such as ZnSe which has normal dispersion at 2 μm, potentially the use of other soft glasses with different dispersions, or perhaps even dispersion engineered fiber such as photonic crystal fibers to achieve the desired degree of dispersion.
6 APPLICATION OF THULIUM FIBER LASER SYSTEMS

The ultimate goal of the development of thulium fiber laser systems is to make them applicable for specific tasks. In order to demonstrate the utility of such lasers, two simple applications have been demonstrated. The first application is the use of CW thulium fiber lasers with spectral control in spectral beam combination applications. The second application shows the utility of pulsed thulium fiber lasers via their use in a frequency doubling experiment conducted with the gain switched system discussed in the previous chapter.

6.1 Spectral Beam Combining Demonstrations

As discussed in 2.1, there are limiting factors to the performance of thulium fiber laser systems and in fact all fiber laser systems in terms of maximum potential output power levels, imposed by nonlinear, thermal and damage limitations. In order to overcome these limitations, techniques for the combination of the output from several lasers into a single beam are being investigated. The following sections outline such different techniques, as well as discussing the application of thulium fiber lasers to the spectral beam combining technique done in collaboration with Andrew Sims, Christina Willis, Pankaj Kadwani, Larry Shah and Vikas Sudesh.
6.1.1 Beam Combination Techniques

There are numerous techniques for the combination of laser beams in order to reach higher average powers or pulse energies and such techniques are currently comprise a large area of laser research. As such, they are only briefly overviewed here for a general sense of the field before one particular technique is selected as suitable for thulium fiber lasers currently available. Beam combination falls into two broad categories: coherent and incoherent beam combination. In turn each category is divided into sub-categories [3, 119].

The basic principle of coherent beam combination is the use of multiple laser gain media to produce a single, high brightness and high power beam in the far field. This is achieved by either active or passive methods. When implemented in fiber laser systems, active techniques usually rely on a single seed laser and a MOPA scheme where a single seed laser is split among several amplifiers and the phase of the seed in each amplifier is controlled to create mutually coherent output of the beams in the far field [3, 119]. This results in a beam that is N times brighter than the beam of a single element, where N is the number of elements [3, 119]. The individual elements can either be tiled in the far field or combined into a single beam by some type of diffractive optical element [3, 119]. Though producing high brightness systems both spectrally and spatially, coherent systems suffer from a higher degree of complexity due to the phase control techniques and limitations of individual amplifiers in terms of their requirement of single frequency inputs, thus inviting SBS [3, 119]. In addition, the far field pattern can be altered by the failure of a single element, since essentially the far field pattern is designed to create a plane wave like output which depends on the mutual interaction of all beams [3, 119]. Passive coherent techniques involve coupling a number of laser oscillators via feedback elements such as fiber combiners with appropriate design, as discussed in [119, 362, 363]. These
techniques are simpler to implement, as they are passively based, but in the case of the fiber devices, they may be limited ultimately by the fact that a single fiber aperture is ultimately the output, thus not necessarily giving an advantage in terms of power scaling outside a single fiber aperture.

The second general category of beam combination techniques is incoherent combination, where no effort is made to maintain the coherence of beams [3, 119]. The simplest technique of incoherent combining is simply beam combination in the far field by placing a large number of collinear beams in close proximity. This might be accomplished by a multi-core fiber or a fiber combiner based on a tapered fiber bundle (run in reverse from typical, hence 7 inputs to a single multi-core output). The beams are incoherent; they do not produce a clean, single beam in the far field, and thus brightness and divergence is limited by the brightness and divergence of an individual element [3, 119]. Power scaling, however, can be easily achieved and such techniques have proven capable of scaling to kW level powers with long distance propagation through the atmosphere as discussed in [114].

Polarization combining is an alternate beam combination technique that takes two beams and combines them with a polarizing beam splitter-like element run in reverse. The technique can be highly effective, but is limited in that only two potential channels are possible (based on only two polarizations available), limiting scaling. Inclusion of such polarization techniques with other beam combination techniques allows a simple factor of two increase in power [3]. A final incoherent technique is spectral beam combination, which uses a number of lasers at a convenient separation of wavelengths (a few nm per channel) in combination with one or several wavelength selective elements to combine the individual beams into a single beam. This technique scales the spatial brightness of the beam by the number of channels, but does not
increase the spectral brightness. In addition, beam quality is maintained close to the beam quality of the individual laser elements (limited only by the ability to maintain beam overlap) [3, 119]. However, in the case of many applications, such as directed energy, the control of spectrum is only critical in that it must fit in an atmospheric transmission window, in which many channels can be easily packed. The limitation on number of channels is otherwise only given by the bandwidth of the laser gain media used [3, 119].

Though thulium lasers can find application in all types of beam combination, their extremely large bandwidth makes them a highly interesting choice for spectral beam combination, as a large number of channels can be packed under either the full 400 nm bandwidth or even in the >60 nm bandwidth of an atmospheric propagation window which has openings from 2.03 - 2.05 and 2.08 - >2.1 μm. In section 4.2.2, highly efficient, high power operation was demonstrated at all of these wavelengths, so clearly an investigation of the combination of thulium fiber lasers is an interesting experiment, utilizing the configuration of the MOPA system in 4.2.2.

6.1.2 Diffraction Grating SBC Experiments

As discussed in previous sections, SBC is can be a useful technique for scaling laser power beyond the capabilities of single aperture fiber based systems, which has been demonstrated in numerous Yb based systems [321, 364-366]. However, there has been minimal effort on the combination of thulium fiber lasers, despite their large bandwidth and eye-safe wavelengths. Only one experimental demonstration (in 2001) has been made and this was done at low powers of ~11 W total combined power [367]. This experiment also used the grating as a feedback element to the three lasers, which couples beam combination to the formation of a laser
cavity. The current experiment discussed here involves independently stabilized lasers. In order to investigate any potential differences, advantages or disadvantages of SBC in the thulium spectral window, a simple experiment is devised to achieve moderate power combination of thulium fiber lasers using a simple diffractive element.

6.1.2.1 Experimental Setup and Results

The SBC setup consists of three thulium fiber MOPA systems. One system utilized is the MOPA system used for atmospheric propagation which is discussed in 4.2.2. The other two systems are mostly similar to the system in 4.2.2 with a few noted differences. The power amplifier is pumped only in the co-pumping direction, due to the reduced demand on the required signal power. In addition, no optical isolator is used between the seed laser and the power amplifier, as the ~30 W power levels desired can be reached without the isolator. Finally, the seed lasers for the two systems are based on ~1 W output power GMRF stabilized lasers created using 25 µm core thulium doped fiber as discussed in 4.1.5. Aside from these differences, the systems are identical in terms of thermal management, optical components and general layout.

Both the GMRF and grating based MOPA systems are able to produce ~30 W power and maintain linewidths in the 100-200 pm range at those power levels, with an efficiency performance in the 50-60% range. The master oscillators of each laser are selected to be at different wavelengths separated by ~10 nm (dictated by the available wavelengths of the GMRFs used as stabilization elements). The two GMRF based lasers are stabilized at 1984.3 nm and 2011.9 nm while the grating tuned laser is stabilized at 2002.1 nm. The M² of the individual lasers is better than 1.2 in all cases, likely limited by the measurement capabilities of the
available equipment. In addition, the $M^2$ is also measured for individual beams after reflection at ~20 W powers and found to be ~1.2 as well, though slightly stretched to a larger value in the axis of the diffraction of the grating due to spatial dispersion of the light.

The output of each system is collimated by 100 mm fused silica single element spherical lenses to produce beam diameters of ~9 mm. The lasers are spread between two optical tables in a lab (one laser on one table and two on another) and their beams are directed by appropriate dielectric mirrors towards a single point on one table and are overlapped at this point. Once overlapping at this point in space, a copper substrate, gold coated diffraction grating blazed for 1.85 µm with 600 lines/mm is positioned to diffract the beams to the first diffracted order of the grating. It should be noted that the grating is ~70% diffraction efficient for 2 µm light that is unpolarized. In addition, due to the slightly absorbing nature of the grating coating, the back surface of the grating is cooled by contact with a water cooled aluminum block, to attempt to minimize thermal effects at high powers.

With the beams overlapped on the grating (which is oriented near the Littrow condition for the incident beams), they are then overlapped in the far field a distance of 2, 4 and 8 meters from the grating surface, then checked for overlap at the grating. If overlap is maintained, the system is considered aligned, if not, the process is iterated (far from and near to the grating) until the beam is overlapped over the 8 m distance. The process is done beam by beam, first overlapping two beams and adding the third. The tunability of the grating based MOPA is also used to set that laser to a favorable wavelength that enabled the simplest combination. With the beams overlapped at the 8 m distance, the power, spectrum and beam quality are monitored. Testing is carried out at various power levels up to the ~30 W potential of each amplifier; a total
of ~73 W is incident on the grating (~10% power from each laser is lost by transmission through the uncoated and slightly absorbing (as they are not low OH− grade) fused silica lenses).

At the full incident power of 73 W, a combining efficiency of ~67% is achieved giving ~49 W combined power, which is in reasonable agreement with the ~70% diffraction efficiency of the grating based on unpolarized incident light. The spectra of the individual lasers is kept stable at <150 pm per laser as seen in Figure 128.

![Image](image1.png)

Figure 128: Output spectrum of the SBC system, showing the three distinct lines for the three lasers at close to identical power levels

If including the total efficiency of the system (optical to optical) from pump diode power to combined power, the efficiency is ~32%, which, of course could be vastly improved with an improved combining grating. The slope of the total system from launched pump power to combined power in a single beam is seen in Figure 129, showing no sign of roll off.

![Image](image2.png)

Figure 129: Slope of the three combined laser system output power with respect to launched pump power showing a total optical to optical slope of ~32%
Power is sufficiently stable such that the ~10 minutes required for making $M^2$ measurements is achievable, however long term power stability is not investigated, though it is speculated that it would be limited by the individual lasers, rather than the combining aspect of the system, and as seen in 4.2.2, stability of such systems can be quite high.

Beam quality is measured at a variety of power levels and at full power is found to be <1.7 and 2.1 parallel and orthogonal to the ruling direction of the grating respectively. This is a noted degradation of beam quality compared to the ~1.2 for each individual beam. It is attributed to the thermal distortion occurring on the surface of the grating causing it to expand, and hence produce a curved reflective surface. This curved surface causes thermal lensing type effects (though the “lensing” is actually from a thermally induced aberrated curved mirror). The thermal effect may also cause the beam overlap to degrade, and since $M^2$ is measured several meters from the combining grating, a small change in the grating could have made a significant change in the far field. There is also error inherent in the imperfect initial misalignment, which is seen in the slightly degraded (~1.4-1.5) $M^2$ values measured at low powers where there is not thermal distortion. The slightly larger $M^2$ in one axis is attributed to spatial dispersion in the beam caused by the 150 pm bandwidth of the individual beams. Figure 130 is an image of the individual beams in the system and the view of the final overlapped beam.

Figure 130: Three individual beams and final overlapped beam in SBC demonstration. The slight fringing in Beam 1 and the combined beams are likely due to an interference effect in the sampling wedge or filters for the camera. The images are at several meters distance from the laser output and combining grating.
6.1.2.2 Conclusions, Limitations and Improvements

Based on the results of the SBC demonstration there are a number of areas where there is a potential for improvement. The improvements can be made to both the individual laser systems and to the combining system itself. With the implementation of these improvements, the SBC system can be stretched to higher operating powers with cleaner beam quality.

The most critical improvements in the laser systems include a reduction in the linewidth of the master oscillators. The linewidth is a limiting factor because the spatial dispersion of the gratings tends to distort the beam quality by stretching it in one axis. This should be well within the capabilities of the GMRF stabilization elements, as they have the potential to produce lines in the 10’s of pm range, which is sufficiently short that spatial dispersion will have minimal effect. A second limitation is the general performance and overall size of the MOPA systems. If the MOPA could be replaced with direct stabilized oscillators, the linewidth could be narrowed significantly. As an alternative, the MOPAs could be made into “all-fiber” systems with the addition of appropriate fiber isolators and mode field adaptors which could be packed into significantly smaller spaces with higher operating stability. Another important aspect would be to implement PM lasers with stabilized output polarization to enable the more effective combination off of elements that are polarization sensitive, such as the diffraction grating. If the current lasers were appropriately polarized, a 20% increase in power would have been achieved inherently, even with the relatively poor grating quality used. Use of appropriate collimating optics and improved fiber composition will also enable higher overall system efficiency, perhaps approaching 70% with respect to launched pump power.
Limitations based on the combining element are obvious in terms of the low combining efficiency observed and the thermal effects on beam quality. Within the boundaries of the current element, there is not much in the way of potential improvement, however by replacing the metal grating with an appropriate dielectric diffraction grating, the improvement in combining efficiency may reach on the order of 97% with polarized light as demonstrated in [366]. In addition to the improved diffraction efficiency, the power handling of such gratings is also significantly higher, as in [366] up to 2 kW was combined at 1 μm wavelength. The packing density of the spectral lines is limited by the line spacing of the grating, as the dispersion with the 600 l/mm grating and limitation inherent in the mounting scheme for the mirrors used in the combining chain force the relatively large separation between channels. Use of more specifically-engineered (custom made) mounts may help alleviate this but the use of a higher line count grating will also help. This packing difficulty is inherent for the longer wavelength of the thulium, as there is less spatial dispersion, requiring greater spacing in spectrum. This issue will be less pronounced for other potential combining options which do not function in the same way.

There are a number of alternate combining schemes which may find use for SBC in place of a traditional grating as demonstrated in [321, 365]. These techniques could include the use of VBG technology as discussed earlier, with each laser reflecting off of a narrow band VBG while other lasers pass through them. This would eliminate the spatial dispersion problems, as VBGs are relatively flat in reflectivity in their spectrum. One potential issue with this scheme is that each channel needs its own VBG, thus increasing the part count demand of the system compared to a system based around a single combining element. In addition, especially at thulium wavelengths, the small residual material absorption may limit the power handling. At 1 μm wavelengths power handling to near kW levels was proven [321, 365], however the power
handling of an individual VBG at 2 µm is thus far only shown to be ~160 W based on the result presented in 4.2.1. Transmissive VBG techniques such as those discussed in [368] promise to reduce the number of elements to a single VBG, however they may still see power handling problems.

An additional alternative SBC technique is the use of simple dielectric filters (dichroic mirrors with sharp long or short pass edges). These filters can be stacked to provide reflection from each channel. This technique was demonstrated in [364] for the case of pulsed lasers at 1 µm but these dielectric filters, if placed on appropriate substrates could easily be scaled to work at thulium wavelengths to provide packing as dense as ~2-3 nm spacing. In addition, these filters have no spatial dispersion effects, as they are simple mirrors. Polarization combining could also potentially double the amount of combining by producing two SBC chains at the same range in wavelength and using polarization combination to combine them. However, if polarization is not possible, the useful property of the narrow line dielectric filters is they do not require polarized beams, unlike traditional gratings. Again, disadvantages are that the number of elements needed scales with the number of channels; however these elements are significantly lower cost and easier to mass produce compared to a VBG.

Overall, the experiment described in this section proves the potential for SBC at thulium wavelengths. The demonstration is the highest power and highest optical to optical efficiency (including pump power) demonstration at thulium wavelengths with only one other demonstration (given in [367]). The tests do reveal one potential roadblock in terms of the lower spatial dispersion of the grating at thulium wavelength. Though this reduces loss of beam quality in an individual beam caused by its linewidth, it would limit the packing density of the laser as a whole. Several potential solutions to circumvent the issues associated with the thermal effects in
dielectric gratings have been suggested and with appropriate availability of components, could be implemented at reasonable power levels.

6.2  Frequency Doubling of Thulium Fiber Lasers

A thulium fiber laser’s uniquely broad laser spectrum in the 1.8-2.1 μm regime is useful a number of direct applications, as discussed in 1.3. However, there is a further utility to the output of thulium fiber lasers when nonlinear processes are used for conversion to other wavelengths. The broad thulium bandwidth enables wide tunability of the frequency converted sources, and the unique wavelength gives access to a variety of spectral regions, including the THz, Mid-IR, EUV, red, blue and near infrared (NIR) which may not be easily or efficiently accessible by other laser sources.

A wavelength regime of particular interest which can be reached with simple techniques is the NIR. Though frequency doubling thulium lasers at longer than 2 μm in wavelength is not particularly useful, as those wavelengths can be more simply be generated in Yb fiber lasers, the region below 1 μm and particularly below 980 nm where Yb cannot be made to lase is of interest, and can be reached by frequency converted thulium lasers.

This regime has numerous potential applications including spectroscopy, sensing of water vapor in the atmosphere, sensing of other materials with 9xx nm resonances, high power, high brightness core pumping of Yb and Er fiber lasers and further conversion to blue wavelengths in the range of current argon-ion lasers for applications such as optical data storage writing [209, 369-372]. However, the regime is somewhat difficult to reach with direct laser lines, the transition in Nd is three level, and it is difficult to remove the potential for four level 1060 nm operation, and Yb lasers cannot be produced below ~980 nm [209, 369-371]. Thulium, with its
potential for operation below 1920 nm is a potential alternative to these techniques if used in conjunction with well established, highly efficient frequency doubling techniques, such as periodically polled lithium niobate (PPLN) [373]. The following sections discuss the basic theory of frequency doubling using PPLN and experimental results using the system described in 5.2.2.

6.2.1 Basic Theory of Frequency Doubling

Second harmonic generation (SHG or frequency doubling) is achieved using a nonlinear crystal with a $\chi^2$ nonlinearity and appropriate transmission properties at the intended laser wavelength and its second harmonic. The background of the physics driving such processes are well understood and found in references such as [146]. There are two important parameters for SHG, first is the phase matching factor $\Delta k$, which gives information about the overlap in phase of the fundamental beam and its second harmonic [9, 146]. In the case of SHG, $\Delta k$ is given by

$$\Delta k = 2k_{laser} - k_{SHG}$$ (94)

where $k$ is equal to $2\pi n/\lambda$ at either the laser or SHG wavelength where $n$ is the refractive index at the given wavelength [9, 146]. If the beams do not overlap in space and in phase, no energy transfer between the two will take place and SHG will not occur efficiently [9, 146]. This phase mismatch results from a difference in refractive index in the material at the laser and SHG wavelengths. Temperature control and appropriate angling of a birefringent crystal are potential techniques for achieving this match, however these require precise control and alignment and still cannot maintain matching over extremely long paths [9, 146].
This leads to the use of an alternative technique, known as quasi-phase matching (QPM) which is achieved by essentially switching the sign of the nonlinearity every time the two beams begin to walk out of phase [9, 146]. Steady growth of a SHG signal is maintained, rather than that SHG transferring energy back to the fundamental. The length of a crystal when this back-conversion process begins to occur is known as the coherence length [9, 146]. The period for the poling for optimum conversion efficiency assuming the simplest first order poling (typically the type used) requires that it reduces the phase mismatch to zero and thus

$$\Lambda = \frac{2\pi}{2k_{laser} - k_{SHG}}$$

(95)

where $\Lambda$ is the period of the poling, and $k$ is defined as earlier [9, 146]. This enables constant growth of a nonlinear signal in a crystal and is achieved by periodically exposing a crystal to a field that essentially flips the direction of its nonlinearity [9, 146]. This so called periodic poling (PP) process produces the potential for long interaction lengths, enabling more efficient nonlinear conversion.

The second important parameter in frequency conversion is the effective nonlinear coefficient $d_{eff}$. This value tells how strong the nonlinearity is and higher values enable more efficient conversion. According to analysis in [9, 146] this parameter is decreased by a factor of $2/m\pi$ where $m$ is the order of poling, thus in the case of most PP crystals which use first order poling, $m=1$ and the $d_{eff}$ is decreased by $2/\pi$.

Regardless of the method for phase matching the equation for the growth of the SHG signal is the same. It is determined from the solution of coupled Maxwell’s equations for two beams propagating in a nonlinear material. The Manley-Rowe relations are invoked as is done in
[9, 146]. Carrying out the analysis, an equation for the growth of SHG power with respect to fundamental power can be derived, including the effects of saturation and phase mismatch as

\[
\frac{P_{\text{SHG}}}{P_{\text{laser}}} = \tanh^2[l \left( \frac{8 \pi^2 (\frac{377}{\varepsilon_0} \varepsilon_0 c^2 d_{\text{eff}}^2)}{\lambda^2} \right)^{0.5} (\frac{P_{\text{laser}}}{A})^{0.5} \sin \left( \frac{\Delta k l}{2} \right) \frac{\Delta k l}{2}]
\]  

(96)

where \(l\) is the length of the crystal, \(\varepsilon_0\) is the permittivity of free space, \(n\) is the refractive index of the laser wavelength, \(P\) is power in laser or SHG, \(A\) is the area of the beam in the crystal, \(d_{\text{SHG}}\) is the \(d_{\text{eff}}\) coefficient reduced by the \(2/\pi\) factor as discussed earlier, \(\Delta k\) is given by

\[
\Delta k = 2k_{\text{laser}} - k_{\text{SHG}} - \frac{2\pi}{\Lambda}
\]

(97)

and all other variables are defined as earlier [9, 146]. Using (96) with \(\Delta k=0\) gives the maximum efficiency, and using a variation in \(A\) based on a change in temperature or sectional poling period gives the change in efficiency for a mismatch to the poling period for a given crystal, which can be altered by temperature control of the crystal. For SHG at thulium wavelengths near 1.9 \(\mu\)m, \(\Lambda\) is ~27.25-27.5 \(\mu\)m and for PPLN used in the experiments discussed in the next section \(d_{\text{eff}}\) is ~27 pm/V, thus the \(d_{\text{SHG}}\) is ~17.2 pm/V. The next section discusses the frequency doubling of a thulium fiber laser and the results are compared to theory based in the previously described principles.

6.2.2 Frequency Doubling of a Pulsed Thulium Fiber Laser System

In order to make a simple demonstration of the ability of a thulium fiber laser to be efficiently frequency doubled to the useful 9xx nm regime, the laser described in 5.2.2 is configured for a SHG experiment. The experiment is also published in [341]. The output from
the laser system is collimated with a 26 mm focal length aplanatic triplet lens which gives a beam diameter of ~8.5 mm. This beam is focused with a 500 mm AR coated singlet into a PPLN doubling crystal. The crystal is 40 mm long with a number of different poling periods, of which the periods with \( A = 27.25 \) and \( A = 27.5 \) \( \mu \text{m} \) are used at crystal temperatures of ~168 and 121°C respectively. The commercially available PPLN is AR coated (though coatings are imperfect as described later), with the individual periods taking the form of 500 \( \mu \text{m} \) square aperture channels. The Rayleigh range of the beam on the 500 mm lens is sufficient to allow the full length of the crystal to be used while keeping as large as possible of a spot on the crystal surface to avoid surface damage. During testing it is found that the performance of both PPLN periodicities are similar and the slightly better \( A = 27.5 \) \( \mu \text{m} \) period is used for the tests described.

For the purposes of the experiments discussed here, the laser is operated at a power of up to 2.2 W with a repetition rate of 60 kHz and pulse duration of ~45 ns, corresponding to maximum peak powers of ~900 W. Other laser pulse configurations have been tested, however the 60 kHz regime is found to be the best balance between laser stability and peak power. Before the actual full power doubling experiment is completed, the temperature tuning of the PPLN is investigated to determine the optimal operating temperature. This is achieved by using a low incident laser power to avoid saturation effects. The temperature is tuned from ~117°C to ~125°C using an oven to produce the curve seen in Figure 131.

![Figure 131: Tuning curve of PPLN and qualitative theoretical trend overlaying data](image_url)
The theoretical curve in Figure 131 is produced by using (96), substituting in the appropriate parameters for the crystal and the 1908 nm laser used as well as modifying (97) to be a function of temperature by writing \( \Lambda \), the poling period, as a function of temperature based on linear thermal expansion,

\[
\Lambda_{\text{actual}} = \Lambda (1 + \alpha (T - T_0))
\]  

(98)

where \( \alpha \) is the coefficient of thermal expansion and \( T \) is temperature. Plotting the resulting function with respect to temperature, with appropriate input parameters yields the theoretical plot above. The main caveat with this theoretical plot is that the actual room temperature poling period \( \Lambda \) is unknown, nor is the thermal expansion coefficient, so the values are selected to make the theory fit the data, however it is not clear whether the model assuming linear expansion of the periods with temperature or the thermal coefficient selected are in agreement with reality, so the plot should be viewed only as a guide showing that the trend of side lobes of higher conversion are realistic.

With the optimal temperature selected, and hence phase matching essentially perfect, the crystal is aligned to produce maximum SHG by monitoring the SHG signal as separated from the fundamental via a dichroic mirror (HR at 2 \( \mu \)m, \(~85\%\) transmissive at 955 nm). It should be noted that the data shown in the following plots is corrected for the imperfect mirror transmission.

Again, the SHG is conducted using the laser operating at up to 2.3 W with 45 ns pulses at 60 kHz, corresponding to maximum output peak powers of \(~900\) W. It should be noted that the theoretical comparisons shown in the next two figures are plotted in terms of average power, but
the actual equations used to make the theoretical curve are in terms of peak power, the repetition rate and pulse duration were used to make the conversion in the theory to enable average power to be plotted, however the real driving factor behind the conversion here is the pulsed, and hence high peak power nature of the laser.

The maximum achievable SHG power at ~954 nm is ~1.3 W with a maximum attained conversion efficiency of ~60%. Figure 132 is a plot of the SHG power versus the polarized laser power. The efficiency is based on polarized laser power, as the PER of the amplifier is relatively low and only a beam in the appropriate polarization orientation is useful. This value is determined by measurement through a polarizing beam splitter.

Figure 132: SHG output power versus polarized signal power and a comparison to an approximate theory based on (96), assuming perfect phase matching. Points are raw data and solid line is theory.

Figure 133 is determined using the same data, but is plotted in terms of conversion efficiency with respect to polarized fundamental power. It also contains a theoretical value.

Figure 133: SHG conversion efficiency versus polarized signal power and a comparison to an approximate theory based on (96), assuming perfect phase matching. Points are raw data and solid line is theory.
As is clear from the two above figures, the frequency conversion roughly follows the trends set out by theory. Growth of the SHG signal follows the theory quite well until higher powers are reached. The same is true of the conversion efficiency; roll off in efficiency begins to occur as might be predicted by theory due to depletion of the fundamental, but then continues faster in the experimental data than predicted. It is important to note that the theoretical plots in both Figure 132 and Figure 133 are only very approximate based on estimated values for the parameters in (96), assuming perfect phase matching. The theory assumes a constant beam waist in the nonlinear crystal (a value of 300 μm diameter is used), while the reality is that the beam is Gaussian and has a Rayleigh range, so the beam is 1.41 times smaller at the center of the crystal than at the ends. The 300 μm used is a middle ground number between the minimum waist diameter of ~150 μm and the ~500 μm diameter at the crystal facets, and is only approximate. More sophisticated modeling should be made for accurate predictions if desired, especially for the very long crystal used here. In addition, a number of the other parameters for the PPLN including \( d_{\text{eff}} \), and the refractive indices of the signal and harmonic are not known exactly. Estimated values of 27 pm/V for \( d_{\text{eff}} \) and 2.12 and 2.16 respectively were used for the refractive indices.

The large divergence between theory and experiment at fundamental powers over ~1.5 W pump can be explained by a number of potential causes. First, the SHG crystal is not perfectly AR coated, and thus, because there is no optical isolator, feedback to the amplifier and laser occurs and becomes stronger as power is increased; thus, ultimately limiting the maximum output power from the system to a value well below its ~6 W capability. In addition, as power increased it is noted that the generation of red and blue light is also seen, which are understood to
be third and fourth harmonics generated by additional nonlinear processes occurring in the long crystal. At high powers these effects may be stealing efficiency from the SHG process, and since the basic theory does not account for these processes the final results may be thrown off slightly. Despite the combination of potential error effects, the theory is in reasonable agreement with the actual experiment at least in terms of the general trends. There is clear SHG occurring with high efficiency, only limited by the lack of proper AR coatings and isolator in the system.

The pulsed output from the system in the second harmonic is ~32 ns in duration, which is the expected $\sqrt{2}$ decrease from the ~45 ns fundamental pulse duration [146]. There is no distortion seen in the pulses and they maintain the clean Gaussian shape that originates from the gain switched oscillator pulse shape. Examples of the pulses from the SHG and fundamental are seen in Figure 134.

![Figure 134: SHG and fundamental pulses showing the expected $\sqrt{2}$ decrease in duration from the fundamental to the SHG pulse](image)

Overall, as a proof of concept experiment, the system has proven useful in generating reasonable power levels of 9xx nm radiation, with reasonable high 60% efficiency. It is likely, as seen by the theoretical plots in Figure 132 and Figure 133, that efficiency could be pushed significantly higher with more stability to the system and based on (96) even higher than this with a further increase in pulse energy, as the intensity in the crystal is still below its damage threshold. Because of the broad tuning spectrum of thulium, which can be achieved well below
1900 nm, the ability to generate high brightness 9xx nm radiation can be readily achieved with appropriate system design. In addition, as already hinted at by the unintentional generation of red and blue, the potential use of frequency conversion techniques to achieve a vast number of other wavelengths in thulium can be readily achieved with appropriate system design and nonlinear materials.
7 SUMMARY AND CONCLUSIONS

Thulium fiber lasers are a rapidly rising laser medium of interest. In only a few years, achievable power levels and efficiencies have moved from hundreds of mW at less than 30% efficiency to near kW levels at upwards of 60% efficiencies. Development has occurred as a consequence of thulium’s potential for achieving high powers in a spectral region that is not accessible by many other laser media. The access to this spectral region enables systems which are capable of long distance propagation through the atmosphere at wavelengths which are safer with respect to potential human exposure. Coupled with the inherent compact size, high beam quality, high power handling and simple scalability, this eye safety and atmospheric propagation enables many future applications in remote sensing, communications, laser radar and directed energy. The unique spectral region of thulium also enables numerous medical applications, and other materials interaction applications. The closer proximity to the Mid IR and THz regime enable more efficiency frequency down conversion, while the frequency upconversion to NIR and visible wavelengths enables access to bands less accessible with high power levels. These, along with numerous other potential applications, are only made available with improved control over the spectral and temporal behavior of thulium fiber lasers while scaling power and energy.

Progress towards this control is the goal of this dissertation. Through the development of various spectral control techniques, including FBGs, GMRFs, VBGs, and diffraction gratings and investigation of the power scaling of such techniques via amplification and direct laser
oscillators, high power, spectrally agile thulium fiber laser systems have been constructed. These systems have been built with applications in mind and have been demonstrated capable of such applications. As part of this work, a simple model for the steady state operation of thulium fiber lasers has also been developed; this proves capable of predicting trends in fiber laser operation which enable optimization and investigation of future laser systems designs.

Scaling of powers with temporal control has also been demonstrated in both the ultrashort pulse and nanosecond pulse regime. In the nanosecond regime, power levels have been scaled to multiple watts with 100 µJ level energies and such pulses have been proven useful in frequency conversion applications achieving up to 60% efficiency. An understanding has been developed with respect to techniques for controlling the duration of nanosecond pulses in the thulium wavelength regime by selection of appropriate fiber lengths and pulse generation techniques to match the demands of the applications. The picosecond pulse regime has also been accessed at near watt levels for the first time from a direct thulium based oscillator and amplifier system. The system is the first stepping stone to high average power thulium fiber systems based on ultrashort pulses, which can further enable new applications.

The use of a novel technique for mode field diameter scaling via Gain Guiding Index Anti-guiding has also been discussed; the potential applications to the future of thulium fiber lasers is considered, as an enhancement to the already inherent benefits of thulium fiber’s spectral regime.

The future potentials of thulium are great. The inherent benefits stemming from the naturally longer wavelength give advantages not only for applications but for power scaling in general, due to the reduced potential for nonlinear effects and ability to increase core diameters with minimal impact on beam quality. With the appropriate attention given to fiber optimization
and design, future thulium laser systems with mode field diameters on the order of 70 μm based on completely conventional fiber are possible. Coupled with the inherent benefits on reduced nonlinear effects, this may enable thulium fibers to reach multi-mJ pulse energies and perhaps even 10’s of mJ, bringing them into a regime that makes them useful for many pulsed applications. The huge spectral bandwidth coupled with a variety of optimized pumping schemes including in-band pumping and optimal cross relaxation pumping will also enable single mode lasing in the multi-kW level from a single fiber aperture, and coupled with spectral or other beam combination techniques, thulium lasers open a pathway for 10’s to 100’s of kW level fiber based systems in the eye-safe regime without the need for specialized LMA fibers and with simple and robust packaging.

Overall, this dissertation has strived to advance the level of operation of high average power thulium fiber laser systems with spectral and temporal control. The results from experimental work prove that this is possible and that there are clear pathways to further scaling with conventional fiber laser technology. With the lessons learned from this work and concepts and suggestions made, the further advancement of high power pulsed and CW thulium lasers with spectral control will be realized in the near future. Thulium fiber laser technology will not only advance the field of and applications for 2 μm laser emission, but because of the inherent advantages of long operating wavelengths and efficiency pumping schemes, thulium based fiber lasers can drive the advancement of fiber laser technology as a whole.
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