Pulsed Tm-fiber Laser For Mid-ir Generation

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PULSED TM-FIBER LASER FOR MID-IR GENERATION

by

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ABSTRACT

The thulium fiber laser has gained interest due to its long emission wavelength, large bandwidth (~1.8 – 2.1 µm), high efficiencies (~60 %), and high output power levels both in cw as well as pulsed regimes. Applications like remote sensing, machining, medical tissue ablation, and mid-infrared generation benefit from high peak power thulium laser sources. Pulsed thulium fiber laser systems are advancing rapidly towards higher peak power levels and are becoming the preferred sources for these applications. This dissertation work describes the development of novel nanosecond pulsed thulium fiber laser systems with record high peak power levels targeting mid-infrared generation.

The peak power scaling in thulium fiber lasers requires new fiber designs with larger mode field area (MFA) than commercially available step index large mode area (SI-LMA) fibers. Two different prototypes of thulium doped photonic crystal fibers (PCF) were investigated for high peak power generation. The first prototype is a flexible-PCF with MFA twice as large as SI-LMA fiber and the second prototype is a PCF-rod with six times larger MFA. A robust single stage master oscillator power amplifier (MOPA) source based on flexible-PCF was developed. This source provided narrow linewidth, tunable wavelength, variable pulse duration, high peak power, and high energy nanosecond pulses. The PCF-rod was implemented as a second stage power amplifier. This system generated a record level of ~1 MW peak power output with 6.4 ns pulse-duration at 1 kHz repetition rate. This thulium doped PCF based MOPA system is a state of the art laser source providing high quality nanosecond pulses.
The single stage MOPA system was successfully implemented to pump a zinc germanium phosphide (ZGP) crystal in an optical parametric oscillator (OPO) cavity to generate 3 - 5 \( \mu \text{m} \) wavelengths. The MOPA source was also used to demonstrate backside machining in silicon wafer.

The PCF based laser system demonstrated an order of magnitude increase in the peak power achievable in nanosecond thulium doped fiber laser systems, and further scaling appears possible. The increase in peak power will enable additional capabilities for mid-infrared generation and associated applications.
To my Parents
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LIST OF ACRONYMS/ABBREVIATIONS

AOM – Acousto-Optic Modulator
ASE – Amplified Spontaneous Emission
CR – Cross Relaxation
DFG – Difference Frequency Generation
EOM – Electro-Optic Modulator
ESA – Excited State Absorption
ETU – Energy Transfer Upconversion
FWM – Four Wave Mixing
HR – High Reflectivity
LIBS – Laser Induced Breakdown Spectroscopy
SI-LMA – Step Index Large Mode Area
MFA – Mode Field Area
MFD – Mode Field Diameter
MFP – Mode Fractional Power
MI – Modulation Instability
MOPA – Master Oscillator Power Amplifier
MPI – Multi-Path Interference
OPG – Optical Parametric Generation
OPO – Optical Parametric Oscillator
OSA – Optical Spectrum Analyzer
PCF – Photonic Crystal Fiber
PER – Polarization Extinction Ratio
PM – Polarization Maintaining
PRF – Pulse Repetition Frequency
QPM – Quasi Phase Matching
RIFS – Raman Induced Frequency Shift
SBS – Stimulated Brillouin Scattering
SCG – Super-Continuum Generation
SF – Self Focusing
SFG – Sum Frequency Generation
SHG – Second Harmonic Generation
SI-LMA – Step-Index Large Mode Area
SPM – Self Phase Modulation
SRS – Stimulated Raman Scattering
SSFS – Soliton Self Frequency Shift
VBG – Volume Bragg Grating
WDM – Wavelength Division Multiplexer
YDFA – Ytterbium Doped Fiber Amplifier
TDFL – Thulium Doped Fiber based Laser
CHAPTER ONE: INTRODUCTION

1.1 Fiber Laser Properties

Fiber lasers have shown rapid advancements in the last two decades as a competitive source for high power generation, in cw and pulsed mode. Recent developments in high power/high brightness pump diode lasers and improvements in fiber-waveguide designs have led to the increased use of fiber lasers as high power sources.

Single transverse-mode beam quality: Due to the waveguiding property of the fiber, the transverse-mode output beam quality is determined strictly by the way the electro-magnetic field propagates in the fiber as opposed to other laser systems where the resonator design determines the transverse-mode behavior. Since the beam quality is determined by the design and fabrication of the fiber, robust single mode outputs are possible which are generally invariant of the power and thermal effects in the system.

Double clad for pumping: Double cladding in a fiber is one of the very important achievements that facilitated the growth of high power fiber lasers. The double clad pumping scheme in a fiber is shown in Figure 1. The inner cladding typically has high numerical aperture (NA) to accept the light from the single/multiple emitter diode pump. The outer cladding is generally a polymer material with a lower refractive index that facilitates pump confinement and also provides mechanical protection to the fiber. This geometry results in efficient pump absorption and effective brightness conversion.
Figure 1: Schematic of cladding pumping in a fiber structure. The refractive index structure can be seen towards right of the figure. The Inner cladding generally has higher NA to accept the high divergence of the diode pump.

**Thermal advantages:** Fused silica possesses a lower value of thermal conductivity (~1.3-1.4 W/mK) as compared to solid state laser crystals (for e.g. > 8 W/mK for YVO₄ [1]). However, the high surface area to volume ratio in fiber allows efficient removal of thermal load. The heat distribution along the entire length of the fiber allows most fiber laser types to be simply air-cooled. Solid state lasers exhibit thermal lensing and thermal birefringence effects which need to be considered and compensated for in the laser cavity. Due to the strong waveguiding of laser signal, fibers are generally free of such effects.

**Integrated system design:** The various components of the laser systems like pump combiners, Bragg gratings, isolators, mode field adaptors, polarizers etc. can be fiberized and connected together, thus eliminating the need for free space components. This contributes towards integrability of the fiber laser systems requiring minimal optical alignment.

All the above advantages have led to fast development and wide acceptance of fiber lasers. However, there are two major limitations of fiber lasers. The first limitation originates from the fact that fibers cannot store large amount of energies, hence they cannot match the pulse energies generated from solid state lasers. The second limitation is restricted peak power due to
buildup of nonlinear losses. These losses are a result of small core size and long interaction length in the fiber.

1.2 Historical Development of Fiber Lasers

The kW level fiber lasers available today have gone through several technological advancements and breakthroughs. The development of fiber lasers can be understood with the perspective of the initial flashlamp pumped systems followed by the core pumped systems, the advent of double clad fibers and the current large mode area fiber systems.

1.2.1 Flashlamp Pumping

The development of the fiber laser followed right after the demonstration of first laser by Maiman in 1960 [2]. Elias Snitzer, working at American Optical Company saw the potential of using a fiber waveguide structure as gain medium for ‘optical maser’ (as was then called) [3]. He demonstrated the first glass based laser in the same year (1961) using Nd$_2$O$_3$ doped barium crown glass [4]. The doped core with a refractive index of 1.54 was enclosed by soda-lime-silicate glass cladding with index of 1.52. The obtained NA of ~0.25 in combination with the 300 µm core diameter generated a highly multi-moded output. The fiber length was 7.5 cm. To improve the gain medium volume, helically coiled structure of ~1 m fiber was fabricated and implemented [5]. In spite of these engineering improvements, the fiber laser system design did not generate enough interest due to low powers and efficiencies.

Flashlamp pumping was the main reason for lack of development of fiber lasers in the early years. This pumping scheme was more beneficial to bulk solid state lasers and hence they
received majority of research and development. Fiber lasers needed more technological advances to create interest.

1.2.2 Core Pumping

The interest in fiber lasers was renewed with the potential seen in fibers for optical communication. Flashlamps could not be used for pumping these fiber lasers. The next option was direct core pumping of the fibers which enabled improved pump absorption. J. Stone et al. demonstrated the first fiber lasers using neodymium doped fused silica glass [6]. The output was multi-modal because of > 15 µm core sizes and high NA. Pulsed dye laser and argon-ion laser were used as pumps in different configurations. J. Stone et al. also suggested the use of semiconductor diodes and LEDs for pumping in the core pumping scheme. Later, they demonstrated the first GaAs injection laser pumped Nd:silica fiber lasers in 1974 [7]. This was the first scheme of diode laser pumped fiber laser and similar (and improved) schemes are being used even today.

The decade from 1975 – 1985 witnessed the development of high quality fibers, diode laser pumps, and optical components like wavelength multiplexer and couplers [8]. These technological improvements which were targeting the optical communication field have also benefitted fiber laser development. The improvements in fiber manufacturing technology enabled fabrication of high quality rare earth doped fibers [8]. As a result of these improvements (and the four level energy structure of Nd ion), R. Mears et al. were able to achieve less than 1 mW lasing threshold in Nd:silica fibers [9]. A 20 mW, 820 nm GaAlAs semiconductor diode
was used as a pump with 20% coupling efficiency. This result was significant in establishing the silica fiber as a promising host for laser systems.

The years after 1985 showed development towards manufacturing low loss fibers targeting the long distances required for telecommunications and low noise/high gain Erbium doped fiber amplifier (EDFA) systems [10-12]. The development of high efficiency, high power fiber lasers was not seen at the time but it benefited eventually due to advancements in fiber manufacturing [13]. However, the output powers were still limited by the pump beam quality and the obtained pump-coupling efficiencies, hence another technological breakthrough was required.

1.2.3 Double Clad Fiber - End Pumping

By the year 1988, semiconductor diode lasers were capable of generating < 1 W in single emitter array configuration and 100s of Watts in fiber coupled arrays of emitter bars [14]. However, the available diode pumps could not be efficiently coupled in the fiber core due to the extremely small overlap of single mode core (< 10µm) and diode beam spot size (typically 100s µm elliptical beam) [14].

The next breakthrough in technology was the introduction of double clad fiber with offset core by Snitzer et al. in 1988 [15]. In this configuration, since the pump could be launched in the inner cladding (and not the core), there were two significant advantages. 1) The multimode pump sources (with non-circular beams) could be focused with simple focusing optics, and 2) the pump traveled along the length of the fiber and was absorbed efficiently. This enabled 40% slope
efficiency with maximum of 45 mW output power which was an enormous improvement in fiber laser performance [15].

This advancement led to a rise of output powers from the diode pumped fiber laser systems. The output power reached Watt level in a couple of years [16], 5 W in 5 years [17] and reached ~110 W in 10 years [18]. However, the single mode fibers could only handle these power levels and damage and other nonlinear effects started to show up at higher powers [18]. The next step was to increase the core area.

### 1.2.4 Large Mode Area Fibers

The development of high energy Q-switched fiber lasers was one of the driving forces behind the requirement for increase in the modal area of the fiber. The pulse energy obtained from single mode fiber was less than 100 µJ [19]. The next requirement going forward was increase in the core area. Increased core areas could store higher amounts of energy and also resulted in higher limits for onset of optical damage and nonlinear loss mechanisms. The solution came in the form of large mode area step index fiber [20]. This fiber design enabled mJ pulse energies with > 10 kW peak powers [19, 21]. These fiber designs typically have core diameter of 20 µm and higher, with the minimum NA of ~0.06 which makes them slightly multi-moded. However, single-mode beam quality is obtained by bending the fiber so that the higher order modes experience losses [20]. These fibers became the prime choice for high power/energy generation. In addition to the large mode area and good beam quality, they were also very compact. This is because for single mode operation, the bend diameter is typically less than 20 cm.
Another large mode area fiber which has been an important device for high energy/peak power pulse generation is photonic crystal fiber (PCF). The PCF can be designed to support core sizes in excess of 100 µm. In a short span of 2 years after the first demonstration of Yb:PCF laser in 2000 [22], Teodoro et al. generated ~4.5 MW peak power with sub-ns pulses in PCF. The core diameter of the PCF was ~140 µm and it generated multi-moded output [23]. Teodoro generated similar 4.5 MW pulses in 2007 [24] with single-mode beam quality due to improvements in fiber design. The trend of development of nanosecond pulsed Yb:fiber lasers is shown in Figure 2. The significant role played by PCF in reaching MW peak powers can be seen. The highest pulse energy generated in Yb:PCF was shown by Stutzi et al. in 2012 [25]. They extracted 26 mJ pulses from ~135 µm core diameter large pitch photonic crystal fiber (LPF). The PCF and LPF fiber designs have the largest mode field area currently available.

![Graph showing development of nanosecond regime peak powers in Yb:fiber laser systems. The highest peak power is ~4.5 MW and the highest pulse energy is 26 mJ [19, 21, 23-28].](image-url)

Figure 2: Development of nanosecond regime peak powers in Yb:fiber laser systems. The highest peak power is ~4.5 MW and the highest pulse energy is 26 mJ [19, 21, 23-28].
Yb:fiber laser technology has reached performance levels where it can be used for applications previously restricted to solid-state and gas lasers [29]. One of the main reasons is the well-established 910 – 980 nm diode laser pumps [30]. The highest power generated in Yb:fiber laser system is >10 kW in tandem pumping schematic where 1018 nm pump wavelength emitted around 1070 nm [29]. Eye safe wavelengths (i.e. $\lambda >1.3 \ \mu m$) are preferred for applications in communications, sensing and mid-IR generation via nonlinear conversions. For high power generation, efficient cladding pumped erbium fiber lasers (emitting around 1.55 $\mu m$), erbium fibers need to be sensitized with ytterbium [31] so that pumps in $\sim$910 – 980 nm band can be used [32]. However, slope efficiencies achieved in Er,Yb co-doped fiber lasers are still about 40 – 45 % [33]. The maximum output power is limited due to parasitic emission/lasing at ytterbium wavelength of $\sim$1 $\mu m$ [33]. The maximum cw output power obtained in Er,Yb co-doped fiber laser is $\sim$300 W [34]. In light of the above mentioned requirements and the limitation of efficient pumping in erbium fibers, thulium has the focus for high power developments at eye safe wavelength. Thulium doped fiber laser (TDFL) development is the focus of this thesis.

1.3 Historical Development of the Thulium Fiber Laser

The first thulium fiber laser and the first ytterbium fiber laser were demonstrated at the same time, but ytterbium became the laser element of choice because of following reasons; simple energy level structure, low quantum defect, easy availability of optical components (because of overlap with Nd:YAG wavelength) and high power diode pump laser available. However, application of thulium wavelengths for communications (initial period), medical, remote sensing, LIDAR and spectroscopy [35] were the motivation towards their development.
Hanna et al. demonstrated the first TDFL in 1988 [36]. In this experiment, a 70 mW dye laser operating near 800 nm wavelength was used to pump 27 cm long Tm:fiber and 2.7 mW of cw output was generated. The 1.96 µm output wavelength was the longest wavelength generated in silica fiber at that time. The same group showed tunability in Tm:fiber across 1780 – 2056 nm wavelength range and an improved slope efficiency of 36 % in 1990 [37]. They had used a similar dye laser based pumping scheme but replaced the highly reflective output mirror by a 20 % reflective mirror. In another experiment, Watt level power was achieved by increasing the pump power. The dye-laser pump was replaced by a 10 W Nd:YAG laser [16]. Thus, Hanna et al. showed a quick development of TDFLs employing different pumping schemes, demonstrating the tunability and Watt level output power in a span of just two years after the first TDFL in the year 1988.

After the initial demonstration of Watt output-level at 2 µm wavelength, TDFL development started targeting wavelengths corresponding to S communication wavelength band (1.46 – 1.53 µm) [38] and blue upconversion band (~0.48 µm) [39]. This work saw a shift from the 2 µm development in Tm:fibers and will not be considered in the scope of this thesis.

The next step towards high power TDFL development was seen in 1998, supported by two main technological developments. The first is the implementation of cladding pumped double clad fiber [40] and second, the development of high power multimode laser diodes [30, 33]. Stuart Jackson et al. implemented cladding pumping with sixteen 2-W diode lasers at 790 nm in a Tm:fiber with 300 µm x 110 µm rectangular cladding in 1998 [35]. This system generated 5.4 W output power with 31 % slope efficiency. The diode laser pump was evolving,
but the limiting characteristic in TDFL was identified as the 30 – 35 % slope efficiency. The efficiency for 790 nm pumped TDFL is limited to the Stokes limit of 40 %. The much desired improvement in slope efficiency was seen in 2000 by Hayward et al. surpassing the Stokes limit and demonstrating 46 % slope efficiency with 12 W output power [41]. The reason behind this improvement was the ‘two for one’ cross relaxation (CR) process where one pump photon effectively generates two signal photons (will be covered in greater detail in section 2.1.3). Jackson et al. performed significant work to improve the CR process with increasing the thulium concentration [42-44]. Improvements based on the above investigations in combination with the increase in diode power helped rapid growth in TDFL power. The optimum Tm:fiber composition enabled Jackson et al. to achieve efficiency of 74 % [42]. These techniques are since being used to achieve high slope efficiencies in thulium lasers. Figure 3(a) shows slope efficiencies in cw operation of TDFL systems. Slopes in the range of ~60 % are being consistently achieved after the year 2003.

Figure 3: a) Slope efficiencies and the corresponding b) CW Powers achieved in TDFLs. The highest power is demonstrated by Q-peak of ~1 kW in 2009 [35, 42, 45-54].
This improvement in slope efficiencies propelled the high power laser development in Tm:fibers. Figure 3(b) shows the historical development of the cw power levels. The highest power level seen is 1 kW by Ehrenreich et al. (Q-peak Inc.) [46]. This was shown in a monolithic system comprising of 12 m of 20/400 µm Tm:SI-LMA fiber with a slope efficiency of 53 %. Even at the kW level performance with the improved slope, thulium lagged behind ytterbium fiber lasers which were reaching >10 kW power levels.

The inherent advantage of longer wavelengths is the larger mode field diameter possible in LMA fibers and increase in the nonlinearity/damage thresholds (will be covered in section 2.3). Hence, higher peak power can theoretically be generated in Tm:fibers as compared to Yb:fibers with similar configurations. Figure 4 shows the development of high peak power nanosecond pulses with thulium fiber systems. After the first demonstration of Q-switching in TDFL in 1993 by Myslinski [55], the pulsed development resumed only after the better efficiencies had facilitated high power in thulium fibers.
Following the Yb:fiber development, PCF fiber design has been implemented for the first time with thulium-doping. Using the PCF structure, MW level peak powers have been achieved in sub-10 ns pulses [59] as part of this thesis work. The performance shown is approaching Yb levels [24]. A variation of PCF, large pitch fiber (LPF) design has already been implemented with thulium-doping generating >150 kW pulses [65]. However, the limitations at 2 µm wavelengths have not been reached. This continual improvement towards high peak power development in Tm:fibers is part of an ongoing effort in Laser Plasma Laboratory in the Townes Laser Institute, College of Optics & Photonics at University of Central Florida, USA.
1.4 Target Applications for High Peak Power Thulium-Systems

TDFLs have gained interest due to long emission wavelength, large bandwidth (~1.8 – 2.1 µm), high efficiencies (~60 %), and high output power levels both in cw as well as pulsed. The thulium emission bandwidth includes water and carbon dioxide absorption bands, in addition to being one of longest lasing wavelength in silica fibers. Applications like remote sensing, machining, medical tissue ablation, and mid-infrared generation benefit from high peak power thulium laser sources.

1.4.1 Mid-IR Frequency Conversion

The mid-IR spectral region (generally considered to cover 4000 – 400 cm\(^{-1}\) corresponding to 2.5 – 25 µm) is important for medical, defense and remote sensing applications. The solid state mid-IR sources can be divided into direct and indirect laser sources. The direct sources consist of inter-band and intra-band diode lasers, transition metal lasers, quantum cascade lasers (QCLs), inter-band cascade lasers (ICLs), optically pumped semiconductor lasers (OPSL) and soft glass based fiber lasers [69-71]. Indirect sources consist of nonlinear frequency conversion like optical parametric generation (OPG), optical parametric oscillator (OPO), difference frequency generation (DFG) and supercontinuum generation (SCG) [72-74].

For the scope of this thesis, the focus is on generation of mid-IR using OPO configurations. The two particularly important crystals used for nonlinear conversion to mid-IR extending beyond 5 µm are Zinc Germanium Phosphide (ZGP) and Gallium Arsenide (GaAs) (will be discussed in greater detail in section 5.2.5). These crystals exhibit high effective nonlinear coefficient and high damage threshold [75]. The crystals exhibit significant linear and
two photon absorption at wavelengths less than 1.9 µm [75] prohibiting direct pumping by conventional Neodymium/Ytterbium systems. The pumping scheme used over the past decades for mid-IR (>5 µm) OPOs was a two-step process. 1) The established Nd:systems was used to pump a nonlinear crystal, like periodically poled Lithium Niobate (PPLN), to generate wavelengths ranging from 2 to 5 µm and 2) using this output to pump ZGP or orientation patterned GaAs (OP-GaAs) for mid-IR generation [76-78].

There are two rare earth elements with efficient laser emissions >1.9 µm: thulium and holmium. In recent years, holmium-doped, solid-state, laser systems have been developed for pumping ZGP/OP-GaAs crystals. Holmium laser systems have two benefits, 1) they can be resonant-pumped with the established cw TDFLs and 2) the output wavelengths of >2.05 µm are in the low loss wavelength band for ZGP/OP-GaAs. These holmium laser systems display a quasi-three level laser transition. Because of this energy structure, at elevated temperatures very high excited state densities are required to achieve significant gain. The increased densities lead to increased up-conversion processes (\(^5I_7 - ^5I_5\) transition) because of long lifetime of \(^5I_7\) level (~14 ms) [79]. This combination of long lifetime and limited excited state densities is best suited for the generation of high pulse energies but at relatively low pulse repetition rates (<1 kHz) [80].

In comparison to holmium solid state lasers, nanosecond TDFLs offer several potential advantages in generating pulses with moderate to high pulse energy and high pulse repetition rates (>10 kHz). There has been rapid developments in cw, nanosecond and femtosecond TDFLs [63, 64, 81] in recent years. With the improvements in TDFLs, especially in high peak power
generation, these sources are emerging as a viable source for pumping ZGP and OP-GaAs crystals [82]. A major part of the thesis work is dedicated to this development leading to the realization of a relatively simple, flexible, and high power mid-IR source driven by high peak power Tm system.

1.4.2 Remote Sensing

The thulium wavelength band from 1.8 to 2.1 µm encompasses absorption resonances of water vapor and carbon dioxide gas [83]. Light detection and ranging (LIDAR) is a sensing technique which can be tuned across resonances of molecules providing sensing and ranging information. Coherent Doppler LIDAR is able to measure the horizontal and vertical velocities of wind. Single-frequency, 2 µm, Q-switched laser systems have been verified as a source for these applications [84]. A modification of LIDAR, the differential absorption LIDAR (DIAL), uses precisely wavelength-controlled two laser pulses overlapping with ‘on’ and ‘off’ resonance features to determine the range as well as concentration of trace gases. Efforts at NASA Langley Research Center using 2 µm DIAL for CO$_2$ sensing have been ongoing [85, 86]. They use Ho:Tm:LuLiF oscillator based source with high energy level (~100 mJ) and transform limited pulses [86]. These levels are currently not obtainable from TDFL systems. However, with the advancements in TDFLs, it seems feasible to replace the solid-state source with the inherent advantages of good efficiency and excellent beam quality of a thulium fiber system which could improve the overall performance of LIDAR/DIAL measurements.
1.4.3 Medical Applications

Thulium lasers cover the water absorption wavelength band in the range 1.91 - 1.94 µm. Since water is the primary constituent of a tissue, these absorption peaks are closely associated with tissue absorption features. Tissue resonance wavelengths combined with excellent beam quality and high average/peak power available in TDFLs make it an excellent source for tissue ablation/cutting [87, 88]. One of the specific applications is lithotripsy, which is the procedure of fragmentation of urinary stones. The 2 µm source used for this application historically has been Ho:YAG laser [89, 90]. There are certain limitations associated with these systems like beam delivery, multimode beam profile, low repetition rate operation and overall inefficient system [91, 92]. TDFLs show all-fiber architecture combined with excellent beam quality, high average powers/repetition rate, and good efficiency with controlled non-used radiation (cladding light). These benefits have led to recent shift from holmium lasers to TDFLs as a lithotripter source [91, 92].

In addition to the 1.94 µm band, water (and hence tissues) show strong absorption features near 3 and 6.5 µm wavelengths [93]. Experimental analysis of ocular and neural tissue ablation, comparing the output of free electron laser (FEL) with mid-IR OPO has been performed [94]. These experiments suggest the importance and requirement of comparatively compact and rugged OPO systems. TDFLs now capable of generating high pulse energies are potential pumps for high power/energy mid-IR OPOs.

Future medical applications targeting direct resonances of the tissues and cells require precise spectral control of the laser systems. High power, narrow linewidth and tunable TDFLs with compact and robust structure can be a potential source for medical applications.
1.4.4 Other Novel Applications

As seen earlier, thulium fiber systems are not competing currently with ytterbium fiber laser sources in high average power/brightness dependent applications such as machining. The advantage of the thulium wavelength band can be utilized in combination with high achievable power for novel machining applications where the operational wavelength has an important role. Several polymers display higher absorption coefficient at 2 µm wavelength as compared to 1 µm. In the scope of this dissertation, TDFL has been used to investigate welding between similar and dissimilar polymers [95]. It can enable low power, compact and rugged polymer machining. A similar unique application has been tested for Silicon which is transparent at 2 µm which opens up the possibility of backside machining of the Silicon wafers. Initial experiments have been reported [96]. This selective backside machining without damaging the front surface can open up new processing techniques, especially catering to solar cell and microelectronics industries.

1.5 Structure of Thesis

The thesis covers the development associated with TDFLs and specific, non-conventional applications. The thesis is structured in six chapters, where the first chapter introduces the topic.

Chapter two describes the required background and discusses the spectroscopic properties of thulium fibers. Current thulium fiber and new PCF design are analyzed, providing a picture of their performance in terms of waveguiding and modal behavior. The limitations in a fiber comprising of nonlinear losses and optical and thermal damage are covered.
Chapter three presents cw laser system designs based on oscillator and amplifier configurations involving different fibers. It compares the SI-LMA and PCF fibers targeting greater than 10 W of output power. It forms the foundation of laser performance targeting high average and peak power generation.

Chapter four provides the background and experiments leading to high peak power performance in different fiber designs. It shows the performance of flexible-PCF based amplifier scaling peak power to ~100 kW. It further demonstrates the implementation of power amplifier based on PCF-rod to achieve MW peak power nanosecond pulses. Novel applications with high peak power 2 µm sources like laser induced breakdown spectroscopy (LIBS), and Silicon backside machining are examined. These applications have been tried for the first time.

Mid-IR generation using nonlinear conversion process is examined in Chapter five using the source developed in Chapter four. Supercontinuum generation and mid-IR generation using ZGP-OPO are presented.

Chapter six summarizes the dissertation and gives future paths to explore the potential of thulium fiber technology.
CHAPTER TWO: FIBER LASER TECHNOLOGY

The development of TDFLs has seen a rapid rise after the year 2003 (Figure 3). This has been possible due to the optimization of fiber composition to avail “two-for-one” cross relaxation process. This process has taken the slope efficiency beyond the 40 % Stokes limit. This current chapter will go through the ionic properties of thulium which facilitate this cross relaxation process.

Scaling towards high peak powers require development of large mode area fibers. These fibers are not robustly single moded and hence a comprehensive study of their modal performance is essential. Also, the nonlinear processes like SPM, SRS, SBS, etc. restrict the maximum peak power extractable from a fiber. Scaling peak power requires a constant watch on the start of these harmful effects. In addition, thermal and optical damage will be considered in this chapter.

2.1 Thulium as a Dopant

Thulium doping supports a large bandwidth (~1.8-2.1 µm) as compared to other rare earth dopants in silica fibers. For efficient TDFL systems, it is important to consider the pumping schemes and other thulium spectroscopic properties. It is especially important to understand the pumping at 790 nm of thulium and the inter-ionic energy transfer phenomena which give high efficiency in TDFLs.
2.1.1 Spectroscopic Properties

For an easier understanding of thulium laser wavelengths, only the lower four energy levels i.e. $^3\text{H}_4$, $^3\text{H}_5$, $^3\text{F}_4$, and $^3\text{H}_6$ are considered. Glass hosts typically show the characteristic feature of broad, continuous range of emission/absorption wavelengths for a given energy level. This has the effect of reduced cross sections as compared to crystalline hosts [97]. The broadening mechanism in thulium is mainly given by inhomogeneous broadening. In this broadening process, each ion exhibits a distinctive spectroscopic signature since each ion experiences unique surrounding field parameters [43, 97]. The combinations of different ions with slightly varying energy levels display overall effect of broadband wavelength transitions resulting in broad absorption/emission bands. The thulium energy levels are shown in Figure 5. The stark splitting in the energy levels is shown as a group of slightly off-energy lines; although in lasing applications, it manifests into a continuum-like band.
Figure 5: Thulium energy level diagram showing the lowest four energy levels. The various pumping bands and lasing band is shown. The energy transfer processes between two adjacent Tm$^{3+}$ ions i.e. cross relaxation (CR) and energy transfer upconversion (ETU) is shown based on [43].

The lasing transition occurs between the $^3F_4$ energy level and $^3H_6$ ground level giving a 1.8-2.1 µm lasing band. However, an ultra-wideband amplified spontaneous emission (ASE) ranging from ~1.6-2.1 µm has been seen in PCF-rod [98]. This effect is possibly the result of smaller absorption cross sections and shorter fiber lengths. Similar wide band emission property has also been seen in [43]. Thulium is a three level laser system where the bottom lasing level is the ground state. However for wavelengths beyond ~2025 nm, the transition occurs at the higher energy levels in the $^3H_6$ band which then behaves like a quasi-four level laser system since these sub-levels are typically not thermally populated [99].

One of the important parameters for lasing is the upper level lifetime. The upper level radiative lifetime for thulium ($^3F_4$) is about 6.3 ms [43]. There is another important practical effect that places a limitation on this life time. The phonon energies corresponding to 1050-1100
cm\(^{-1}\) (0.13-0.136 eV) are sustained in silica [43]. The narrow bandgap of \(^3\)F\(_4\) – \(^3\)H\(_6\) transition of \(~\)4900 cm\(^{-1}\)(\(~\)0.6 eV) facilitates multiphonon emission which is a non-radiative energy transfer process [43] leading to material heating. This multiphonon emission reduces the upper level lifetimes to \(~0.2\)-0.6 ms [43, 100]. It is an important parameter for pulsed operation as for repetition rates <2 kHz (corresponding to \(~500\) µs lifetime), the population-inversion built-up between two pulses is reduced since the excited upper level ions can decay non-radiatively. Decreased gain and extraction efficiency are the consequence of the lower repetition rates.

### 2.1.2 Pump Considerations

Optimum optical pumping of a laser system at a certain wavelength is determined based on the pump sources with high power efficiency and commercial availability. Another important consideration is the selection of appropriate pumping band in thulium.

The red arrows in Figure 5 show the potential pump photon energy (i.e. wavelength) for three higher energy bands \(^3\)F\(_4\), \(^3\)H\(_5\), and \(^3\)H\(_4\). The \(^3\)H\(_5\) level pumping requires pumps at \(~1.2\) µm where mature pump technology is currently not available in addition to inefficient lasing. The \(~1.5\) - \(~1.8\) µm pumping, which is ‘in-band’ with the lasing, produces efficient lasing due to the small quantum defect. Quantum defect (QD) is defined as the theoretical loss associated with quantum conversion from one pump photon to one signal photon and is given as

\[
QD = 1 - \frac{\lambda_{\text{pump}}}{\lambda_{\text{signal}}}. \tag{1}
\]

For example pumping with 1.56 µm and lasing at 1.95 µm shows a QD of 20 %. The commonly available Er:Yb laser operating in the wavelength range 1.55 - 1.57 µm is the preferable pump
for high efficiency. However, high power, high brightness diode laser pumps are not available readily at these wavelengths. The Er:Yb laser systems are pumped by 976 nm pump diodes and operate with ~40 % slope efficiencies. This cascaded system is inefficient and is not preferred for high power operation. However, 1.55 µm systems are ideal pumps for core pumping TDFLs. Core pumping gives high pump absorption (resulting in high gain) per unit length and is used for single frequency [101], mode locked [102] as well as Q-switched performance [60] based on short cavity lengths.

Figure 6: The absorption and emission cross section to thulium doped silica fiber [103]

The pump most widely used is 790 nm corresponding to \(^3\)H\(_6\) to \(^3\)H\(_4\) transition. This pump wavelength benefits from the largest absorption cross section (Figure 6). Although the quantum defect is ~60 %, this pumping scheme benefits from matured AlGaAs based diode pumps commonly used for Nd pumping (808 nm). Currently, 500 W fiber coupled cw laser diodes are
available for 793 nm pumping (DILAS GmbH) with wall plug efficiencies exceeding 40 % [104].

**Cross relaxation (CR)**

CR is an inter-ionic energy transfer process where an ion in the excited state transfers part of its energy to a surrounding ion. This is a non-radiative process which is dependent on the proximity of the dopant ions. The process is proportional to \( \sim R^{-6} \) where \( R \) is the interionic distance. [43]. As can be seen in the thulium’s energy diagram (Figure 5), energy transfer occurs between adjacent ions where one pump photon at \( ^3\text{H}_4 \) level can excite two ions at \( ^3\text{F}_4 \) energy level. The interionic distance can be decreased by increasing the thulium ion \((\text{Tm}^{+3})\) concentration. For example, for an increase in \( \text{Tm}^{3+} \) concentration from 1 to 4 wt. %, the CR probability improves \( \sim 15 \) times [43]. Slope efficiencies greater than the Stokes limit (\( \sim 40 \% \) efficiency limited by the quantum defect) are observed for concentrations larger than 1.2 wt. % of \( \text{Tm}^{+3} \) in silica fibers [42]. In general, doping concentrations of 2 - 5 wt. % of thulium are required for the CR process to influence the slope efficiency.

**Energy Transfer Upconversion (ETU)**

ETU is another inter-ionic energy transfer process which manifests as opposite of CR process. As shown in Figure 5, this process takes place between two excited state ions. Dipole-dipole energy transfer occurs from the excited \( ^3\text{F}_4 \) energy level of one ion to adjacent excited ion (in \( ^3\text{F}_4 \) energy level) and then to either \( ^3\text{H}_5 \) level (ETU1) or \( ^3\text{H}_4 \) level (ETU2) [42]. This process
leads to lifetime quenching effect (decrease of upper level decay time) in the host which leads to lower lasing efficiencies [43].

2.1.3 Obtaining Efficiencies beyond the Stokes Limit

The CR process requires high doping percentage of thulium (typically beyond 2 - 3 wt. %). However, silica has limited solubility of rare earths leading to microscopic clustering effects with increase in doping concentration [42, 97]. These clusters contain closely associated thulium ions. This leads to $^3F_4$ energy level lifetime quenching due to ETU process which in effect degrades the performance levels. The concentration of Tm$^{+3}$ ions needs to be increased considering the onset of clustering for efficient operation of TDFLs [43]. The technique generally employed is increasing the solubility of Tm$_2$O$_3$ in silica (SiO$_2$) by adding Al$_2$O$_3$. Jackson et al. have presented an extensive study on the dependence of thulium doped silica fiber laser performance on thulium concentration and Al$^{+3}$/Tm$^{+3}$ ratio [42-44]. The authors have found that for thulium concentrations of ~1.3 wt. %, the efficiency scales with Al$^{+3}$/Tm$^{+3}$ ratios (from 5:1 to 10:1). Beyond the ratio of 10:1, the efficiency increases with increased Tm$^{+3}$ concentrations. The highest efficiency which has been obtained is ~75 % with Tm$^{+3}$ concentration of 2.2 wt. % and Al$^{+3}$/Tm$^{+3}$ ratio of 8:1 [42].

Commercially available Tm:SI-LMA fibers (Nufern) typically have a Tm$^{+3}$ concentration of ~4 wt. % and Al$^{+3}$/Tm$^{+3}$ ratio of 10:1 [105]. Efficiencies > 60 % [51] are generally achieved in lasers based on these fibers. NKT Photonics A/S provided us with two different Tm:PCF fiber designs. These two PCFs have Al$^{+3}$/Tm$^{+3}$ ratio of 8:1 and thulium concentrations of 2.5 and 3.6 wt. %. In spite of the high doping concentrations, the slope efficiencies obtained were <40 %
Concluding, more work is required for the optimization of glass composition for these fibers.

### 2.2 Fiber Designs

Before the concepts of fiber designs are considered, it is important to discuss fibers as waveguides. A step index fiber is a cylindrical light waveguide which guides the light on the principles of total internal reflection (TIR). It is achieved when the refractive index of the core (where the light is guided) is higher than the refractive index of the cladding. One of the important factors which governs the fiber waveguiding property is numerical aperture (NA) which depends on the refractive indices of the fiber core and cladding

\[
NA = \sin(\theta_{\text{out}}) = \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2}.
\]  

Here the angle $\theta_{\text{out}}$ is the maximum angle (i.e. acceptance angle) of the light which would be guided in the fiber, and $n_{\text{core}}$ and $n_{\text{cladding}}$ are the refractive indices of core and cladding respectively. The guided modes in a fiber can be understood by a thorough analysis of electromagnetic field in a circular geometry [107]. A detailed discussion of this analysis is available in Reference [107].

However, there are certain terms and concepts which need to be familiarized to understand the working and limitations in the fibers. The first is the normalized frequency (also called as fiber number or V-parameter).

\[
V = \frac{2\pi r}{\lambda} NA
\]  

26
Here, \( r \) is the core radius and \( \lambda \) is the signal wavelength. The \( V \) number is an important indicator of the number of supported modes in a given fiber. For the guidance of only the fundamental mode, this \( V \) number needs to be \( < 2.405 \). The fundamental guided mode is essentially a Bessel field distribution which can be approximated with a Gaussian field. The mode field diameter (MFD) (effective diameter) of this guided mode is given by,

\[
MFD \approx 2r \left( 0.65 + \frac{1.619}{V^2} + \frac{2.789}{V^6} \right)
\]  

(4)

This applies in the fundamental/single mode regime (i.e. \( V < 2.405 \)). The guided mode propagates with MFD as given above.

Another important parameter is M-square parameter used to characterize the beam exiting from a fiber. It is measured by comparing the beam divergence to a perfect Gaussian beam profile and defining the similarity in terms of M-squared number. A focusing lens is placed in the beam path to generate a secondary beam waist which is measured at varying distances and plotted using [108]

\[
W_{x,y}^2(z) = W_{0,x,y}^2 + M_{x,y}^4 \left( \frac{\lambda}{\pi W_{0,x,y}} \right)^2 (z - z_{0,x,y})^2.
\]  

(5)

In the above equation, \( W_{0,x,y} \) is the beam waist in \( x, y \) direction, \( z \) is the distance at which the beam size is measured, \( z_{0,x,y} \) is the location of the focusing lens and \( \lambda \) is the wavelength of the signal. The \( M \) is fitted in the data to approximate its value. In all measurements supporting this thesis, the M-squared measurements have been performed with a knife edge 90/10 measurement technique using beam profiler (Pyrocam III; Ophir Spiricon, LLC).
The nonlinear and thermal effects affecting the performance of the fiber systems are discussed in section 2.3. The largest contributor in reaching high power levels in fiber systems is mode diameter (MFD) scaling. Different fiber designs support increased mode diameter while maintaining single mode beam quality.

2.2.1 Step-Index Large Mode Area (SI-LMA) Fiber

In a standard step index fiber design, the diameter of the core is kept < 10 µm to provide perfectly single mode operation. But the core diameter scaling to large mode area fibers is essential for high power operation. Large core sizes not only have the advantage of high thresholds for deleterious effects, but also lead to higher gain and extractable energy because of the larger doped volume. However, this increase in core diameter is generally accompanied with decrease in the NA of the fiber in an attempt to compensate the V number. In spite of this adjustment, the large mode area fibers generally guide more than 2-3 modes. Special considerations are required for ‘handling’ of these higher order modes to obtain single mode beam quality.

Fiber Design

Traditionally, the SI-LMA design has targeted at maintaining low NA to achieve large core diameters. The high power designs employ higher rare earth doping concentrations to use shorter amplifier length increasing nonlinear process thresholds. The SI-LMA design was first implemented in ytterbium doped fiber. Ytterbium can be doped at higher concentrations in silica fibers without adding co-dopants which modify the glass matrix. The lowest NAs which have
been consistently maintained in these fibers are around 0.06 [109]. These fibers support multiple modes; thus additional techniques need to be implemented to obtain single-mode output. A common technique is single-mode seeding [110] where only the fundamental mode is excited. But the most commonly used technique is filtering the higher modes by bending the fiber [111].

Erbium and thulium doped SI-LMA fibers require additional considerations. Erbium doped fibers specifically require sensitization of the glass host by adding co-dopant like ytterbium for improved efficiency. Thulium-doped fiber sources require specific consideration for the 790 nm pumping case since it involves the CR process. Section 2.1.3 shows that higher efficiencies in thulium doped fibers require the CR process where two signal photons are generated for single pump photon. This is an ‘inter-ionic’ energy transfer phenomenon, benefits from higher concentration of Tm$^{+3}$ ions in the glass. The energy transfer up-conversion (ETU) process needs to be kept in check to avoid quenching of the lasing energy level ($^3F_4$ level) [97, 112]. Co-doping with a high concentration of Al$^{+3}$ ions helps to curb ETU by avoiding clustering of Tm$^{+3}$ ions. The aluminum has the effect of increasing the refractive index in the core. This effect increases the obtained NAs. To lower the NA, second cladding region around the core is fabricated which is doped with a specific dopant (germanium) to raise the refractive index. This region is called pedestal and is engineered such that the NA (which is now defined for core and the pedestal) lies in the ~0.1 range.
The Tm:SI-LMA fibers used in this thesis are from Nufern and employ the pedestal SI-LMA design. The NA obtained is about 0.09 for the non-PM SI-LMA fiber and ~0.10 for the PM SI-LMA fiber. The fibers are fabricated with thulium concentration of ~4 wt. %. The concentration ratio of Tm$^{+3}$:Al$^{+3}$ ions is maintained at 1:10 [112]. These fibers give high lasing efficiencies and have been used extensively for high power/energy amplifier operations [51, 67].

**Modal Features/S$^2$ Analysis**

The NA commonly achieved in the above mentioned Tm:SI-LMA fiber is about 0.09 - 0.10. Even at these small NAs, the fiber supports multiple modes. The number of modes guided can be directly found by the evaluation of the V number. The V number obtained for this fiber is 3.95 (assuming refractive indices for core and cladding as 1.4500 and 1.4465 respectively). As a consequence, this fiber guides LP01, LP11, LP21 and LP02 modes.
The technique often employed in SI-LMA fibers to suppress higher order modes and improve the beam quality is by bending the fiber. Bending induces higher losses for the higher order modes. The bend dependent losses for the different fiber modes is given by Marcuse [114]

\[
2\alpha = \frac{\sqrt{\pi} \kappa^2 \exp\left[-\frac{2}{3} \frac{\gamma^3 R}{\beta_g^2}\right]}{e_v \gamma^2 \nu^2 \sqrt{R} K_{\nu-1}(\nu a) K_{\nu+1}(\nu a)}.
\]

Here, \(2\alpha\) is the fractional loss of signal; \(\kappa\) and \(\gamma\) are the longitudinal field components, \(\beta_g\) is the propagation constant for a given mode, \(R\) is the radius of curvature of the fiber, \(\nu\) is the order of the Bessel function, \(e_v\) is 2 for \(\nu=0\) and 1 for \(\nu>0\), \(a\) is the fiber core radius and \(K\) is the Bessel function. The value of the Bessel function reduces for higher order modes which increases the fractional loss coefficient. As a result, higher bend losses are experienced for the higher order modes.

Digressing slightly from the bend loss, practical techniques for beam quality measurement and their limitations need to be considered. A widely used parameter to quantify the beam quality is the M-square parameter as given by A. Siegman [115]. M-square value close to 1 corresponds to a single mode beam quality. However, higher order modes can be present for low value of M-square [116]. Nicholson et al. proposed a new technique by which all the guided modes, their types and relative power content can be quantified in a fiber [117]. This technique is based on the primary idea that different modes propagating in a fiber will generate characteristic spectral and spatial interference patterns for a broadband source.

The investigation of the different modes in a fiber using the above mentioned method is performed in the following way. A broadband light is launched in the input end of the multimode
fiber which is to be investigated. The output of this fiber is imaged (magnified) in a plane which is then raster-scanned using a SMF coupled to an optical spectrum analyzer (OSA). The optical spectrum is recorded at each of the spatial point. Whenever two different modes overlap spatially, the Fourier transform of spectrum shows different beat modes. This is a result of the spectral interference due to group delay difference (GDD) between the different modes of the fiber. For a given combination of two modes the beat frequency will always correspond to a particular GDD value. This spatially dependent information at each of the points then is combined to provide information on the intensity profile and the fractional power (with respect to the strong fundamental mode) for the higher order modes (HOMs). This method is called $S^2$ imaging since it is based on spatially and spectrally resolved imaging of the fiber mode content [117]. This technique is based on the fulfillment of two conditions. The multimode fiber should sustain only a few modes and one of them has to be the dominant mode. $S^2$ imaging has been successfully implemented with erbium [118] and ytterbium fibers [119].

Dr. Axel Schülzgen and Clemence Jollivet from the Fiber Optics Lab in CREOL collaborated with us and provided $S^2$ analysis of the SI-LMA fiber and flexible-PCF. For the $S^2$ analysis of the SI-LMA fiber, a ~3.1 m long, passive fiber version was used corresponding to the thulium doped version used in this dissertation work. This fiber had 25/400 μm core/cladding ratio and the core NA was ~0.10. The excitation source used was a single-mode Tm:fiber amplified spontaneous emission (ASE) source which was provided by us. The excitation could be either perfectly centered or off-centered by controlling the launching conditions from the output end of the ASE source to the input end facet of the fiber under test.
Figure 8: The $S^2$ analysis of the SI-LMA fiber with the bend diameter kept at 60 and 10 cm. With lower bend diameter, the LP02 mode shows lower comparative amplitude [113].

Figure 8 shows the $S^2$ measurements for centered excitation condition. The interference between the dominant LP01 and the HOMs generates beat frequencies corresponding to each of the HOMs but at a different GDD value. This data is then analyzed to get information on the relative power distribution and intensity profiles of the different HOMs (as shown in Figure 8).

The analysis was performed on the fiber bent at two different bend diameters. The first bend diameter of 60 cm represents a quasi-straight fiber. The LP01 (fundamental), LP11, and LP02 modes are seen in the reconstructed images. About 40 % of the total input power was launched in the LP02 mode and about 4 % was launched in the LP11 mode at 60 cm bend diameter. Only for centered excitation with perfect launch conditions is the third HOM LP21 not excited. Coiling the SI-LMA fiber to 10 cm diameter induced a 10 dB power loss for the LP02 mode and less than 1 dB power loss for LP11 mode. Even with 10 cm diameter coiling, a total of
~5% of the power was guided in the higher order modes (HOMs). This work was reported jointly between our group and Fiber Optics Lab in [113].

The $S^2$ analysis shows that SI-LMA fiber supports HOMs which are not completely suppressed (even with tight coiling). This impacts the laser performance negatively and is considered in Section 4.2.

**Tm:SI-LMA features**

In the Tm:SI-LMA fiber based systems used in this dissertation, the core light is kept free of HOMs by coiling the fiber on a ~11.5 cm diameter mandrel. In addition to maintaining the coiling diameter, the mandrel is also used to actively cooling the active fiber by placing it on a water-cooled plate. The modal analysis demonstrates that higher order mode content in the core decreases by bending. The bending effectively leaks the light from the core to the cladding where it continues to travel as cladding modes. As a consequence, the output of the fiber is given by the output of the core overlaid by residual cladding light.

In spite of the above concerns, the Tm:SI-LMA fiber is an excellent candidate for use as fiber amplifier. The excitation of the higher order modes is less when compared to Tm:SI-LMA based oscillator system. The M-square values obtained for the SI-LMA amplifiers are <1.25 for high average powers [52]. The obtained slope efficiencies are in excess of 60 % mainly due to optimized glass composition which demonstrates successful CR process. The maximum thulium concentration is limited to ~4 wt. % which prohibits highly doped, short length, fiber amplifier systems. In addition, the small coiling diameters of ~11.5 cm allow efficient cooling.
Commercial optical components like mode field adaptor and pump combiners are available for step index fibers. The availability of components combined with standard fiber preparing equipment for splicing, cleaving and recoating improves the usability and management of these fibers. Tm:SI-LMA fibers are the preferred choice for thulium high power fiber laser.

2.2.2 Photonic Crystal Fiber (PCF)

The minimum NAs currently available in a double clad SI-LMA fiber are of the order ~0.06 for Yb doping and ~0.09 for Tm doping [112, 120]. This limitation confines the maximum modal area to <1000 µm² (30 µm MFD) for obtaining acceptable beam quality. The refractive index profile and the induced NA is primarily limited by the precision of fiber preform fabrication [105]. One of the revolutionary fiber designs which has managed to extend beyond this limit is PCF. The PCF design consists of doped silica core surrounded by an air-hole lattice which can be precisely engineered to give desirable guiding performance.

The requirements for high power scaling are efficient pump coupling, mitigation of deleterious nonlinear effects, good efficiency and effective thermal management [121]. Fibers are required with high cladding NA (for high pump brightness), large core size, high pump absorption (hence short lengths), and low core NA (to maintain fundamental mode). All these features are integral in PCF laser systems.

Flexible PCF/PCF-rod design

The basic design of a PCF is an air hole lattice enclosing the core. This lattice is surrounded by an air-hole cladding which is the pump cladding. This air cladding provides the
high pump NA which is an important feature of this fiber. Pump NA as high as 0.8 have been achieved [122] by optimal air-hole cladding. The core is obtained by replacing the cylindrical air holes in the center by solid core (doped for active fibers) during the preform stage. Typically, the air holes are replaced in hexagonal symmetry; i.e. 1, 7, 19 etc. air holes can be replaced giving a hexagonal core which is generally approximated to circular profile. The guiding and modal properties are governed by the diameter of the holes and the pitch between the holes. For example, for PCF when a single air-hole is replaced by a solid core, it gives an endlessly single mode performance for d/Λ (hole diameter to pitch ratio) of <0.4 [123]. Stress applying parts (SAP) have been incorporated in these PCFs within the air-hole cladding to induce birefringence. This stress induced birefringence gives the polarization maintaining feature [124]. Due to the flexibility in the fiber design, these fibers can be designed to propagate only one of the polarization mode allowing polarizing fibers [125]. PCFs generally show higher bend losses as compared to step index fibers due to weakly confined modes. Designs with extremely large core diameters (typically > 50 μm) and very low effective NA (< 0.03) cannot be bended because of strong bend losses. These fibers are usually fabricated with large capsule of solid glass around the air-hole cladding with typical outer diameters in the mm range and are called PCF-rods.

The first thulium doped PCFs are fabricated and supplied by NKT Photonics A/S. The experiments were performed with two types of flexible PCFs. The first PCF was doped with 2.5 wt. % Tm2O3 and co-doped with aluminum to maintain 1:8 Tm³⁺/Al³⁺ ratio (Figure 9). In this PCF, 7 central air holes were replaced by thulium doped glass rods. This fiber had a hole-diameter to pitch ratio (d/Λ) of 0.18 with a pitch of 12.8 μm. The core diameter was 50 μm and
the air-hole cladding diameter was 250 µm. The MFD at 1900 nm was about 36 µm (modal area >1000 µm²) and the core NA ~0.04. The large core to cladding ratio gave ~5.8 dB/m pump absorption around 793 nm. The hexagonal air lattice had incorporated Boron-doped stress rods for polarization maintenance. The induced birefringence was estimated to be ~10⁻⁴. This fiber showed polarizing behavior in the wavelength range of 1840 – 2015 nm. The second flexible PCF used was 3.6 wt. % Tm₂O₃ doped with a d/Λ of 0.17.

![Figure 9: a) The effective refractive index in a PCF structure induced due to the holes lattice and b) the end face of 50/250 core/cladding flexible PCF [113].](image)

In the scope of this dissertation, Tm:PCF-rod was also evaluated. This PCF-rod had 80 µm core diameter which was fabricated by replacing 19 of the central air holes by thulium doped glass. The doping concentration was 2.5 wt. % Tm₂O₃ (similar composition to flexible PCF).

**Modal features/S² analysis**

Similar to SI-LMA fiber (section 2.2.1), S² analysis for the flexible PCF was provided to us by Dr. Axel Schülzgen and Clemence Jollivet. An undoped sample corresponding to the 2.5
wt. % thulium doped PCF was used. The $S^2$ analysis was performed on ~1.6 m long sample. The impact of coiling diameter was analyzed and is shown in Figure 10. Two coiling diameters were analyzed; 60 and 40 cm. Only two modes are supported in this fiber, LP01 and LP11. The PCF operates close to single-mode operation with 4.3% of total light in the LP11 mode for 60 cm bend diameter. The modal content in the LP11 mode was < 3% when the bend diameter was reduced to 40 cm [113].

Figure 10: The $S^2$ analysis of the PCF fiber with the bend diameter of 60 and 40 cm. With lower bend diameter, the LP11 mode shows lower amplitude [113].

Quasi-single mode operation was observed in the flexible PCF. For the operation to be strictly fundamental mode, smaller bending diameters were required. In contrast, this has the counter-effect of higher loss for the fundamental mode in the core. To determine the optimum bend diameter, the effect of bending on the light in the core in a similar fiber of 3 m length was studied. A thulium oscillator was used as the input for this setup and the output was measured
with respect to the bend diameter as shown in Figure 11. It can be seen that the amount of light measured in the core was ~34 % for 80 cm bend diameter and ~24.5 % for 33 cm bend diameter. The beam quality for the 33 cm bend diameter was superior indicating fundamental mode.

In general, the smallest possible diameters are preferred for a fiber since they facilitate better implementation of cooling potentially reducing the overall footprint of the system. The flexible PCF was kept at a coiling diameter of ~40 cm in all of the experimental work.

The Tm:PCF-rod is, to the best of our knowledge, the first fabrication of this kind of structure with thulium doping. Modal analysis was not possible to implement with the rod mainly because of practical implementation problems. Clemence Jollivet provided a simulation of the modal content of the rod using a finite element method based software Fimmwave (Photon

Figure 11: The effect of bend diameter on the light in the core of a passive flexible PCF 50/250 μm core/cladding diameter.
Design) [126]. The rod consisted of 80 µm diameter core surrounded by air-hole lattice. The d/Λ ratio is 0.191 with a 13.7 µm pitch. The estimated MFD was ~56 µm. This rod does not have PM stress rods in the design. The air-hole cladding diameter was 220 µm. These parameters were used to simulate the PCF-rod in the software.

The simulation gave six guided modes in the PCF-rod. These are LP01, LP11, LP21 (two for orthogonal polarizations), LP02 and LP31. Since it was not possible to bend the PCF-rod, it was also not possible to filter the different modes. The only way to achieve fundamental mode operation was by perfect launching conditions. For the amplifier configuration, light was launched from the flexible-PCF into PCF-rod using 26 mm triplet lens for collimation as well as focusing. This configuration resulted in a passive launching efficiency of ~60 %.

Other considerations

One of the advantages of standard step index fibers is practical handling compared to PCFs. The PCFs used need special end preparation. The air holes in the core as well as cladding need to be sealed at the fiber end facet in order to protect from possible contamination. It required the PCFs to be cleaved after collapsing the air holes if end caps were not present. The splicing of PCFs was not easily possible due to the presence of the air holes. An associated problem is the incorporation of pump combiners with PCFs. Specialized air hole based pump combiner were demonstrated by Crystal Fiber A/S (now NKT Photonics A/S) taking advantage of the high cladding NA of the PCF [127].
Another limitation occurs due to thulium doping in the core. Similar to the SI-LMA case, thulium doping requires a large amount of Al$^{+3}$ doping to avoid clustering effects. It induces a refractive index difference between the Tm:core and the silica glass air cladding in the fiber. This refractive index can be reduced by co-doping either core with refractive index reducing dopant like fluorine or doping the cladding glass with dopants increasing the refractive index. The effective modal area in Tm:PCFs is smaller than the core area by ~50%. It requires engineering of material as well as the air-hole lattice (i.e. diameter of the air holes and pitch). As was seen in [128] the effective area is dependent on hole diameter and pitch, as is given by

$$A_{eff} \propto \left( \frac{A}{d} \right) A^2 + O \left( \frac{\lambda}{d} \right).$$

$d$ is the air hole diameter and $A$ the pitch for the hexagonal lattice around the core, $\lambda$ is the wavelength and $O$ a constant. It can be seen that increasing the pitch increases the effective area.

Thulium is a 3 level laser system and requires efficient heat removal to obtaining higher lasing efficiencies. Efficiencies were limited to <40% in flexible PCF and PCF-rod laser systems. This requires optimization of glass composition and efficient heat removal. The dissertation includes the experimental work done in the development of thulium doped PCF systems. This research direction has shown promise in the achievable high output and requires more work in PCF design and handling.

2.2.3 Specialty Fiber Designs

There are alternate fiber designs with large mode area without compromising the beam quality. One such design is a chirally coupled core (CCC) fiber [129]. This fiber contains one
central mode and at least one helically wrapped satellite core with precisely controlled distance from the core. The higher order modes are coupled in the helical core/s which are exposed to high losses (>100 dB/m) [129, 130]. It enables core sizes beyond the currently ~30 µm for SI-LMA fibers. In addition, the fiber benefits from being intrinsically polarization maintaining due to the satellite core/s.

Another fiber design of interest is leakage channel fiber (LCF) where the boundary between the core and cladding is periodically broken instead of being uniform [131]. With careful design, the LCF can be designed to show higher confinement loss for higher order modes and significantly low loss for fundamental mode. Lasing have been shown in Yb:LCF [131] and these fibers can be designed with >100 µm core areas. These two fiber types have been shown for ytterbium lasing but have yet to be realized with thulium doping.

The advantage of all solid glass fiber designs like LCF and CCC fibers is the ease in component compatibility. They can be easily cleaved or spliced like a step index fiber. Other advantage over PCF design is the low bend loss. For example LCF fibers have shown <50 cm bend diameters supporting ~100 µm MFD [131]. In comparison, it is not possible to bend PCFs due to weak confinement at MFDs >40 µm. In spite of the above advantages and limitations, these novel fiber designs have not yet matured with thulium doping.

2.3 Limitations of Fiber Systems

Fiber laser systems are excellent candidates for high gain systems due to the long interaction length and high brightness due to the small confined mode. Both, the long interaction length and small mode size, make them vulnerable to deleterious effects like nonlinear
limitations, and optical damage. These effects need to be carefully considered for designing fiber systems.

2.3.1 Nonlinear Effects

Stimulated Raman Scattering (SRS)

Spontaneous Raman scattering phenomenon is seen when a pump photon interacts with the vibrational modes of a medium. A pump photon excites an electron from the ground state into a vibrational state by releasing a lower energy photon [132]. This lower energy photon is released with the Stokes wavelength and the corresponding radiation is called as Stokes wave. Alternately, an anti-Stokes wave can be generated which up-shifts the energy of the generated photon by taking energy from an already excited molecular vibration, i.e. a phonon. The spontaneous Raman scattering is a low efficiency process where \( \sim 10^{-6} \) amount of the incident energy is transferred from the pump to the generated photons. However, under the influence of intense laser radiation, this Raman scattering can take stimulated form, thereby transferring large portions of energy from the pump to the generated Stokes wave (anti-Stokes wave too, but with a lower efficiency). This process is called stimulated Raman scattering (SRS).

In fused silica fibers, the measured Raman gain \((g_R)\) spectrally extends from 0 to 40 THz; thus exhibiting wideband characteristics due to the amorphous nature of the material. This is in contrast to molecular media, where it manifests in discrete and well defined spectral lines. The Raman gain in fused silica fiber shows a peak at \( \sim 13 \) THz corresponding to \( \sim 170 \) nm long wavelength shift for a pump at 2000 nm in optical fiber. In silica fibers, the spontaneous Raman
gain generated acts as the seed for SRS. The buildup is most rapid for the frequency overlying with the highest Raman gain located around 13 THz. If the pump power is greater than its threshold, even the second, third and higher ‘Stokes-shift’ wavelengths can be excited. A large wavelength band in the infrared side can be excited and combined with the effects of SPM and SRS can successfully generate a red shifted supercontinuum, as shown in Chalcogenide fibers [133].

The coupled equations for the pump signal and the generated SRS signal is solved in Reference [132, 134] and gives the Raman threshold value in a passive optical fiber with

$$P_{th}^{SRS} \approx \frac{16A_{eff}}{g_R L_{eff}}.$$  \hspace{1cm} (8)

In the above equation, $A_{eff}$ is the effective mode area, $g_R$ is the Raman gain coefficient ($\sim 10^{-13}$ for 1 µm and $\sim 0.5 \times 10^{-13}$ for 2 µm wavelength), $L_{eff}$ is the effective length given as $L_{eff} = (e^{gL})/g$ [135]. A counter-pumped fiber amplifier is assumed, where the signal growth is approximately exponential $P(z) = P_0 e^{g z}$ and $g$ is the gain coefficient. The factor varies from 16 to $\sim 25$ for power from the mW to kW-level [135]. This is the rough threshold values for cw and the same holds for peak powers for nanosecond pulses. In order to increase the accuracy in analysis of nanosecond TDFL systems, the fiber rate equations have to be solved for SRS (and SBS) using the propagation rate equations as demonstrated for YDFA [136].

Since the pulse durations in this dissertation is typically on the order of 5 ns or higher, the effect of walk off between the pump pulse and the generated SBS pulse is not considered. Thulium fibers have a significant advantage since they scale-up the threshold for SRS. The
Raman gain ($g_R$) scales inversely with the used wavelengths, thus it is half the value at 2 µm as compared to 1 µm wavelengths. The SRS threshold is increased for thulium wavelength since it permits larger effective area with single mode operation. To enable cross relaxation process, the thulium fibers are highly doped thus shortening the fiber lengths and increasing SRS thresholds. In overall, thulium fibers offer an effective advantage as compared to 1 µm fibers for nonlinear effects. In spite of these advantages, the first nonlinear process which limits the high peak power operation is estimated to be SRS (Table 1).

**Stimulated Brillouin Scattering (SBS)**

The primary limiting factor for narrow linewidth pulse amplification is SBS. This effect is a result of the electrostriction process. Electrostriction is the increase in density and hence the refractive index due to application of intense electric field [132]. The spontaneous Brillouin scattering is the scattering of incident light (pump wave) into a photon (Stokes wave) and a phonon (acoustic wave) off the thermally excited acoustic waves. This Stokes wave is downshifted in frequency given by the Doppler shift [132]. Under sufficiently high incident optical intensities, the generated Stokes wave can further interfere with the pump to generate a moving acoustic wave (like a moving Bragg grating geometry). The generated Stokes wave and acoustic wave can re-enforce each other to generate large amplitudes.

Only the forward and backward scattering can occur due to the fiber waveguide structure. SBS generation is primarily manifested in backward direction since the forward direction does
not experience constructive interference between Stokes and acoustic waves. This Brillouin shift is given as [132]

$$\vartheta_B = \frac{2n_p v_a}{\lambda_p}. \quad (9)$$

Here, $n_p$ is the effective mode index at pump wavelength $\lambda_p$ and $v_a$ is the acoustic wave velocity with $v_a = 5960 \text{ m/s}$, $n_p = 1.45$ and $\lambda_p = 2000 \text{ nm}$ for silica. The Brillouin shift is $\sim 8.64 \text{ GHz}$ or $0.11 \text{ nm}$ at $2000 \text{ nm}$ wavelength. The Brillouin gain experienced has the form of a Lorentzian spectral profile and the maximum gain at the peak is given as [132]

$$g_{\text{peak}} = g_B(\Omega_B) = \frac{4\pi \gamma_e^2}{n_p^2 \rho_0 c v_a \Delta \vartheta_B}. \quad (10)$$

Here, $\gamma_e$ is the electrostrictive constant for silica ($\sim 0.902$), $\rho_0$ is the density ($\sim 2.21 \times 10^6 \text{ for silica}$), and $\Delta \vartheta_B$ the Brillouin gain bandwidth ($\sim 100 \text{ MHz}$ for silica). Substituting the values at $2 \mu \text{m}$ wavelength gives $g_{\text{peak}}$ of $\sim 4.46 \times 10^{-11} \text{ m/W}$. The SBS threshold in passive fiber is given by [132]

$$P_{\text{th,SBS}}^\text{th} \approx \frac{21A_{\text{eff}}}{g_B^{\text{max}} L_{\text{eff}}}. \quad (11)$$

In the above equation, $A_{\text{eff}}$ is the effective area (same as modal area for Gaussian beam), $L_{\text{eff}}$ is the effective length given as $L_{\text{eff}} = (1 - e^{2\alpha})/\alpha$ where $\alpha$ is the loss coefficient and $L$ the length of the fiber. When an amplifying fiber is considered, slightly different calculations are used for calculating the SBS threshold power which is given by [137]

$$P_{\text{th,SBS}}^\text{th} \approx \frac{21A_{\text{eff}}}{g_B^{\text{max}} L_{\text{eff}}} \left(1 + \frac{\Delta \vartheta_s}{\Delta \vartheta_a}\right). \quad (12)$$
Here, $\Delta v_s$ is the signal spectral bandwidth, $\Delta v_a$ is the acoustic spectral bandwidth used as 100 MHz, and $L_{\text{eff}}$ is given as $L_{\text{eff}} = L(1-e^{-\Delta L})/g$. If a counter-pumped fiber amplifier is assumed, the signal growth is approximately exponential according to $P(z)=P_0e^{gz}$, where $g$ is the gain coefficient. In the above equations, the waveguide induces inhomogeneous broadening in the Brillouin gain bandwidth which is included as shown by Kovalev et al. [138]. The variation of threshold power with variation in fiber length and pump linewidth is presented in Figure 12. The threshold is significantly high ($\sim 200$ kW) for 3 m of 50/250 core/cladding PCF amplifier for linewidth of 0.5 nm which is typical of the laser system used in this dissertation.

![Figure 12](image_url)

Figure 12: Plots of SBS threshold for different fiber amplifier systems calculated with respect to a) fiber length for a gain of 10 dB (Pout/Pin = 10) keeping linewidth $\Delta \lambda=0.8$ nm, and b) linewidth keeping the gain constant at 20 dB.

It can be seen in Figure 12 (a), the SBS thresholds shows a sharp rise when a gain of 10 dB is extracted from a short fiber. The linewidth dependence is plotted in Figure 12 (b) in log-log scale. The threshold drops to less than kW level for almost single longitudinal mode operation (i.e. transform limited pulses).
The effective $g_{\text{peak}}$ scales as $\lambda^{-2}$ and thus, it seems that thulium has an advantage due to wavelength scaling. However, narrowing of the linewidth $\Delta\nu_s$ scaling with $\lambda^2$ essentially cancels directly the advantages. Thulium fibers benefit in other ways. Thulium fibers are generally doped with higher concentration to enable CR process leading to shorter fiber lengths as compared to ytterbium fibers increasing SBS threshold. The narrow linewidth at 2 µm makes the SBS more susceptible to inhomogeneous broadening effects and also suppression techniques [132, 139]. The main technique of suppressing SBS is broadening the signal bandwidth $\Delta\nu_s$. This can be accomplished by modulating the oscillator to broaden the signal [140]. Another technique is to inhibit the growth of the acoustic wave which can be established by specially designed fibers [141]. The third technique is broadening the SBS gain bandwidth imposing stress and a thermal gradient in the fiber [142].

The laser systems presented in this dissertation typically have a spectral bandwidth of ~0.10 - 1.5 nm or 7.5 – 100 GHz. The used fiber lasers are not transform limited which is the reason that SRS is not the first nonlinear limitation which is encountered; usually it is SRS and SPM. Due to the typical pulse durations less than ~10 ns, the SBS effects are further diminished [132].

**Self-Phase Modulation (SPM) and Self Focusing (SF)**

The refractive index in a nonlinear optical medium is dependent on the incident radiation intensity. This effect leads to SPM in the time as well as frequency domain and SF in the spatial domain. The intensity dependent refractive index generates a phase shift which generates
broadening for non-chirped pulses which is called SPM. For chirped pulses it can produce broadening or narrowing of the spectrum depending on the initial chirp. However, spectral chirp is typically a consideration for ultrashort pulses with pulse duration $\Delta t < 50 \text{ ps}$. For nanosecond pulses (which is the domain of this dissertation), SPM induced broadening assuming a Gaussian pulse input is given by [132]

$$\frac{\Delta \omega_{\text{out}}}{\Delta \omega_{\text{in}}} = \sqrt{1 + \frac{4}{3\sqrt{3}} \left( \frac{2\pi}{\lambda} \frac{n_2}{A_{\text{eff}}} PL_{\text{eff}} \right)^2}. \quad (13)$$

In the above equation, $\Delta \omega_{\text{in}}$ is the input spectral width (RMS width), $\Delta \omega_{\text{out}}$ is the output RMS width, $n_2$ is the nonlinear index ($\sim 3.2 \times 10^{-20} \text{ m}^2/\text{W}$ for silica fiber), $A_{\text{eff}}$ and $L_{\text{eff}}$ are described in the previous section on SBS and $P$ is the pulse peak power. SPM by itself does not induce a destructive effect on the fiber but it leads to spectrally broadened pulses in the nanosecond regime. This can be a concern especially when narrow linewidth pulses are preferred. SPM by itself does not distort the pulse shape, but when combined with group velocity dispersion (GVD) induced chirp effects, can lead to broadening and eventually breaking of pulses in the time domain, especially in amplifier.

SF is another effect which is a direct manifestation of the intensity dependence of the refractive index. The spatial beam profile causes a change in refractive index such that the profile of the refractive index change acts like a positive lens. The critical power for this focusing effect is given as [143]

$$P_{\text{crit}} = N_{\text{crit}} \frac{\lambda^2}{4\pi n_0 n_2} . \quad (14)$$
In the above equation, $\lambda$ is the operating wavelength, $n_0$ the refractive index of the medium, and $n_2$ the nonlinear index of the medium. $N_{\text{crit}}$ is the critical power parameter which includes the effects of pulse spatial profile and other guiding conditions. As studied by Fibich et al. [144], the waveguide effect on $N_{\text{crit}}$ gives a lower bound of $\sim1.8362$ and upper bound of $\sim2$ for Gaussian profiles.

SF can lead to severe consequences where the focusing effect cause a smaller modal area which can propagate as a nonlinear guided stationary mode. It leads to a lower threshold limits for all the nonlinear and thermal limitations. The thulium wavelength has an advantage here compared to Yb, since the SF threshold scales with the square of the wavelength. The value for 2 µm threshold is 4 times higher than for 1 µm. Also the larger mode field diameter in thulium fiber increases the threshold even further. In calculations, the unavailability of the data restrains accurate derivations. For example the variation of the nonlinear index in Silica has yet to be studied for 2 µm wavelength. The above-used model predicts $\sim16$ MW as the threshold for thulium assuming nonlinear index similar to the known 1 µm value. The effect has not been a limitation until recently as the above mentioned peak powers have not been reached in thulium. But in the near future, with possible follow-up on the work performed for this dissertation, these levels could be reachable and it would be possible to study the SF effects in thulium fiber.

**Four Wave Mixing (FWM) and Modulation Instability (MI)**

FWM is a $\chi^{(3)}$ process where the energy transfer takes place between four waves. The typical process in optical fibers is degenerate FWM where two photons from a strong pump
transfers energy to two other photons, one at a higher frequency and the other at lower frequency with a constant frequency difference. Since this process is parametric, phase matching has to be satisfied. In silica fiber, 2 µm wavelengths are in the anomalous dispersion regime and the phase matching can be achieved by SPM. The generated wavelengths are determined by the dispersion coefficients of the fiber, effective fiber birefringence and the peak power of pulses. One of the manifestations of the FWM in anomalous regime in a fiber is breaking up cw or quasi-cw radiation into a train of sub-ps pulses. This effect is due to modulation instability (MI). The gain of MI is maximum for frequencies as shifted by [132]

$$\Omega_{max} = \pm \frac{2\gamma P_0}{|\beta_2|}. \quad (15)$$

Here, $\gamma$ is the nonlinear parameter, $\beta_2$ is the second dispersion coefficient and $P_0$ is the peak power of pulses. Spontaneous MI sidebands seen in the spectrum modulate the pulse in the time domain into a train of pulses. If the SPM induced broadening is large enough to exceed the maximum gain frequencies ($\Omega_{max}$), it provides amplification of the corresponding spectral components for MI.

The MI generates train of pulses and has been used to generate supercontinuum in ZBLAN fibers [145]. The process is not desired in high power nanosecond fiber amplifier as the broken temporal pulse profile is not useful for most of the applications besides supercontinuum generation. To avoid MI from affecting the pulses, the amount of SPM induced broadening has to be controlled. One can approximate for 2 µm; assuming $\beta_2 \sim 100$ ps$^2$/km for silica fiber and peak power of ~1 kW that the frequency-shift is ~1 THz corresponding to ~13 nm. To inhibit
MI, the FWHM spectral width needs to be maintained to less than ~2 nm. At high peak powers (above 100 kW) the required wavelength shift increases beyond 100 nm. Hence the maximum opportunity for MI to initiate is in the oscillator where peak powers are low and propagation lengths long.

2.3.2 Optical Damage and Thermal Limitations

The nonlinear effects studied in section 2.3.1 generally lead to energy extraction from the signal frequency into other frequencies or breaking up the temporal pulse shape. Other damage mechanisms exist which physically damage the medium. These are optical damage, thermal damage and thermal degradation, considered below.

**Optical Surface/Bulk Damage**

Optical damage is typically the first limitation considered in fibers; because it can surprisingly occur at lower than expected power levels. Optical damage shows variation with parameters like pulse durations, wavelengths, purity of material and other nonlinear processes. It can be initiated by sudden spikes in laser performance or by other nonlinear effects such as SF and SBS. The surface quality has an important role for limiting the damage threshold. Micro-fractures in the fiber end facet, debris left by the polishing process or even dust particles can contaminate the end facet effectively lowering the damage threshold.

The most dominant factor inducing damage in the pulse duration ranging from nanoseconds to sub-100 picoseconds is the avalanche breakdown mechanism [143]. Here, processes like thermal excitation or multi-photon excitation create a small number of free
electrons in the material. These are accelerated to high energies by the laser field which can further ionize other atoms in the material causing an avalanche effect. The increasing amount of electrons generates heated electron-hole plasma which can further locally transfer heat and fracture/melt the material [105, 143, 146].

Accurate damage threshold values should be available for determining the operation limits. But it is difficult to obtain absolutely accurate values since these have not been systematically studied or calculated at 2 µm wavelengths in fused silica. A simplified function given in [33] based on [147] and using the wavelength dependence of $\lambda^{0.43}$ from [148] can be used to determine the damage thresholds. The threshold peak power for surface damage for $\sim$50 ps to 100 ns is given by

$$P_{\text{max}} = 2.025 \times 10^3 \times \frac{A_{\text{eff}}}{\sqrt{\tau}} \ W .$$

Here, $A_{\text{eff}}$ is in µm$^2$ and $\tau$ is the pulse duration in nanoseconds. The threshold power can be corrected for SF influence by dividing by the factor $(1-P_{\text{max}}/P_{\text{SF}})$, where $P_{\text{SF}}$ can be estimated from the section 2.3.1.

In order to verify the damage threshold limitations for flexible-PCF, a Nd:YAG laser (1064 nm) source is used which generates $\sim$83 ps pulses and the light is launched with $\sim$50% coupling efficiency. The power is increased until the damage occurred at the input facet. The experiment has been performed by Thomas Ferhat in the Laser Plasma Laboratory Group at CREOL. The damaged end facet can be seen in Figure 13.
The approximate damage peak power is calculated to be ~5.3 MW, where the SF effect is not considered since the damage occurred at the input facet. The measured peak power of the pulses is 3.1 to 3.6 MW. The end face damage is usually a factor of 2 to 5 times lower than bulk material damage even for a very high quality end [33]. The result confirms the reliability of the performed damage threshold calculations.

**Thermal Limitations**

One of the advantages of fiber lasers over solid-state lasers is the comparatively large surface to volume ratio allowing effective heat extraction. But there are other associated effects which can degrade the performance and restrain the laser output levels. Heat is generated in fiber lasers mainly due to the quantum defect, excited state absorption (ESA) and energy transfer upconversion (ETU) processes [149]. In addition to the above, impurities, non-radiative sites, light trapped in outer cladding and absorption of stray lights can also lead to additional heating.
Thermal Fracture

The first important consideration is the thermal fracture limit. This effect is the mechanical damage occurring in the fiber (end facet) due to deposition of high temperature on the surface. The heat load deposited per unit length leading to damage is given by [135]

\[
\frac{P_{\text{heat}}}{L} \geq \frac{4\pi R_m}{1 - \frac{r_{\text{core}}^2}{2r_{\text{clad}}^2}}.
\]  

(17)

Here, \( P_{\text{heat}} \) is the heat power, \( L \) the length of the laser, \( R_m \) the rupture modulus of glass (2.46 kW/m for silica), and \( r_{\text{core}} \) and \( r_{\text{clad}} \) the core and cladding radius, respectively. The equation gives an estimate of \( \sim 31 \) kW of heat load per unit length (SI-LMA fiber) as the limit for onset of damage.

Thermal Degradation and Meltdown

If sufficient heat load is generated and not efficiently extracted, it could lead to damage of fiber constituents, namely meltdown of the core and damage of the polymer coating. To understand this limitation, it is important to comprehend the heat dissipation in a fiber. This can be straightforward in a step index fiber configuration due to the uniformity of the material, but it becomes an important consideration in specialized fibers like PCF which contains patterns of air holes incorporated in the design.

Analytical solutions of heat profile are given by Zintzen et al. [150]. The fiber is treated as collection of cylindrical jackets with specific thermal conductivities. For the analysis of PCF, the heat equations from [105, 149, 150] are combined to obtain solutions in the form of
In the above equations, $r$ is the fiber radius at different locations as stated, $\text{Temp}(z,r)$ is the temperature profile as a function of radius of fiber and position in the fiber, $T_{\text{amb}}$ the ambient temperature outside the polymer, $K$ the thermal conductivity, $H_t$ the heat transfer coefficient defined by the cooling method and $H_{\text{load}}(z)$ the thermal load per unit length in the fiber as a function of position.

The pump absorbed and the dependent thermal load is calculated by using [149]

$$P_{\text{pump}}(z) = P_{\text{pump}}(0)e^{\alpha_{\text{pump}}z}$$  \hspace{1cm} (19)$$

and

$$H_{\text{load}}(z) = P_{\text{pump}}(z)\alpha_{\text{pump}}(1 - \eta).$$  \hspace{1cm} (20)$$
In the above equations, $P_{pump}$ is the pump power at different positions and $\eta$ the slope efficiency obtained in the laser (a better value would be an optical to optical conversion efficiency).

To find the values for PCF, the thermal conductivity is taken to be 0.13 W/mK for polymer coating and 1.4 W/mK for glass (silica) [105, 150]. The input pump is assumed 100 W as was the maximum used in the laser experiments. The length of flexible PCF is taken as 2.7 m and 1.4 m for PCF-rod. The absorption for flexible PCF is $\sim$5.7 dB/m and for the PCF-rod is $\sim$17 dB/m. The thermal conductivity for the air-holes is not well defined. After considering the arguments given by Zintzen in [150], the factor of thermal conductivity for glass (fused silica) is decreased by the ratio of single air-hole diameter and single glass bridge. The bridge thickness was considered to be $\sim$400 nm and the cladding air-hole diameter roughly deduced from the images.

Figure 14 shows the radial heat profile for the flexible PCF. Two cases are considered for polymer cooling, conduction-cooling ($H_t \sim 10^4$ W/m$^2$K) and second convection-cooling ($H_t \sim$400 W/m$^2$K) [150]. It is seen that the only difference is caused by the ambience temperature with 14 $^0$C for conduction cooling and 25 $^0$C for convection cooling. In either case, the polymer coating does not reach melting or damage limits. A limit is assumed to be about 150 $^0$C [149] beyond which damage or degradation is expected to occur for the polymer coating. The core temperature is well below silica melting point of $\sim$1800 $^0$C.
Figure 14: Simulated temperature distributions in the 50/250 µm core/cladding flexible PCF when at 100 W pumping. Convection air cooling with fans (red) and conduction cooling with a water cooled chilled plate (black) is compared.

The analysis has been applied to PCF rods which exhibit higher pump power absorption. Figure 15 shows the effects with high temperature values for the core. The plots reflect the profile at the incident pump end which has highest thermal load. Since the simulation values were not experimentally verified, the plots can be used as a reference but not for absolute values. The obtained numbers are in a similar range as obtained with a finite element method (FEM) based modeling [151]. An important conclusion is that a bi-directional pumping method gives a uniform heat profile along the length of the fiber as compared to only a forward pumping method.
Figure 15: Simulated temperature distributions shown for 80/220 µm core/inner-cladding PCF rod. The fiber is conduction cooled using water cooled plates at 14°C.

One of the important factors is the temperature of the polymer which is not preferred to be kept above 100 °C for extended duration. In spite of the lowered heat transfer in PCFs because of the air hole cladding, heat is still efficiently removed from the core and the polymer never reaches damage temperatures. In addition, TDFL systems generate higher heat loads as compared to ytterbium systems due to the quantum defect. The observed lasing efficiencies are lower than 40 % in Tm:PCF lasers. Any increase to higher powers would require better thermal management in these fibers. The polymer coating has no significant impact on the overall thermal profile. But if the pumping is increased to >500 W level, the air-hole cladding starts acting as an insulation barrier for effective heat removal. The air holes can be decreased in
number with thicker silica bridges which would help overall diffusion of the heat, although at a price of lower pump acceptance NA.

**Other Thermal Effects**

The high temperatures affect the lasing threshold and amplifier gain. Elevated temperatures increase the thermal occupancies in the energy levels. This increase in occupancy changes the effective cross-sections of the laser pump and signal wavelengths. It leads to the effect of shifting of the population to higher energy manifolds and higher re-absorption losses. The lasing efficiency decreases and the threshold of a laser system increases. This effect is stronger in a three level laser system like thulium. Hence, effective heat management is a critical parameter for achieving efficient high power lasing in TDFLs.

In addition, effects such as thermal guiding (especially in large core fibers), thermally induced stress and external optical components like lenses, isolators, polarizers etc. show thermally induced degradation in the system performance [149].

**2.3.3 Limits in Several Fiber Designs**

Based on the considerations seen in previous sections for nonlinear limits and other damage mechanism, calculations are performed for the fibers being used in the presented work. Four fibers have been considered are presented in 10/130 µm core/cladding Tm:SMF fiber from Nufern Inc., 25/400 µm core/cladding Tm:SI-LMA fiber from Nufern Inc., 50/250 µm core/cladding flexible Tm:PCF from NKT Photonics A/S and 80/220 µm core/cladding Tm:PCF-Rod from NKT Photonics A/S. Table 1 shows the comparative values of nonlinear effects like
SRS, SBS, SPM, and SF, thermal fracture, surface damage and stored energy for the different fibers. Based on the table, it is seen for high peak power levels the PCF-rod and flexible PCF fibers are preferred due to the large MFD and increased thresholds of various limitations.
Table 1: Comparison of the thresholds for the used fiber types. The values are considered as rough estimations for the associated processes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
<th>3m of 10/130 µm fiber (MFD 11.5 µm)</th>
<th>3m of 25/400 µm fiber (MFD 23 µm)</th>
<th>3m of 50/250 µm fiber (MFD 36 µm)</th>
<th>1.5m of 80/220 µm fiber (MFD 56 µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Length (15 dB Gain)</td>
<td>$l_{\text{eff}} \approx 4.343L/G(\text{dB})$</td>
<td>0.868</td>
<td>0.868</td>
<td>0.868</td>
<td>0.434</td>
</tr>
<tr>
<td>SRS[137]</td>
<td>$P_{\text{SRS}} \approx \frac{16A_{\text{eff}}}{g_0l_{\text{eff}}}$</td>
<td>36.1 kW</td>
<td>144.5 kW</td>
<td>354.0 kW</td>
<td>1,713 kW</td>
</tr>
<tr>
<td>SBS: input/output ($\Delta \lambda \sim 0.1$ nm) [137]</td>
<td>$P_{\text{SBS}} \approx \frac{21A_{\text{eff}}A_{\text{eff}}}{g_0l_{\text{eff}}^2}$</td>
<td>2.9 kW/90 kW</td>
<td>11.4 kW/353 kW</td>
<td>42.7 kW/1,323 kW</td>
<td>328 kW/10,168 kW</td>
</tr>
<tr>
<td>SPM ( $\Delta \lambda$ from 0.1-1 nm)</td>
<td>Fiberdesk simulating software</td>
<td>0.13 kW/4 kW</td>
<td>0.83 kW/25 kW</td>
<td>3.9 kW/130 kW</td>
<td>25 kW/756 kW</td>
</tr>
<tr>
<td>Surface damage (5 ns pulses)[33]</td>
<td>$E_{\text{max}} = \frac{\tau X A_{\text{eff}}}{\sqrt{\tau}}$</td>
<td>0.45 mJ</td>
<td>1.82 mJ</td>
<td>4.42 mJ</td>
<td>10.74 mJ</td>
</tr>
<tr>
<td>Self-focusing[137]</td>
<td>$P_{\text{cr}} = \frac{1.896\lambda^2}{4\pi n_0 R_2}$</td>
<td>15.4 MW</td>
<td>15.4 MW</td>
<td>15.4 MW</td>
<td>15.4 MW</td>
</tr>
<tr>
<td>Extractable energy[149]</td>
<td>$E_{\text{max}} \approx \frac{10E_{\text{sat}}}{\eta_1(\sigma_\gamma(\lambda_i) + \sigma_\sigma(\lambda_i))}$</td>
<td>0.25 mJ</td>
<td>1.4 mJ</td>
<td>5.1 mJ</td>
<td>13.0 mJ</td>
</tr>
<tr>
<td>Thermal Fracture [135]</td>
<td>$P_{\text{heat}} \geq \frac{4\pi R_m}{L} = \frac{4\pi R_m}{1 - \frac{\Delta_{\text{core}}^2}{2\Delta_{\text{clad}}^2}}$</td>
<td>31 kW/m</td>
<td>31 kW/m</td>
<td>31.5 kW/m</td>
<td>33 kW/m</td>
</tr>
</tbody>
</table>
2.4 Summary

Thulium-doped fibers have evolved over the last decade as high power laser source. It has benefitted largely from the optimization of the glass geometry facilitating CR for 790 nm pumping. Commercially available Tm:SI-LMA fibers facilitating more than 60 % slope efficiencies surpassing the Stokes limit of 40 %.

Generation of high power and high energy in fibers require increased modal area. The commercially available SI-LMA fiber has a modal area of ~415 µm$^2$ (MFD: 23 µm). $S^2$ analysis shows that the output from this fiber is multi-mode with 40 % core light being coupled in the LP02 mode and 4 % in LP11 mode. On other hand, a novel thulium-doped flexible-PCF shows increased modal area of >1000 µm$^2$ (MFD: 36 µm) with low amount of power (~5 %) in the higher order mode LP11. An optimum bending diameter is found to be ~11 cm for the SI-LMA fiber and <40 cm for the PCF. These diameters introduce losses for the higher order modes which leak into the cladding keeping the core light quasi-single-moded (~5 % light in HOMs for SI-LMA fiber and <3 % light in HOMs for flexible-PCF in the core). A novel PCF-rod (modal area ~2500 µm$^2$) (MFD: 56 µm) supports 6 modes and precise launching is required to obtain fundamental mode.

The limits in fiber amplifiers are divided into nonlinear effects and optical damage/thermal effects and presented in this section. The nonlinear limits like SRS, SBS, SF, FWM, and MI are studied. The optical damage and thermal damage are discussed to obtain the optimum operating regimes for different fibers.
CHAPTER THREE: UNIQUE THULIUM CW SOURCES

The development of cw thulium fiber sources is covered in detail in the introduction chapter of this thesis. After 2003, the improvement in the slope efficiencies led to a rapid growth in the output power level obtained from TDFL systems. CW laser experiments are critical for characterizing and optimizing slope efficiency, thresholds, pump coupling efficiency, beam quality, polarization etc. for a given fiber type. This chapter covers the implementation of the prototype Tm-doped PCF in cw oscillator/amplifier configuration. This provides the basis for the subsequent analysis of pulsed laser operation in the next chapter.

3.1 ASE Source

Thulium based fiber source can generate high power ASE spanning the wavelength range of 1.8 - 2.1 µm [152]. Fiber based ASE sources are particularly attractive because of the high brightness resulting from the fiber waveguide structure despite the incoherence of the light. We have constructed several such systems with output powers >100 mW, and used the broad bandwidth as a tool for absorption spectroscopy and characterization of optical components. In this section, we describe the ASE output of Tm-doped PCF and SI-LMA as the first step in characterizing the active performance of the fiber.

Figure 16 shows the setup of a Tm:SI-LMA fiber based ASE source. The fiber used was ~2 m of 25/400 µm core/cladding ratio. The fiber was pumped using a 35 W, 790 nm diode laser (DILAS GmbH). A 1:1 telescope system was used to launch the light into the end face of the fiber. The ends of the thulium doped active fiber were spliced with passive leads so that the
active fiber could be efficiently cooled. Only the ASE output propagating in the opposite direction of the pump was measured, and ejected from the system by a dichroic mirror which was highly reflective from 1.8 – 2.1 μm and highly transmissive for the pump.

Figure 16: The ASE generating setup shows a ~2 m 25/400 μm SI-LMA fiber pumped with a 790 nm diode pump. The backward propagating ASE is characterized.

The above system produced ~100 nm wide broadband spectrum measured at -10 dB from the peak value. The typical spectrum is shown in Figure 17 (a). The broadband covers the water vapor absorption features from ~1850 – 1950 nm which are obvious in Figure 17 due to the free space propagation from the source to the detector in the OSA.
Backward propagating ASE configuration was used since it gave higher conversion efficiency and broader bandwidth as compared to forward propagating ASE [97, 153]. The prime reason is that forward ASE sees absorption due to the three level nature of thulium as it propagates towards the non-pumped end of the fiber. This effect is more pronounced in Tm:SI-LMA due to high doping concentrations (~4 wt. % Tm$_2$O$_3$).

This ASE source generated output power > 250mW at modest pump values of 27 W. The spectral density of the generated broadband was ~2.3 µW/nm average with peak values higher than 6 µW/nm. This source has been used to investigate carbon dioxide sensing in [154].

In comparison, backward propagating ASE for 3.6 wt. % Tm:flexible-PCF in a similar configuration (but with a 100 W, 790 nm pump) is shown in Figure 17 (b). The fiber length was ~2.8 m. The output spectrum was ~130 nm wide and was shifted towards shorter wavelengths by ~50 nm. The ASE power level was lower with ~25 mW at 50 W of pumping. The shifted ASE between the SI-LMA fiber and PCF could be attributed to the difference in glass composition of
the fibers. The glass composition, absorption and emission cross sections and smaller lengths of the PCF fiber were the reasons for lower ASE power levels.

In conclusion, Tm:SI-LMA fiber is a suitable choice for high power broadband ASE generation but would have higher concentration of ASE for pulsed amplification. On the other hand Tm:flexible-PCF is more suitable for pulsed amplification.

3.2 Oscillator Sources

The next step in the fiber evaluation is to construct a cavity around the fiber for laser oscillator configuration. Compared to the ASE system described in the previous section, CW oscillators provide higher power, higher efficiency, and narrow spectral output. The following section describes the oscillator operation and setups. The performances of the SI-LMA fiber and flexible-PCF are evaluated in terms of their potential to provide sources which are robust, efficient, generate high average power, and maintain fundamental beam quality.

3.2.1 Concept

The two most important parameters that characterize a given laser oscillator configuration are lasing threshold and output conversion efficiency. Additional important parameters include pump coupling/absorption efficiency, output beam quality and polarization.

In general, to achieve higher slope efficiencies and lower lasing thresholds in a fiber laser, the output coupler needs to have very low value of reflection and the feedback element should be almost 100 % reflective mirror [149]. The practical and most convenient technique to
achieve this is by using flat cleaved fiber end as the output coupler. This gives a Fresnel reflection of \( \sim 4\% \) for fused silica fiber.

In terms of pump threshold, shorter lengths of the fiber are preferable. However, the fiber length must be sufficient for the pump absorption. The optimum length depends on the specific fiber used and generally requires exact solutions for the rate equations. The lengths used in the context of this thesis are typically 3 – 5 m for SI-LMA fibers, 2 – 3 m for flexible PCF and 1 – 1.5 m for the PCF rod.

Co- and counter-propagating configurations are defined with respect to the direction of the pump propagation and the output laser propagation. The small signal gain is almost the same in both the configurations but the level at which gain saturation occurs is generally higher in the counter-propagating pump configuration. Another benefit of counter-pumped amplifier systems is that the cw (or pulsed) high power doesn’t travel long distance in the fiber (since it builds up primarily close to the output end) hence it doesn’t accumulates lower values of nonlinearities. Hence high power amplifiers are generally pumped in the counter-propagating direction.
Figure 18: The schematic of a co-propagating oscillator cavity. The laser cavity is formed between the feedback element and the flat cleave. PBS and HWP are utilized only for a PM cavity.

Figure 18 shows the oscillator configuration with co-propagating pump geometry. The signal output from intra cavity end of the fiber is first collimated using a triplet lens, and then a feedback element (a highly reflective mirror or a diffraction grating for wavelength control/tuning) reflects the signal back along the same path. The pump was launched via a 1:1 telescope system through a dichroic mirror (highly reflective for the pump and highly transmissive for the signal) into the fiber. The 1:1 telescope imaged the output facet of the diode delivery fiber onto the end face of the fiber in the cavity. The dimensions for the DILAS GmbH delivery fiber used were 220/240 μm core/cladding with NA of 0.22. The SI-LMA fiber (Nufern) had a cladding diameter of 400 μm with NA of ~0.4. The 1:1 telescope system under-filled the SI-LMA cladding greatly simplifying the pump coupling. The same pump arrangement was used for the flexible PCF fibers with cladding diameter of 250 μm and cladding NA of ~0.45. The signal output was collimated using a 26 mm focal length aplanatic triplet.
Figure 19: The schematic for a counter-propagating cavity. The PBS and HWP are utilized only for a PM cavity.

Figure 19 shows the counter-propagating cavity setup. In addition to PM fiber, to achieve polarized output the cavity included a HWP and PBS. The additional losses in the PM elements generally decrease the slope efficiency for a PM cavity (Figure 21).

Figure 20: Schematic for output power measurement. The collimating lens is used to image the fiber tip to ~ 1 m distance to place the aperture. The ‘Output Power’/’Polarized Output Power’ is the total/polarized output power free of cladding light. The ‘Total Output Power’ is the total 2 micron power (free of residual pump light).

As mentioned in the introduction of this chapter, beam quality is an important parameter as this has a significant impact on the brightness of the source. If the signal is multi-mode, this will also have a significant impact on the polarization of the output light. Due to the LMA
structure, higher order modes have larger propagation losses as compared to the fundamental mode. As such, if there is a significant excitation of the higher order modes, the light will generally be coupled into the cladding. Thus, the characterization of the laser output requires taking into account the polarization and the cladding light. Figure 20 is a schematic of our characterization setup. To measure the power in the core (free of any cladding light), the output is imaged at a distance of ~1 m from the fiber output by adjusting the collimating lens. An aperture is placed at this position to block the cladding light. The polarization is checked using the HWP and PBS in this path. As shown in Figure 20, the ‘Total Output Power’ is the total signal generated (i.e. core + cladding) and the ‘Output Power’ is the signal measured through the aperture. The ‘Polarized Output Power’ is characterized using both the aperture and the HWP/PBS. These definitions will be used throughout this thesis. Additionally, the output power is always measured after a pump rejection filter.
### 3.2.2 SI-LMA CW Oscillator Performance

Figure 21: The slope efficiencies for SI-LMA based PM and non-PM fibers for a) Total output power and b) Output power/Polarized Output Power in the core.

The Figure 21 shows results obtained for ~3.3 m of Tm:SI-LMA fiber used in a counter-propagating scheme similar to Figure 19. The pump laser diode provides up to 100 W at 790 nm (DILAS GmbH). The feedback element was a HR mirror since no linewidth control was required. The obtained threshold power was 11.8 W for the non-PM case and 11.9 W for the PM case. The slope efficiency obtained for the output power in the non-PM case was 51.8 % which indicated improved efficiency due to the cross relaxation process. In comparison, the total output power (core + cladding) slope obtained for non-PM SI-LMA and SI-LMA fiber was 60.8 % and 54.3 % respectively. The slope efficiency obtained for the polarized output power in the case of PM cavity was ~37 %. The slope efficiency decreased due to the additional losses in the PBS and HWP. In addition to the loss of the rejected polarization, the PBS and HWP induced ~6 % loss in the transmitted polarization.
Figure 22 shows the M-square measurements for the PM SI-LMA fiber oscillator for low power and high power operation. The M-square deteriorated for higher power levels. This performance degradation in LMA fiber will be critically analyzed in section 4.2.3.

![Graphs showing M² measurements](image)

Figure 22: The M-square measurements for the PM SI-LMA fiber oscillator for a) 60 mW cw operation and b) 2.3 W cw operation.

Although not discussed in this section, the output wavelength can be controlled by the choice of an appropriate feedback element such as a diffraction grating or VBG.

### 3.2.3 Flexible Tm:PCF CW Oscillator Performance

The flexible Tm:PCF (fabricated by NKT Photonics A/S) is a prototype design, and the implementation of a PCF-based laser with thulium doping is described in this section. Two flexible Tm:PCF fiber types have been tested for the lasing performance. The first PCF was a 2.7 m long, 2.5 wt. % Tm₂O₃ doped with a hole size to pitch (d/Λ) ratio of 0.18 and a pitch of 12.8 μm. The second PCF was doped with higher concentration of 3.6 wt. % Tm₂O₃ and the d/Λ ratio
was 0.17. It was ~2.7 m in length. The fibers were co-doped with aluminum maintaining a Tm/Al ratio of 1:8 and the pump absorption was ~5.8 dB/m.

Figure 23: Characteristic performance obtained with ~2.7 m of 3.6 (red) and 2.5 wt. % Tm$_2$O$_3$ (black) doped flexible PCF.

The oscillator configuration was counter-propagation pumped, similar to Figure 19 except without the PBS and HWP in the cavity. This basic configuration gave slope efficiencies of 32.4 % for the 2.5 wt. % doped fiber and 37.1 % for the 3.6 wt. % doped fiber (Figure 23). Notably, the laser thresholds obtained were higher (~ 15 W) than SI-LMA oscillator and the slope efficiencies were lower (Figure 21).
Figure 24: M-square results for a) 2.5 wt.% Tm$_2$O$_3$ doped PCF and b) 3.6 wt. % Tm$_2$O$_3$ doped PCF. It is important to note that the M-square value is excellent (<1.15) for both the cases indicating fundamental mode operation.

The M-square was measured to characterize the beam quality and the result is shown in Figure 24. The M-square value for both fiber oscillators was <1.15. The measurements were taken at low powers (~ 1 W) as well as high powers (>5 W) with no degradation of beam quality. This data supports the fact that the flexible-PCF is resistant to higher order mode propagation as was confirmed with $S^2$ measurements in section 2.2.2.
Figure 25: a) The PCF tuning curve using a reflection grating for 2.7 m of 2.5 wt.% Tm$_2$O$_3$ PCF showing wide tunability (1840-2015 nm) and b) The ASE spectrum obtained.

We have also characterized the wavelength tunability of the flexible-PCF oscillator. A 600 line/mm gold coated diffraction grating provides wavelength tunable feedback. Using this grating, the oscillator was tuned from 1.84 – 2.015 µm with a linewidth less than 0.2 nm [51]. The slope efficiency is shown in Figure 25 along with comparison to the ASE spectrum. It can be seen that >20 % slope efficiencies were obtained over the complete tunable wavelength range. This analysis shows the wide tunability possible in the PCF extending >150 nm.
The PCF design is discussed in detail in section 2.2.2. This PCF incorporates boron stress rods which induce a birefringence of $>10^{-4}$ in the core. This fiber showed polarizing behavior in addition to polarization maintaining behavior. The polarizing behavior is achieved through the fiber design and the bend induced propagation loss, such that the slow axis (polarization along the stress rods) is guided and the fast axis experiences strong loss [125]. The PCF was found to be polarizing across tuning range shown in Figure 25(a). Ideally no intra-cavity polarization elements were required but an improved stability and polarization quality was observed with the addition of these elements. The output showed $>20$ dB polarization extinction ratio (PER) with this fiber (Figure 26). The PER is the ratio of the power in the two polarizations expressed in Decibel (dB). The PER is always measured for the Polarized Output Power (Figure 20) free of
cladding light. This high value of PER (\(> 20 \text{ dB}\)) was maintained for both types of fiber in oscillator as well as amplifier configurations.

The oscillator performance was reported for the first time [106]. The oscillator showed excellent beam quality and polarization maintaining/polarizing behavior. But, the lasing slope efficiency was lower with higher pump threshold than was observed for the SI-LMA fiber-based oscillator. The importance of the Tm/Al ratio for obtaining cross relaxation for improved slope efficiency is discussed in section 2.1.3. Because of the comparatively lower slope efficiencies and higher thresholds of flexible Tm:PCF laser oscillator, it is non-optimal for high power cw generation. However, the single mode beam quality, high polarization quality, high gain availability, strong pump absorption and lower ASE levels (Figure 51) makes it a preferable source for the pulsed oscillator as well as amplifier system.

### 3.3 Amplifier-based Sources

Amplification is required in both cw as well as pulsed operation to reach higher power levels. This section will describe cw master oscillator power amplifier (MOPA) experiments and compare the performances of the novel PCFs in amplifier configurations.

#### 3.3.1 CW Amplification

In comparison to constructing a high power/high energy oscillator, MOPAs have the inherent benefit that a low power/low energy oscillator provides the spectral and temporal characteristics whereas the amplifier can be separately optimized for high power and/or high energy as shown schematically in Figure 27.
The oscillator in a cw MOPA system determines the output wavelength and spectral linewidth. Even for high power applications, the oscillator can operate with low extraction efficiency and/or incorporate optical elements with large insertion loss or low damage threshold. Some considerations for cw amplification in fiber laser system are given below.

1. Gain: It is the ratio of output power to input power. The observed gain can be roughly divided into two ‘zones’, small signal gain and saturated gain. Input signal power exceeding the saturation power is required to achieve efficient power extraction. The signal saturation power is given as \[ P_{\text{Sat}} \approx \frac{h v_L A_{\text{core}}}{[\sigma_a(\lambda_L)+\sigma_e(\lambda_L)]\tau_f} \] .

\( \tau_f \) is the lifetime of the upper state, \( A_{\text{core}} \) is the core area, \( h \) is the Planks constant, \( v_L \) is the laser frequency, and \( \sigma_a \) and \( \sigma_e \) are the absorption and emission cross sections at the lasing wavelength. The value of this saturation power is plotted in the 1.75 – 2.1 µm wavelength range for the flexible PCF and PCF-rod in Figure 28. These plot is generated under the assumption that the absorption and emission cross sections of the flexible-PCF and PCF-rod are similar to the values used in [103]. This term varies inversely with the sum of emission and absorption cross-sections. Comparing with Figure 6, it is obvious that for
longer wavelengths, larger seed is required to efficiently extract the gain from an amplifier due to the lower emission and absorption cross section areas.

![Graph showing saturation power](image)

Figure 28: The saturation power calculated for PCF-rod amplifier and flexible PCF amplifier based upon the absorption and emission cross-section for thulium doped silica.

For the input signal much below saturation power, the gain varies linearly with the increase in pump. This is the small signal gain region. This gain region can be used to generate a gain of 20 - 30 dB. In the saturation gain regime, the gain is comparatively lower for input seed powers above the saturation power however higher output power can be extracted with higher efficiency. As it can be seen in Figure 29, the amplifier is typically optimized for either ‘high gain’ or ‘high power’.
Figure 29: Simulation of gain in the 2.7 m flexible PCF amplifier with pump power of 50 W and variable input seed between 20 and 500 mW. The amplifier can be operated in either the ‘high gain’ region or ‘high extraction’ region but not both at the same time.

For pre-amplification, where a small seed needs to be boosted to higher output levels, the small signal gain regime is preferred. In a power amplifier (the last amplifier in a laser chain), the goal is to extract the maximum power and the saturated gain regime is better suited.

2. ASE: ASE in amplifiers competes with the signal amplification and is strongest in the small signal gain regime. To keep the ASE in check, either ASE filters need to be employed in between two amplification stages and/or fiber designs with inherently lower ASE content are required.

3. Parasitic Lasing: Parasitic lasing can occur in a fiber amplifier with high gain if there is insufficient seed and/or if there is feedback from back reflections originating from fiber facets, or external components such as polarizers, wave plates, isolators, etc.
Considering the parasitic lasing and ASE, the operating gain in a fiber amplifier is often lower than 30 dB [149], thus, largely reducing the above mentioned competing processes. To achieve efficient power scaling using MOPA architecture, multiple stages of amplifiers may be required to achieve multiple orders of magnitude amplification. After each consecutive amplification stage, the core area and available pump power needs to be increased to increase the onset of gain saturation and provide higher extractable output.

### 3.3.2 Flexible-PCF Amplifier

The amplifier performance of the flexible PCF was verified using an oscillator based on ~4 m of thulium doped 10/130 µm single mode SI fiber (Nufern). This fiber was pumped using a 35 W fiber coupled, 790 nm pump diode (DILAS GmbH). Figure 30 shows the schematic of the MOPA i.e. the Tm:PM 10/130 µm single mode fiber based oscillator and Tm:flexible-PCF based amplifier.
Figure 30: Although the schematic was for a Q-switched MOPA system, it was operated in cw regime. The oscillator utilizes ~4 m of Tm doped PM 10/130 µm core/cladding fiber, an AOM for Q switching and a grating for wavelength control. The output from the oscillator passes through a pulse picker, isolator into a PCF-based amplifier pumped by up to 100 W at 790 nm.

The schematic will be described in detail in section 4.3. For these experimental studies, the AOM was operated in cw mode and the pulse slicer was not used. In order to characterize gain as a function of the seed wavelength, the wavelength of the oscillator was fixed at 1966 and 2008.5 nm, with 0.11 – 0.13 nm linewidth using a reflection grating. To optimize seed coupling, the beam divergence (i.e. NA of the fiber) as well as diameter (i.e. MFD in the fiber) of the launched light was needed to match the fiber amplifier. In practice, the high NA of the oscillator fiber (0.15) and the MFD (~11.5 µm) must be transformed to match the NA (~0.04) and MFD (~36 µm) of the amplifier fiber. This was accomplished by forming a telescope between the 7.5 mm focal length aspheric collimating lens (Thorlabs, Inc.) and the 26 mm focusing lens. The free
space path between the oscillator and amplifier was >0.5 m which leads to divergence of the beam. The overall coupling efficiency from the oscillator to the amplifier was ~60 %.

Figure 31: a) The ASE spectrum of the flexible PCF (2.5 wt. % Tm$_2$O$_3$) with the two wavelengths of interest and b) the HITRAN transmission of water vapor in the wavelength of interest [155]

The locations of the 1966 and 2008 nm seed wavelengths relative to the ASE spectrum and the corresponding water absorption lines are shown in Figure 31 (a). The two wavelengths were chosen as they avoid the majority of water absorption lines. Figure 32 (a) shows the amplification seen in the flexible PCF with 515 mW seed power incident at 1966 nm and 511 mW at 2008 nm. The slope is plotted for the linearly polarized light localized in the core after
propagation through the collimation lens, PBS, HWP and an aperture to remove any cladding light.

Figure 32: a) Characteristics for the flexible-PCF amplifier at 1966 and 2008.5 nm cw operation. The input power is maintained to ~515 mW. b) Measured gain plotted along with the input pump power for both wavelengths.

The seed power for both wavelengths corresponds to the saturation power (~411 mW for 1966 nm and ~537 mW for 2009 nm). The seed wavelength and linewidth was maintained during amplification. We reported the CW amplifier performance for a flexible Tm:PCF for the first time [156], with a slope efficiency of 21.7 % at 2008 nm and 27.6 % at 1966 nm. As shown in Figure 32, the lower gain value was higher but the overall gain was lower for 2008 nm primarily because of smaller absorption cross section at this wavelength as compared to 1966 nm.
### 3.3.3 Tm:PCF-Rod Amplifier

The Tm:PCF-rod amplification work was done with Christian Gaida. The output from the flexible-PCF is further launched in PCF-rod amplifier. The experimental setup is shown in Figure 33.

![Diagram of the two stage amplifier comprising of a Tm: PCF-rod power amplifier.](image)

**Figure 33**: The layout of the two stage amplifier comprising of a Tm: PCF-rod power amplifier.

The PCF rod was doped with 2.5 % Tm$_2$O$_3$ and co-doped with aluminum with a Tm/Al ratio of 1:8. The rod was 1.36 m long with 80 µm core and 220 µm air cladding. The mode field area was estimated to be $>2800 \, \mu m^2$ for MFD of $\sim56 \, \mu m$ with a core NA of $\sim0.02$. The cladding NA was $>0.4$ for 790 nm with pump absorption of $\sim17$ dB/m. The air lattice around the core has air-hole diameter to pitch ratio of 0.191 with a pitch of 13.7 µm.

The rod was placed on a 1.36 m long metal V-groove which was held between the metal blocks as shown in Figure 33. This V-groove was cooled with water cooled aluminum blocks. Six metal blocks were placed to maintain the outside temperature of the rod to $\sim13 \, ^o \, C$. The rod
ends were collapsed and angle cleaved to ~4 % to avoid parasitic lasing. The amplifier was counter-pumped by a laser diode at 793 nm with up to 100 W (DILAS Diodenlaser GmbH). The pump output was fiber coupled with a 200 µm delivery fiber which was then launched in the end facet of the rod via a 1:1 telescope system.

The flexible-PCF output was collimated using a 26 mm triplet lens and the similar triplet lens was used to seed the PCF rod. Precise launching was required since the rod supports propagation of higher order modes. The coupling efficiency was not accurately measurable because of the lack of comparable passive PCF-rod but was approximated to 80 %. The obtained amplifier output including coupling loss and signal absorption was ~64 %.

![Graph](image)

**Figure 34:** a) CW amplification in the PCF rod with ~4 W of seed at 1961 nm. ~20 % slope efficiency is obtained. b) The corresponding gain in dB [98].

The flexible PCF amplifier output, ~4 W at 1961 nm, was coupled into the PCF rod. The seed power was larger than saturation power for the PCF-rod of ~1 W (Figure 28). The result of cw amplification is shown in Figure 34. A slope efficiency of ~20 % was obtained with a
maximum output power of 22 W. Given there was no sign of deviation from a linear slope, the maximum achievable output power was limited by the 110 W pump power \[98\].

![Figure 35: The M-square measurement taken at 4 W cw seed with pumping at 87 W \[98\].](image)

Unlike the flexible PCF amplifier, coupling into the rod amplifiers had a significant impact on the output beam quality. The M-square values obtained were in the range of 1.01 - 1.35 depending on the coupling \[98\]. In addition, the beam was slightly astigmatic since the diverging beam passes through the angled pump mirror. The aberration caused a slight offset in beam waist positions for the x and y axes as shown in Figure 35. The M-square value obtained for 4 W seed pumped with 87 W was \(~1.24\). The quasi-single-mode operation of the rod did not degrade at highest pump levels utilized in these experiments.
3.4 Summary

To summarize, the performance of novel Tm:PCF based lasers is compared against the established SI-LMA fibers in oscillator configuration. The slope efficiencies obtained with SI-LMA fiber for the total powers were in excess of 54.3 % for the PM fiber and 60.8 % for the non-PM fiber. In comparison, PCF showed a slope efficiency of 32.4 % (for 2.5 % doped) and 37.1 % (for 3.6 % doped). Although somewhat disappointing in terms of overall power and efficiency, the primary advantage of the PCF technology is the ultra-large mode area, single-mode beam quality and excellent polarization properties (PER> 20 dB). The cw oscillator systems operated in either ASE mode or high average power mode have been used to investigate CO₂ absorption spectroscopy, polymer welding, and characterization of thermal lensing in chalcogenide glasses (APPENDIX A).

The performance of the flexible-PCF and PCF-rod were characterized as amplifiers in MOPA systems. The flexible-PCF achieved 9 W output power at 40 W pumping (> 15 dB gain) with 27.6 % slope. The PCF-rod enabled amplification larger than 22 W with 110 W pumping with ~20 % slope. Higher power and greater efficiency can be achieved if the glass chemistry in the PCFs is optimized to realize cross-relaxation process. However, the beam quality and PER were virtually ideal for the flexible PCFs and the beam quality was acceptable for the rod-type PCF. Given the current state of the technology, we have focused on maximizing the output energy and peak power at repetition rates <10 kHz due to current limits on average power.
CHAPTER FOUR: HIGH PEAK POWER, THULIUM, MOPA LASER

Thulium based nanosecond systems have seen a fast growth in the last 5 years. The high scalability and higher nonlinear thresholds of thulium doped fiber systems, open up an interesting avenue to reach high peak powers with pulsed fiber systems. Limitations in thulium fiber systems are low optical power efficiency and high thermal load in the fiber in comparison to the inherently efficient ytterbium fiber laser systems. New thulium fiber designs are evolving to reach high peak powers and one of those designs, i.e. PCF, is investigated in this section.

The primary focus of this thesis is the development of narrow linewidth (<1 nm FWHM), high peak power (>100 kW), widely tunable (~1.85 – 2.01 µm) laser source with excellent beam quality. The prototypes of thulium-doped PCF-rod and flexible-PCF systems were taken to extreme high peak powers which will be shown in this chapter. We have demonstrated ~1 MW peak power with sub-10 ns pulse-duration which is a current record in thulium fiber sources.

These sources were also used for mid-IR generation (CHAPTER FIVE) and other novel applications which are shown in this chapter. The associated problems and limitations as well as the possibility of advanced systems are discussed.

4.1 Background

This section provides a conceptual and theoretical overview of the generation and amplification of the laser pulses. The design of the best-suited laser configuration requires the understanding and full consideration of the underlying laser concepts.
4.1.1 Concept of Q-switching

Q-switching is a comparatively simple, widely used technique which enables generation of laser pulses with kW level peak powers and short (nanosecond) pulse duration. The quality factor (Q) of a resonator cavity is defined as the ratio of energy stored to the energy lost in one resonator cycle. A high Q indicates lower intra-cavity losses and vice versa. The principle for generation of pulses by Q-switching is based on suddenly changing the Q from low to high value which subsequently generates high peak power, high energy optical pulses.

A comprehensive review of the Q-switched theory can be found in the reference [148]. The population inversion in a Q-switched laser cavity is generated by pumping the gain material. In the initial state of a Q-switched laser the cavity is “open” (the losses are high) which leads to a continuous increase in inversion. As soon as the population inversion (gain) reaches multiple times the lasing threshold value, the cavity Q is quickly switched by modulating the losses. This large inversion is then depleted through the built-up of a high energy optical pulse.

Q-switching in a fiber gain medium requires different considerations than crystalline gain medium due to the very high single-pass gain (typically >20 dB) in the fiber. The most commonly used Q-switching element to achieve high repetition rates is an acousto-optic modulator (AOM), meanwhile an electro-optical modulator (EOM) is used for lower repetition rates. An AOM device operates on the principle of diffraction into multiple orders at different angles when a beam is passed through the device [148]. Strain is induced in the AOM material due to an acoustic wave changing the local material density. As a result, a periodic modulation of the refractive index of the material is produced which further acts as diffraction grating for the beam. The diffraction efficiencies in the first diffraction order can reach 70 - 80 %. To
successfully achieve Q-switching in high gain oscillator, the cavity is formed from the first diffracted order. The primary reason for not operating in the zero order is that the high gain fiber laser system can start to lase in spite of the ~70 % loss due to switching of the AOM.

The Q-switched pulse duration in a fiber laser can be expressed as [157]

$$\Delta t = \tau_c \frac{N_{in} - N_f}{N_t \ln \frac{N_k}{N_{in}} (N_t - N_{in})} .$$

(22)

Here, $\tau_c = 2nL/c\delta$ is the cavity photon lifetime, $L$ the cavity length, $n$ the refractive index, $c$ the speed of light, $\delta$ the high Q round trip loss, $N_t$ the threshold inversion level, $N_{in}$ the initial inversion and $N_f$ the final inversion. $N_t$ and $N_{in}$ can be expressed as

$$N_t = \frac{\delta A}{2\sigma F_1}, N_{in} = \frac{\tau_s}{h\nu_p} P_{abs} .$$

(23)

In this equation, $\sigma$ is the stimulated emission cross section, $A = \pi d^2/4$ is the cross section (area of fiber core), $F_1$ is the overlap coefficient between signal and pump beam, $\tau_s$ is the upper state lifetime, $h\nu_p$ is the pump photon energy and $P_{abs}$ the absorbed pump power. Equation 22 shows that the pulse duration depends on the cavity length, cavity losses, and the pump power levels. As a consequence for a given system, higher pump powers lead to shorter pulse durations. Also, shorter fiber length leads to reduced cavity round trip time; hence shorter pulses. However, a fundamental limit exists since the pulse duration cannot be shorter than the cavity round trip time as the pulse has to travel through the cavity at least once to form the Q-switched pulse. This is the limiting factor in obtaining <20 ns pulses in fiber lasers due to typical fiber lengths of more than a meter.

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4.1.2 Concept of Pulsed MOPA

The pulsed MOPA concept is similar to the cw MOPA as discussed in section 3.3. Some of the output characteristics of an oscillator, e.g. spectral bandwidth, temporal pulse shape, and repetition rates are utilized and carried through the amplifier system. However, the amplification can have a significant impact on the pulse temporal profile and spectrum.

![Block diagram of a MOPA system. The isolator is required to prevent (higher power) feedback to the oscillator from affecting the overall performance.](image)

The basic parameters to be considered for the design of a cw MOPA (section 3.3.1) are gain, ASE and the onset of parasitic lasing. But for pulsed MOPA, ASE considerations are significant especially for repetition rates less than 10 kHz. Temporal and spectral changes due to amplification also need to be considered. The important considerations for pulsed MOPA are:

1) ASE: The ASE background occurs in high gain systems operating at lower repetition rates (<10 kHz). ASE content can be significant if the optical efficiency of the amplifier is low and if the time between two pulses is higher than the upper level lifetime. The upper state lifetime in thulium is ~200 - 550 µs corresponding to a frequency of ~ 2 kHz. A laser repetition rate below this 2 kHz will see more energy transferred to ASE built-up. In addition, longer length fiber amplifiers (especially for counter propagating configuration) show higher ASE content.
2) Distortions in spectral bandwidth and temporal pulse shape: The temporal shape of a pulse being amplified sees severe deformation when the pulse energy approaches the saturation energy of the amplifier.

![Graph](image)

Figure 37: The pulse distortion as seen from simulation when input 1.05 µJ pulses at 10 kHz are amplified in a flexible Tm:PCF to 530 and 680 µJ energies.

The leading edge of the pulse experiences higher gain and depletes the inversion/gain available for the trailing edge. Figure 37 shows the simulation of this effect. This pulse steepening effect was shown theoretically by Frantz and Nodvik in 1963 [158]. It has been studied comprehensively and controlled to produce desired pulse shapes [159, 160].

In addition to the temporal distortion, generally the spectrum also changes depending on the peak power initiated nonlinearities like SPM, SRS, SBS, and MI (Section 2.3.1).

3) Beam Quality: Fiber amplifiers inherently can offer fundamental beam quality. Recently, a new beam degradation process has been observed in very large mode diameter PCF
under high thermal load: modal instability. The output beam quality degrades rapidly and the modal output jumps from single-mode to fluctuating multimodal beyond a power threshold depending on the fiber design [161].

Apart from the above considerations, the amplifiers require isolation from feedback to the oscillator. A small amount of power fed back from the amplifier to the oscillator can distort the obtainable output or in worst case can even lead to catastrophic damage.

4.1.3 Historical Overview of ns-Peak-Power Generation in Thulium Fibers

The first Q-switched Tm-doped silica fiber system was demonstrated in 1993 by P. Myslinski et al. [55]. This system used an AOM for the pulse generation via Q-switching with modest levels (<150 mW) of Ti:sapphire laser pump. The output was limited to less than 10 mW with ~150 ns pulse-durations and ~4 W peak powers. El-Sherif et al. demonstrated a Q-switched configuration using a 17 μm core large mode area (SI-LMA) fiber to generate up to 2.3 mJ pulse energies operating at <100 Hz [162]. In this case, the pump was a 1.319 μm Nd:YAG laser and the output pulses were 320 ns in duration with 3.3 kW peak powers. The average power was below 100 mW due to the relatively low repetition rate.

The average power in TDFLs has increased after the advancement in AlGaAs diode laser pumps and improvement in fiber designs to avail the beneficial CR process. Jackson et al. used two 30 W, 792 nm pump diodes, an AOM Q-switched cavity, 2.3 m long double clad silica fiber to achieve 30 W power in 2007 [57]. In this case the minimum pulse duration obtained was 41 ns.
A fundamental limitation in obtaining short pulse durations of less than 20 ns is the round trip time in the fiber cavity. Cladding pumped silica step index fibers are often limited by maximum of 3 dB/m pump absorption at 790 nm. This essentially requires greater than 3 m of fiber length to absorb about 90% of the pump. It is possible to core pump the fiber at ~1550 nm wavelength leading to higher pump absorption and potentially allows to use shorter sections of Tm doped fiber [60]. The host glass can be changed to accommodate greater doping concentration of thulium ions leading to higher absorption. Fluoride, silicate and germanate host glasses not only provide increased upper-state ($^3F_4$) lifetimes but also allow higher doping concentration as compared to silica [100, 163]. However, the thermal and mechanical properties of these glasses greatly limit their abilities in high power applications.

An alternate technique to generate short pulses is gain switching, where the pump is pulsed/modulated to generate pulses shorter than the pump pulses. This technique relies on the availability of high energy/short duration pulsed pump laser (in the thulium case, typically Er: fiber lasers or single mode diode lasers at 1550 nm) and associated fiber components. Recently an all fiber gain switched thulium laser has been developed providing ~25 ns, 23 µJ pulses with 1.55 µm , 100 ns pump [64].

Geng et al. have demonstrated a single frequency Q-switched laser based on a distributed Bragg reflector (DBR) cavity with highly doped (5 wt. %) silicate fiber [60]. Since only 100s of nJ energy pulses were obtained, several amplifier stages were required to generate output at usable energy levels. A similar approach with germanate host fiber was used to generate pulses and amplify in three stages to obtain ~0.22 mJ pulse energies with 80 ns pulse-duration [63]. An
alternate technique was used to generate single frequency, temporally tunable sub 20 ns pulses. In this system, a single frequency cw oscillator output was chopped with a modulator and passed through subsequent amplifiers to obtain 0.5 mJ pulse energies with ~15 ns pulses [62]. Although the above system provided temporal tunability with transform limited pulses, the wavelength was fixed by the cw oscillator. In 2013, Stutzki et. al generated 2.4 mJ, 150 kW pulses with 33 W average power in a Q-switched oscillator involving Tm-doped large-pitch fiber [65]. This was a high pulse energy/peak power source but it lacked any spatial/temporal control on the obtained pulses.

The major portion of this thesis was dedicated to development of high peak power, narrow linewidth, spectrally and temporally tunable Tm:fiber nanosecond source which can be used for further OPO pumping. All the above mentioned systems do not fulfill a few/many of the requirements from the source. This thesis work demonstrates the steps towards the development of an extremely versatile, flexible and a high quality nanosecond source at 2 µm wavelength.

4.2 High Peak Power Oscillator

The first source to be developed was a simple, and robust high peak power/energy Q-switched fiber oscillator system. Two types of fiber designs have been verified for operation in high energy oscillator system. The SI-LMA 25/400 µm core/cladding fiber (Nufern, Inc.) and the flexible-PCF 50/250 µm core/cladding (NKT Photonics A/S). These fiber design properties have been described in detail in Section 2.2. Based on the modal analysis of these fibers, 40 % of the input is launched into the LP02 mode and 4 % into the LP11 mode. Upon coiling to 10 cm diameters, in spite of the bending induced losses for the HOMs, ~5 % of the light still remains in
the HOMs. The cladding light content increases due to the loss induced in the HOMs. In comparison, the flexible-PCF launches only 4.3 % into the LP11 mode which is reduced to less than 3 % for about 40 cm coiling. Apart from the modal properties, pump absorption is higher (~5.8 dB/m) in the flexible-PCF as compared to ~2.3 dB/m for SI-LMA fiber. Hence the oscillator length is kept lower for PCF in comparison to SI-LMA.

Building up on the work on cw-oscillator (Section 3.2), the PCF fiber’s usability for pulsed operation is compared to SI-LMA fiber. Q-switched oscillator configuration is used for comparison of high energy pulses.

4.2.1 SI-LMA based Oscillator

A Q-switched oscillator has been built to generate greater than 100 µJ pulse energy with ns pulse-duration. The high amount of stored energy in the SI-LMA fiber offers a simple cavity design. In addition, the SI-LMA fiber allows the overall output to be highly polarized.
Figure 38: The schematic of Q-switched oscillator utilizing ~3.3 m of Tm:SI-LMA PM fiber as active medium. The laser is formed between the feedback element and the 4%-reflecting flat cleave. The AOM is the Q-switching element. Intra-cavity HWP and PBS are used to lock the polarization. The external HWP, PBS and aperture are utilized to determine the signal in the core.

A schematic of the oscillator setup is shown in Figure 38. The laser cavity was formed between feedback element and the flat cleave (4 % Fresnel reflection). The pump source for the system was a 100 W, 793 nm diode laser (DILAS Diodenlaser GmbH). The pump delivery fiber had 200/240 µm core/cladding diameter with a core NA of 0.22. The pump delivery fiber output was coupled in the fiber end via a 1:1 telescope system and a dichroic mirror (HR @ 800 nm, HT @ 2000 nm). Both the ends of ~3.3 m active Tm:SI-LMA PM fiber were spliced to passive leads for the purpose of thermal management. The angle-cleaved (~6-7°) passive fiber was followed in the resonator by a triplet (f = 25 mm) lens for collimation, PBS/HWP to lock the polarization as well as an AOM for Q-switching. The AOM deflected ~66 % of the light in 1st diffraction order which was fed back with the feedback element. This element can be a reflection grating, mirror or volume Bragg grating (VBG). The results discussed below are obtained with a HR mirror.
The output was measured with the aperture setup as described in section 3.2.1, Figure 20. The high cavity loss modulations by the AOM suppressed any cw lasing or parasitic self-pulsing of the resonator. Pre- and post-pulses were avoided by the sharp on/off switching time of the AOM (~300-400 ns). The ASE content was verified for the SI-LMA oscillator case in a relatively simple setup: the output was transmitted through an electro-optic pulse picker setup (Figure 39). The output in this pulse gate was compared to the total average power and it was found that about ~94 % of the total power was measured in the gate at 10 kHz operation. The ~6 % loss was verified separately to be in the PBS at the output of the electro-optic gate system. As a consequence of this test, the measured average power corresponded directly to the pulse energy of the emitted Q-switched pulses, without ASE background; hence the pulse energy can be directly retrieved.

![Figure 39](image)

Figure 39: The setup of the electro-optic gate to determine the component between the pulses. The first HWP was used to align the input beam polarization with in the ‘p’ polarization and the 2nd HWP was used to align the beam polarization with ‘s’ polarization. HWP: half wave plate and PBS: polarizing beam splitter.

The pulse energies were verified by the schematic shown above and the output pulse energy is shown in Figure 40(a).
Figure 40: a) The pulse energy at different pump levels and repetition rates for the Q-switched oscillator, b) The pulse duration at different launched pump powers and repetition rates, and c) The corresponding peak power levels.

The maximum pulse energies obtained for 10 kHz and 20 kHz were about 270 µJ (corresponding to ~1.62 kW peak power) and for 50 kHz was 190 µJ (~0.9 kW peak power). This output spectrum was not controlled since HR mirror was used as the feedback element.

The laser source showed stable output with ~150 ns pulse-duration and output energies of >250 µJ at different repetition rates. A similar laser source was used for performing LIBS on copper samples which will be discussed in section 4.4.1.
4.2.2 Flexible-PCF based Oscillator

The flexible-PCF was tested for cw-operation (section 3.2.3). Its performance was directly compared to the SI-LMA in a Q-switched oscillator system. The fiber design with its larger MFD of 36 µm allows the operation at higher peak powers as compared to the SI-LMA fiber (Table 1).

The oscillator setup (Figure 41 (a)) was kept similar to the one for SI-LMA Q-switched oscillator (Figure 38). The active fiber used in the setup was 50/250 µm core/cladding diameter flexible-PCF doped with 2.5% wt. thulium doping. The air cladding NA was >0.45 and encompassed a hexagonal air hole lattice with a d/Λ of 0.18 and a pitch of 12.8 µm. The incorporated boron-doped stress rods induced birefringence of $\sim10^{-4}$ giving PM properties to the fiber. The pump source was a 790 nm, 100 W fiber coupled laser diode (DILAS Diodenlaser GmbH). It was free-space coupled in the fiber as shown in Figure 41(a). The Q-switching element was an AOM. The output was measured using an aperture in similar setup as shown in Figure 20.
This configuration was able to generate ~49 ns pulses with ~8.9 kW peak powers with excellent polarization properties (>18 dB PER) and nearly diffraction limited beam quality at 10 kHz [61]. The feedback element used for this measurement was high reflectivity (HR) mirror. The performance of this laser was measured at repetition rates of 10, 20 and 50 kHz and the average power slope efficiencies obtained were 25.9, 31.9 and 33.0 % respectively. The output spectrum was stabilized by replacing the HR mirror with a gold-coated reflection grating as the
feedback element. Using the grating in the cavity, the laser produced ~75 ns pulses with >5 kW peak powers at 10 kHz and maintained a linewidth of ~0.25 nm FWHM.

4.2.3 Comparison of SI-LMA and PCF-based Oscillator

In spite of similar total output powers for both the fibers, the maximum pulse energy was ~270 µJ for SI-LMA system as compared to ~435 µJ for PCF case. The corresponding peak power was <2 kW for the SI-LMA whereas it was ~8.9 kW for PCF. To analyze the difference in output better, the cladding light was obtained using the rejected light in the aperture setup (Figure 20). This obtained power is plotted as a percentage of the total output power with the obtained pulse energies. Figure 42 (a) and (b) shows the results obtained for SI-LMA and PCF respectively.

![Graph](image)

Figure 42: The cladding light as a percentage of the total power (core + cladding) for a) SI-LMA fiber oscillator, and b) PCF oscillator. The percentage of cladding light sees a steep rise after ~100µJ in the SI-LMA fiber [113].
It can be seen from Figure 42 (a) that the percentage of cladding light started to increase after \(~100\ \mu J\) pulse energy for the different repetition rates. Hence the amount of light in the HOM increased proportionally to the power in the cavity. Since the degradation accelerated with high pulse energies, it can lead to the conclusion that it occurs due to strong mode-coupling and onset of lasing of higher order modes (HOMs), in particular the LP02 mode. It can be explained in a simple (but unproven) picture in the following way. As shown in Section 2.2.1, the fiber supports multiple modes which share the same gain medium (core of fiber) as the fundamental mode. When light is launched in the fiber, up to \(~40\ %\) of power can be transferred to the LP02 mode. The LP02 mode has higher bending loss and typically leaks out completely into the cladding, thus prohibiting this mode from any participation during lasing. The strong coupling from fundamental to HOM is responsible for the observation of \(~20\ %\) of output light from the cladding in the case of SI-LMA and \(~15\ %\) in the case of PCF. In addition, at higher cavity photon densities, i.e. for pulse energies above \(~100\ \mu J\) for the SI-LMA fiber, the coupling between fundamental mode and LP02 results in a considerably high amount of coupled seed power in the LP02 mode. If the pump power is increased further, this seeded LP02 mode will eventually overcome its high lasing threshold resulting in a seeded-oscillator configuration. This increase of considerable power in the LP02 mode corresponds to the onset of accelerated degradation. A further increase of pump power will increase the output power of both lasing modes as well as increase the absolute seed power for the LP02 mode. Thus, the output power of the LP02 mode grows faster than a typical linear slope leading to accelerated overall output power degradation, as seen in Figure 42 (a).
The cladding light of 15 - 20 % was observed in the flexible-PCF Q-switched oscillator but without the accelerated increase. This is accredited to the robustly fundamental mode operation of the flexible-PCF. As a consequence, this PCF-based system gives efficient high energy Q-switched operation with high and non-degraded fundamental mode content.

4.3 High Peak Power MOPA

The output obtained with linewidth control in the Q-switched oscillator was greater than ~ 5 kW peak power. Higher peak powers (typically >50 kW) with flexibility in the wavelength and pulse-duration (5-100 ns) are preferred for nonlinear conversion and other ablation experiments. In order to increase the obtainable peak power beyond the performance of the oscillator, a master oscillator power amplifier (MOPA) was developed. The MOPA configuration enabled scalability of the output power while preserving and controlling the relevant parameters, such as spectral bandwidth and temporal pulse shape. Fibers with increasing MFA and shorter lengths are generally used in subsequent amplifier stages primarily to extract higher gain and prevent the onset of nonlinearities/damage.
Figure 43: Schematic of the Q-switched MOPA setup. The oscillator utilizes ~4 m of Tm doped PM 10/130 µm core/cladding fiber, an AOM for Q switching and a grating for wavelength control. The output from the oscillator passes through a pulse picker, isolator into a PCF-based amplifier pumped by up to 100 W at 790 nm.

Figure 43 shows a schematic of the single-amplifier MOPA system. The oscillator was based upon a step-index 10/130 µm PM thulium-doped single-mode fiber. The feedback element was a 600 line/mm gold coated reflection grating and the Q-switching element was an AOM. The pulsed output was passed through an EOM (Fastpulse Technologies, Inc.) which can be temporally synchronized with the AOM driver. The EOM consists of a RTP (Rubidium Titanyl Phosphate) crystal and a driver with < 3.5 ns rise/fall times capable of slicing > 5 ns duration pulses. The pulse picker with pulse slicing capabilities allowed significantly shorter pulse durations (< 10 ns) than supported by the Tm:single-mode fiber Q-switched oscillator (~60 ns).

The following section is structured to first show the design and characteristics of the high-quality oscillator. The seeding oscillator dictates the laser parameters which are conserved through the MOPA configuration. A robust, high-quality oscillator with controllable parameters
is essential to obtain the high peak power output. The amplifier design investigated in this MOPA configuration is shown in this section.

### 4.3.1 High-Quality Seed Oscillator

Several parameter constraints are directly imposed on the seed oscillator of the developed MOPA system, including spectral tunability with narrow linewidth. The coupling of the seed into amplifier stage requires a high degree of polarization with robustly single-mode beam quality. Since the system is intended to be highly robust and stable, a minimal amount of free space components were utilized.

The oscillator fiber was thulium-doped single-mode PM 10/130 µm fiber (Nufern) and a schematic of the system is shown in Figure 43. The nature of this fiber was robustly single-mode and the compatible optical components like combiners are available. The fiber was cladding-pumped up to 35 W at 793 nm with a pump diode (DILAS Diodenlaser GmbH) via a 2+1:1 beam combiner. This pumping configuration allowed replacement of traditional free space pump coupling optics increasing the robustness of the overall system. The passive output fiber of the combiner was spliced to ~4 m of the active fiber wrapped around a mandrel placed on a water cooled aluminum plate. A reflection grating was used as the feedback element to control the output spectrum. The other end of the active fiber was spliced to a matching passive fiber and its cleaved end was used as 4 % output coupler. Q-switching was achieved with an AOM.
The nanosecond oscillator provided polarized pulses due to the inclusion of polarization locking components in the cavity (PM fiber, a beam cube and a wave plate). It produced a narrow linewidth spectrum (~0.5 nm) with wavelength tunability extending from 1835 nm to more than 2015 nm. Pulse energies with up to 50 µJ and a minimum pulse width of 60 ns (Figure 44) were generated. The repetition rate of the system can be selected by the AOM driving signal. A comparison of the performances at 10 and 20 kHz is shown in Figure 44.
Figure 45: The spectral evolution of the pulses at 20 kHz with different peak powers. SPM induced broadening is seen at higher peak powers.

The output linewidth was controlled by a grating which gives spectral width typically >0.1 nm, as shown in Figure 45 (black). This did not correspond to a time-bandwidth limited pulse-width considering that the ~75 ns pulse at 1950 nm gives theoretical transform-limited linewidth of ~0.075 pm. The theoretical longitudinal mode spacing is ~0.18 pm (14.22 MHz) and hence, the output contained >500 longitudinal modes.

No saturation effects were observed at high pulse energies (~65 µJ for 10 kHz and >50 µJ for 20 kHz), but the performance of the oscillator was limited by spectral broadening. The ~7 m path (with ~6.5 m in single-mode fiber) and the high peak power lead to the onset of spectral broadening as shown in Figure 45. This SPM induced broadening is based on the principles discussed in Section 2.3.1. As a result, the practical limitations of the system were reached at ~350 W peak powers in order to maintain the spectral linewidth < 1 nm FWHM.
4.3.2 Pulse Picking and Temporal Slicing

The system presented in the previous section generates output pulse duration mainly depending on the gain extraction dynamics. Thus, the minimum achievable pulse duration is limited by the cavity round trip time and the gain in the active fiber. To achieve pulse duration below the cavity round trip time (~55 ns) limit, a pulse picker with temporal pulse slicing capability was employed. In this scheme, the Q-switched pulses were shaped directly by the temporal slicing due to the fast rise and fall times (~3.5 ns) of the EOM based on a RTP crystal (Fastpulse Technology, Inc.). The EOM device supports a maximum repetition rate of 20 kHz with pulse width <6 ns and is placed in the system directly after the oscillator.

This slicing method enabled the generation of sub-10-ns pulses with considerable energy. The ‘traditional method’ used to generate sliced pulses is temporal slicing off a cw output. However, this system is not optimum. For example, the output from a currently available diode at 2 µm wavelength is of the order of 10 - 30 mW [164] and <3 mW with wavelength control [165]. If a pulse of 10 ns was carved out of 20 mW source at 100 kHz, the average power output would be about 20 µW with 200 pJ pulse energies. To amplify this output to 2 µJ pulse energy a gain of ~10⁴ (or 40 dB) is required which demands typically 2 stages of amplification. Thus, multiple amplifier stages and technical complexity can be replaced by the Q-switched oscillator plus pulse slicer system to achieve seed pulses directly at the multi-µJ level.

The Q-switched pulse slicing method requires robust temporal synchronization. The timing jitter of the oscillator was quantified using an oscilloscope with respect to the modulating signal sent to the AOM (Q-switching element). The timing jitter was less than 5 ns for 30 µJ pulse energies when operated at 10 and 20 kHz repetition rates. The timing jitter of the external
cavity pulse slicer (Fastpulse Inc.) was less than 1 ns. To obtain stable pulses, the oscillator was operated at 20 kHz repetition rate and generated ~700 mW average output power. It produced ~30 µJ pulse energy and the pulse duration obtained was ~100 ns. Sub-10 ns pulses were carved from this 100 ns pulse by the external pulse slicer. The amplitude jitter of these pulses was less than 10 % before as well as after amplification.

The above mentioned oscillator in combination with the pulse slicer is a unique system capable of wavelength tunability ranging from ~1850 – 2015 nm, narrow linewidth of < 1 nm, temporal tunability of ~5 – 100 ns and flexible pulse repetition rate from 20 kHz to as low as 100 Hz. The above flexibility with pulse energy of > 30 µJ (at 100 ns pulse duration) makes this a unique, high quality seed which can be amplified to multiple mJ pulse energies.

4.3.3 Flexible-PCF Amplifier (Long Pulse)

The true advantage of the PCF lies in the large MFD and hence, higher energies can be extracted in pulsed operation. The amplifier was first operated for higher pulse energies at ~1990 nm at 1 and 10 kHz repetition rate. The fiber used for the amplifier was ~2.7 m of 2.5 % Tm$_2$O$_3$ doped 0.18 d/ʌ ratio PCF. The input to the amplifier was ~410 mW average power and 106 ns pulse duration at 10 kHz. The amplifier generated an output of 1.01 mJ pulse energy with initial signs of roll off at highest pump powers as shown in Figure 46.
Figure 46: The output energy from the MOPA at ~90 ns pulses leading to maximum pulse energy of ~1.01 mJ at 58 W pumping.

The amplifier performance was verified at low repetition rate (1 kHz) at wavelengths of 1963 and 1990 nm (Figure 47). The input seed was maintained at pulse durations of 90 ns for 1963 nm and 100 ns for 1990 nm with a linewidth of ~1.5 nm. The Figure 47 shows a gain exceeding 20 dB for 5 µJ pulses. The overall gain is lower at 1990 nm as compared to 1963 nm under similar conditions due to the lower emission cross section at 1990 nm (Figure 6).
The next amplification considered was at high repetition rate (100 kHz), with pulses of 300 ns (1965 nm) and ~292 ns (1992 nm) by varying the seed in the amplifier from 25 mW to about 2 W (Figure 48). The output power (hence the gain) shows saturation effect after ~0.4 W of seed input. This shows correspondence to predicted theoretical value of 0.41 W at 1963 nm and 0.48 W at 1993 nm for the flexible-PCF (Figure 28). The slope obtained at 0.5 W input seed was 22.9 %, 25.4 % at 1992 nm and 1965 nm respectively. This is comparable to cw slope efficiencies of 27.6 % at 1966 nm and 21.7 % at 2008 nm (section 3.3.2).
Figure 48: The amplification with change in input seed power at 100 kHz, ~300 ns pulses at 1965 nm (black) and 1992 nm (red). The above plot is seen with pump power of a) 14.5 W, b) 34.7 W and c) 49.3 W.

The repetition rate dependent amplification characteristics were studied and shown in Figure 49.

Figure 49: Measured gain at different repetition rates and at amplifier pump powers of 14.6, 23.7 and 32.8 W. The input seed to the amplifier was kept at ~30 µJ, 115 ns pulses at 1990 nm with ~0.89 nm FWHM linewidth. The development of gain is seen with respect to different repetition rates keeping the input pulse energy constant.
The oscillator was operated at 20 kHz at 6 W pumping resulting in an average output power of 590 mW incident on the amplifier fiber after the pulse picker and isolator. The pulse repetition rate was changed by varying the trigger in the delay generator driving the Pockels cell. The input pulse energy was kept constant at ~30 µJ and the pulse duration was ~115 ns. The oscillator was operated at 1990 nm with 0.89 nm spectral FWHM linewidth. Figure 49 demonstrates the gain at 0.5 – 20 kHz repetition rates keeping the input pulse energy constant. Based on the experiment, it can be seen that the highest gain is achieved for 1 kHz repetition rate and it decays on either side of it. At higher repetition rates, the inversion buildup is not optimum for highest gain while at lower repetition rates, due to the lifetime of the upper level, the inversion buildup is lost and ASE starts increases ‘stealing’ away the signal gain. This feature is noticed at lower gain values whereas for higher gain and shorter pulses (Figure 50(a)), the gain seems to reach a steady state at repetition rates less than 2 kHz.

In conclusion, the long pulses (100 ns) were amplified in this system to 1 mJ-level pulse energy. The corresponding peak powers were rather modest and on the order of 10 kW. The system was then operated in the short pulse duration domain which would enable high peak powers. The pulse duration was reduced below 10 ns by utilizing the temporal pulse slicing capabilities. The amplification of these short pulses towards higher peak powers and the corresponding amplifier characteristics are shown in the following section.

4.3.4 Flexible-PCF Amplifier (Short Pulse)

The obtained Q-switched pulse can be sliced to generate shorter pulse durations using the EOM pulse slicer as mentioned in the previous sections. The pulse slicer is mainly restricted by
the high voltage switching in the driver with a ~3.5 ns rise/fall time generating a clean optical pulse as short as ~7 ns. Below this 7 ns window, the modulation depth of the EOM switching is lower than 100 % and causes lower transmitted pulse energies. In addition, ringing was observed in the high voltage switching system of the Pockels cell driver when operating below 7 ns. As a consequence, clean pulses were only observed when the EOM switching and corresponding pulse width was kept >6.5 ns corresponding to a shortest optical pulse width of 6.5 – 7 ns.

The oscillator wavelength was fixed at 1965 nm and pumped at ~6 W to provide ~ 40 µJ pulses with pulse width of ~90 ns. The output is restricted to these energy levels to maintain reasonably narrow linewidth (~0.5 - 0.6 nm FWHM). The pulses are chopped using the pulse slicer to ~6.5 ns with an average power of ~30 mW corresponding to 1.5 µJ pulse energy.

![Graphs](image)

Figure 50: a) Measured gain at different repetition rates and pump powers of 60, 51 and 42 W and b) the pulse energy characteristics with respect to pump power for 1 kHz, ~6.8 ns pulses at 1965 nm wavelength.

The gain at different repetition rates at three pump power levels of 42, 51.1, and 60.3 W is shown in Figure 50 (a). The Figure 50 (b) shows the output characteristics of the amplifier at 1
kHz repetition rate and input of ~1.5 µJ pulses at ~6.8 ns pulsewidth. As seen in the figure, the output pulse energy obtained at pumping levels of 33, 51 and 69 W was 70, 309 and 527 µJ respectively. The corresponding gain obtained was 19, 25 and 28 dB respectively.

![Figure 51: a) The ASE generated in the backward direction as compared to the pump power in the 2.7 m Tm: PCF and b) The rejected light from the electro-optic gating technique (Figure 39) for 1 kHz, 6.8 ns pulses at 1965 nm.](image)

At lower repetition rates than 2 kHz, especially <1 kHz, ASE was generated which was verified utilizing the electro-optic gating technique deployed in Figure 39. The rejected light (Figure 51 (b)) at 1 kHz, 6.8 ns pulses at 1965 nm was corrected for the losses and it corresponded to the ASE content. The total backward propagating ASE without seeding is shown in Figure 51 (a). About 13 % of the total output was rejected in the electro-optic gating when pumping at 70 W. As a consequence, ASE can be readily accounted for in the output powers obtained. In addition, the pulse energies at different pumping levels (Figure 50 (a)) can indicate a trend for other radiation losses. As the repetition rate was lowered from 10 kHz to 2 kHz, the pulse energy obtained at a given power increased almost linearly (in log scale). Below 2 kHz, the
pulse energy obtained at a given power reached saturation; thus any additional pumping at these repetition rates was radiated out of the fiber without being converted to additional lasing pulse energy or ASE. This corresponds to the radiation lifetime of thulium in silica fibers of about 650 µs [100](3F4 to 3H6 energy levels).

Figure 52: Obtained temporal pulse profile for different pulse energies after MOPA at 1 kHz with increase in pump (a) and the corresponding spectral profile (b). Pulse steepening was seen at pulse energies greater than 300 µJ.

The pulse shape and spectrum is shown in Figure 52 (a) and (b) respectively. The pulses start showing strong steepening above ~300 µJ pulse energies. The pulse steepening is discussed in the section 4.1.2. This steepening can be considered beneficial since it produced sub-5 ns pulses but this altered pulse shape could not be easily correlated with Gaussian pulse shape and needed to be specially considered for the applications.

Because of the distorted pulse shapes obtained due to high gain, the peak powers were deduced from the pulse profile using Origin software. The pulses at 369, 435 and 527 µJ energies showed corresponding peak powers of 53, 74 and 104 kW respectively.
Along with the low ASE in the flexible PCF, another important feature of the PCF is single-mode beam quality. As discussed in section 2.2.2, the PCF maintained single-modal beam quality. The M-square measurement in the case of cw and pulsed amplifier is seen in Figure 53. M-square values of <1.05 were obtained for the flexible-PCF for cw amplification. The figures c) and d) show slightly degraded M-square values. The reason of this is mainly the astigmatism introduced in the output due to the >30° angle of the pump reflection mirror. This astigmatism was greatly reduced by restricting the angle <20°.

Figure 53: Measured M-square values of the PCF amplifier output at 1 W cw power levels (a), 5.5 W cw power level (b), 62 W pumping at 2 kHz repetition rate at ~6.8 ns, 1963 nm (c), and 62 W pumping at 10 kHz repetition rate.
rate at ~6.8 ns, 1963 nm (d). The M-square values were higher for 2 and 10 kHz operation as compared to cw operation.

The high pulse energies obtained and the low ASE content allowed the output to be considered for further power amplification stage even at low repetition rates (<2 kHz).

4.3.5 **PCF-Rod Power Amplifier**

A Second stage power amplifier was added after the flexible-PCF stage based on the PCF-rod to obtain higher pulse energies. This work was done with Christian Gaida. The PCF rod is doped with 2.5 % Tm$_2$O$_3$ and co-doped with aluminum with a Tm/Al ratio of 1:8. The rod is 1.36 m long with 80 µm core and 220 µm air cladding. The mode field area is estimated to be >2500 µm$^2$ for MFD of ~56 µm with a core NA of ~0.02. The cladding NA is >0.4 for 790 nm with pump absorption of ~17 dB/m. The air lattice around the core has air-hole diameter to pitch ratio of 0.191 with a pitch of 13.7 µm.

![Diagram of the two stage amplifier](image)

Figure 54: The layout of the two stage amplifier comprising of a Tm: PCF-rod power amplifier.
The rod was placed on a 1.36 m long metal V-groove which was held between the metal blocks as shown in Figure 54. This V-groove was cooled with water cooled aluminum blocks. Six metal blocks were placed to maintain the outside temperature of the rod to \( \sim 13 \, ^\circ C \). The rod ends were collapsed and then angle cleaved to \( \sim 4 \% \) to avoid parasitic lasing. The amplifier was counter-pumped by a laser diode at 793 nm with up to 100 W (DILAS Diodenlaser GmbH). The pump output was fiber coupled with a 200 µm delivery fiber which was then coupled in the end facet of the rod via a 1:1 telescope system.

The ASE spectrum produced with the PCF-rod showed peculiarly broad characteristics [98]. This ‘broadness’ of the ASE is greater than 300 nm of -10 dB bandwidth. The large contribution from wavelengths below 1850 nm can be attributed to the relatively short length of the rod causing lower signal reabsorption in addition to the glass composition.

For the power amplification stage, the oscillator in the single stage MOPA (section 4.3.4) was pumped with \( \sim 6 \) W and produced \( \sim 100 \) ns pulses at 20 kHz. The spectrum was maintained \( \sim 0.8 \) nm centered at 1965 nm wavelength. These pulses were then amplified in the flexible-PCF (first amplification stage). In the \( \sim 100 \) ns amplification, the input pulse energy is maintained at \( \sim 200 \) µJ at both 10 and 20 kHz repetition rates.

The ASE content in the PCF rod was measured to be less than \( \sim 500 \) mW at the highest pumping levels. This makes the rod a promising option for pulsed amplification especially for low repetition rate, high peak power amplification. Another distinct advantage of PCF rod as a final amplifier is the fact that it maintains the polarization of the input beam which was observed but not explored in detail.
Figure 55: a) The pulse energy scaling at different pulse duration and repetition rates. b) The pulse profile at 1 kHz, 6.3 ns with 48 W pumping and c) the profile at 10 kHz, 6 ns at 109 W pumping [166].

The pulses are amplified to 1.56 mJ and 0.9 mJ levels for 10 and 20 kHz respectively at 110 W pumping as shown in Figure 55 (a) (black, red). The obtained gain is 11 dB (or 12.5 times) for the 10 kHz repetition rate and 8.8 dB (or 7.6 times) for the 20 kHz repetition rate. The gain and the output energy here were not limited by the energy in the fiber but by the maximum output power <20 W due to the extremely low slope efficiencies. The slope efficiencies for the output power were 13.4 % for 10 kHz and 13.6 % for 20 kHz.

The pulse slicer was used to produce 6.3 ns pulses with incident pulse energy on the flexible PCF amplifier of ~1.5 µJ. The output pulses of the flexible-PCF amplifier were then incident on the rod with 66.1 µJ pulse energy at the 10 kHz repetition rate. These pulses were further amplified to 1.02 mJ energy levels at 101 W pump corresponding to a gain of ~12 dB (or 15.8). The gain can be increased up to 17 dB when seeding the amplifier at 1 kHz repetition rate.
with 6.3 ns pulse duration and ~250 µJ pulse energy. The total output power obtained was 7.3 W as shown in Figure 56.

Figure 56: The Output power from the PCF-rod amplifier at 1 kHz amplification. The seed was ~0.25 W at 1965 nm at 1 kHz with 6.3 ns pulses [166].

The temporal and the spectral output were analyzed. The spectrum did not show any significant degradation/broadening and the pulse maintained its profile without traces of pulse steepening. The pulse duration was verified using the extended InGaAs photodetector and the trace is shown in Figure 57 (b). In addition, the beam profiles at 1 kHz and 10 kHz for 6.3 ns pulses are shown in Figure 55 (b) and (c), respectively, and are consistent with the good beam quality as seen in cw amplification.
Taking into account the output power, repetition rate, cladding light (~10 %), Gaussian pulse shape, temporal power content of ~97 % in the main pulse of the 6.3 ns pulses, a pulse energy of 6.4 mJ corresponding to 0.92 MW peak powers for 1 kHz can be conservatively estimated. The corresponding values for 10 kHz were ~1.5 mJ and 150 kW peak power. Considering, in addition the ASE content as measured without the signal, the peak power was estimated conservatively to be 0.89 MW [166]. The presented peak power is currently the highest peak power reported in a nanosecond pulsed thulium fiber system.

4.4 Explored Novel Applications

The target application for the developed high peak power, nanosecond system is pumping non-linear crystals like ZGP and OP-GaAs to generate pulses with mid-IR wavelengths. Also the robust fiber source with high energy and peak power levels at 2 µm wavelengths offered the opportunity to investigate unexplored applications. Due to the lack of comparable systems operating at 2 µm systems, all these applications were carried out in a novel fashion.
4.4.1 LIBS with 2 µm Driving Laser

LIBS was explored using exactly the system shown in Section 4.2.1 [66]. This work was done by Matthieu Baudelet and Christina C. C. Willis. The laser was used with output energy of ~100 µJ and ~200 ns pulse-duration at 1992 nm at 20 kHz repetition rates. The output was focused on copper sample using 11 mm aspheric lens to produce ~10 µm spot size on the sample.

![LIBS Spectrum](image)

Figure 58: The LIBS spectrum obtained with 2 micron irradiated copper sample. The inset is an extended version of the obtained spectrum [66].

The generated LIBS signal was analyzed in a 250 mm Echelle spectrometer (Acton HRE, Princeton Instruments). The first characteristic of the spectrum was the absence of laser signal since it lied comfortably outside the detection range. The second was the lack of continuum emission which due to low electron density of the plasma resulting from the low irradiance of 2 µm signal (~600 MW/cm²). The third important characteristic was that the spectrum did not
exhibit atmospheric nitrogen and oxygen transitions again because of the low irradiance of the 2 µm signal.

This work demonstrated LIBS on Copper samples using TDFL as the ablation source for the first time [167]. It is a proof of concept experiment and has proved that the robust thulium Q-switched oscillator can be a novel interesting source for LIBS applications [66, 167].

4.4.2 Silicon Backside Machining

Silicon is transparent for 2 µm wavelength since it corresponds to energy lower than the bandgap of 1.1 eV (~ corresponding to 1.13 µm wavelength). The transparency can be used to carefully ablate only the backside of silicon material under with tight focusing due to the increased irradiation given by the focusing geometry. The source presented in section 4.3.4 with high peak power, sub-10 ns pulses and >300 µJ pulse energies in the thulium bandwidth was utilized for this set of experiments. This work was done by Tobias Bonhoff and Ilya Mingareev. The source was used to verify the backside ablation in a 500 µm thick silicon wafer sample.

The backside of the silicon wafer was targeted with a tight focus of ~10 µm diameter for the pulsed source. Backside ablation was observed without damage on the front side. Figure 59 shows the back side ablation in reference to front side ablation.
Figure 59: Experiments with ablation in silicon wafers with ~6.8 ns pulses at 1965 nm with a repetition rate of 1 kHz. The potential use of the system is characterized for the first time for comparison of a) front-side ablation and b) back-side ablation [96] (Courtesy: Tobias Bonhoff).

The single pulse backside ablation threshold was estimated to be ~40 J/cm² with ~6.8 ns pulses at 1985 nm. This experiment is a proof of concept and the underlying process needs to be understood better. With the successful implementation in initial stages, backside machining in semiconductor materials can find specific usability in advanced manufacturing of solar cell and microelectronics industry. The work was presented in SPIE Photonics West 2013 [96].

### 4.5 Summary and Outlook

A high peak power and high energy source is desired for the target application of frequency-conversion into the mid-IR in nonlinear crystals. The Q-switched nanosecond thulium fibers presented in Section 4.2.1, based on SI-LMA-fiber was limited in pulse energies to ~270 µJ corresponding to ~1.6 kW peak powers. The output performance shows increased onset of HOM content after about ~100 µJ pulse energies. This limits the peak power and pulse energy obtained. Novel thulium doped flexible-PCF and PCF-rod were used for high peak-power-
scaling. The flexible-PCF in a Q-switched oscillator configuration produced ~49 ns pulses with ~9 kW peak powers as shown in Section 4.2.2. A MOPA configuration was deployed to reach peak powers higher than the ~10 kW limitation of the oscillator-only design. The flexible-PCF-based power amplifier was able to produce ~ 100 kW peak power with sub-6-ns pulses at 1 kHz repetition rates. Further peak power increase was achieved by an additional power amplifier based on a PCF-rod with larger MFD of ~56 µm. This system was able to generate record level ~0.9 MW peak powers as shown in Section 4.3.5. The spectral width was maintained to <1 nm with a wide wavelength tunability in the thulium band.

Figure 60: Some simulation results for the Tm:PCF rod. The energy extracted at 100 W pumping at 1 kHz repetition rate is plotted against a) increase in input seed energy for 6 ns pulses and b) increase in the input pulse duration keeping the peak power at 10 kW (courtesy: Christian Gaida).

The output power and pulse energy obtained from the PCF-rod was verified by simulating the thulium doped PCF-rod amplifier (by Christian Gaida). The output from the simulations was in close agreement with the experimental data. The model was further used to predict the pulse energy which could be extracted at 100 W pump level with increased seed
energy (Figure 60 (a)) and increased seed pulse-durations (Figure 60 (b)). It can be concluded that greater than 1 MW peak power can be obtained from the current system with increase in the input seed. However, scaling beyond 10 MW requires increase in the pump level to > 200 W and input seed with sub-ns pulse duration. These sub-ns pulses cannot be generated from the current system. Either mode-locked laser system needs to be implemented or modulators with fast switching (<100 ps) are required. The seed can be generated by mode locked laser system. The first anticipated nonlinear limitation on the output is SRS at ~1.7 MW (Table 1). The damage threshold for the fiber end facet is suggested to be >1.6 MW (for 5 ns pulses). But the accuracy of this estimation of damage threshold needs to be verified at 2 µm wavelength. However, the damage threshold can be increased by appropriate end-capping the PCF-rod.

The above mentioned system was further used to explore novel applications benefiting from high peak power and high pulse energy as well as the 2 µm wavelengths. Applications like LIBS on a Copper substrate, and silicon backside ablation were explored and summarized in Section 4.4.
CHAPTER FIVE: NONLINEAR MID-IR CONVERSION

Mid-IR generation starting with the 2 µm nanosecond laser source has been one of the main motives behind the development of the high peak power, versatile source described in section 4.3. The Tm-MOPA system generates high beam quality, sub-10 ns pulses with narrow linewidth (< 1 nm) and high peak power (> 20 kW). This source is an attractive pump for broadband supercontinuum generation in the mid-IR as well as nonlinear conversion using crystals like ZGP and OPGaAs to convert to pulses with >5 µm wavelength. This section covers the nonlinear conversion by supercontinuum generation and processes like DFG and OPO. The underlying theory is discussed first, followed by description of recent experiments, concluding with an outlook and summary.

5.1 Supercontinuum Generation

Supercontinuum generation (SCG) is the result of spectral broadening resulting from the interplay of nonlinear and linear effects for a propagating optical pulse. Supercontinuum can be generated during propagation through various materials. The focus here is silica-and fluoride-based optical fibers due to their compatibility with nanosecond Tm:fiber pumping.

5.1.1 Background Considerations

Several factors are associated with the dynamics seen in SCG. The primary contributions are dispersion, SPM/XPM (cross phase modulation), soliton dynamics, dispersive waves/Raman scattering, and four wave mixing (FWM)/modulation instability (MI). The dispersion and soliton concepts are explained in APPENDIX B and the other phenomena are explained in section 2.3.1.
This section describes SCG in anomalous regime pumped by ns (long) pulses. In this specific SCG regime, first the pulse breaks into solitons due to MI process in the anomalous dispersion regime. These solitons collide, resulting in a few solitons with high peak power and many low power solitons. Long wavelengths are generated by each of these solitons since they experience a Raman induced frequency shift (RIFS) given by [132]

\[
\frac{d\Omega}{dz} = -\frac{8\tau_R|\beta_2|}{15T_0^4} = -\frac{8\tau_R}{15} \frac{\eta_2^5(2\pi)^4E_0^4}{A_{eff}^4\lambda^4|\beta_2|^3}.
\] (24)

In the above equation, $\Omega$ is the soliton frequency shift with propagation distance $z$, $E_s$ is the energy of the pulse, $\beta_2$ is the group velocity dispersion (GVD), $A_{eff}$ is the effective area and $\lambda$ is the wavelength. This process generates new frequency components with predominantly longer wavelengths. These solitons tend to be noise-like and the resultant supercontinuum is incoherent.

From equation 24, it can be seen that for efficient frequency conversion, the fiber area should be small with lower magnitude of dispersion and they should be pumped with high pulse energies. The frequency shift results from the combination of effective length and nonlinearity, so these must be balanced along with the pump energy/intensity in order to achieve optimal supercontinuum generation and to avoid fiber damage.

In the subsequent experiments, the primary nonlinear fiber is a fluoride glass composition ZBLAN ($\text{ZrF}_4$-$\text{BaF}_2$-$\text{LaF}_3$-$\text{AlF}_3$-$\text{NaF}$). Fibers made from this glass are well established for fiber-based supercontinuum generation as they have low background loss and wide transparency window ($0.22$-$8$ $\mu$m for $1$ mm thick sample, $T>10\%$) when compared to silica glass ($0.16$-$4$ $\mu$m) [168].
5.1.2 Incoherent Supercontinuum Generation

In the most exemplary demonstration of supercontinuum generation in ZBLAN fiber to date, O. Kulkarni et al. generated a broadband signal extending from 0.8-4 µm with 10.5 W average power, pumped with a 1.54 µm, ~ns source with 3.33 MHz repetition rate cascaded in SMF-28 and ZBLAN fibers [74]. In the results above, the breakup of pulses occurred in ~2 m of SMF-28 fiber and the spectrum was further broadened in ~7 m of ZBLAN. The same group added an additional stage of thulium doped fiber amplifier to amplify the broadened spectrum overlapping with the thulium gain bandwidth around 2 µm and passed the amplified pulses in ~8.5 m ZBLAN to generate SC extending up to 4.5 µm [145]. The following experiments explored supercontinuum generation in SMF-28 and ZBLAN fibers via direct pumping with ns pulses for the Tm-MOPA system described in section 4.3.4.
Figure 61: a) The setup for the broadening experiments with ZBLAN. b) The broadening seen in 5m SMF-28 when coupled with a ~6m ZBLAN. The input was ~6ns pulses at 1985 nm. The output values are normalized.

The pump source produced pulses with 20 kW peak power and <7 ns pulse duration maintaining fundamental mode beam quality. The single-stage MOPA was tested as a source for SCG in ZBLAN at low repetition rates. Similar to [74], MI was initialized to initiate pulse breakups in SMF-28 and further launched it into ZBLAN for broadband generation.

The MOPA pulse duration was reduced to ~5 ns prior to amplification in the PCF in order to produce the highest peak power with relatively low pulse energy in order to reduce the likelihood of fiber damage. The repetition rate was maintained at 10 kHz with ~1 W average
power (corresponding to 100 µJ pulse energies or 20 kW peak power) from the MOPA system. The output was coupled into ~5 m of SMF-28 with ~44 % coupling efficiency to generate the spectrum shown in Figure 61(b) (black). The output from the SMF-28 was ~360 mW which included losses due to absorption in Silica fiber for wavelengths >2300 nm. The output was coupled into ~6 m of ZBLAN fiber, with a maximum of output power of only ~25 mW. Unfortunately, this output power slowly deteriorated with time due to progressive damage within the bulk of the ZBLAN fiber. It was only possible to characterize the output spectrum with an optical spectrum analyzer (OSA) capable of measuring from 1.2 - 2.35 µm, corresponding spectrum is shown in red in Figure 61(b), before the ZBLAN fiber was critically damaged. Although it was not possible to verify with a spectrometer capable of measuring longer wavelengths, it is likely the supercontinuum extended beyond 2.5 µm.

5.1.3 Outlook

The previous results have shown that 2 µm, ~ns pumping of ZBLAN has the potential of producing supercontinuum spanning beyond 4 µm with higher overall conversion efficiencies in the mid-IR region compared to pumping at 1.55 µm [145]. These results also confirm (qualitatively) the high peak powers of >10 kW generated from the source.

In these experiments, the operating regime and average power are mainly determined by the damage induced in the soft glass ZBLAN fiber. The fiber which was used for the above experiments was consistently damaged internally at a distance of ~10 cm from the input fiber facet at ~30 µJ, ~65 ns pulses. This damage process has not been reported in [145, 169] and appears to be the result of the relatively large pulse energy and long pulse duration. As such, the
incident pulse energy should not increase beyond ~25 µJ in this regime. In order to increase the average power to multi-Watt level in the 2 - 5 µm wavelength region it is necessary to increase the repetition rate to a few MHz, and it appears necessary to decrease the pulse duration to the range of 5 - 100 ps.

Low average power, longer mid-IR supercontinuum (>5 µm) can be generated in highly nonlinear fibers like tellurite and chalcogenide fibers [170]. The ZDW for tellurite is ~2.2 µm and for chalcogenides typically in the 4 - 5 µm range [171]. The 2 µm wavelength from thulium pulsed sources is preferable for ultra-broad supercontinuum generation in these fibers. Unfortunately, fibers based on these soft glasses are not as mature as ZBLAN and therefore tend to be mechanically weaker and have a lower damage threshold.

5.2 Theoretical Background for Nonlinear Frequency Conversion

Nonlinear frequency conversion processes such as like DFG and OPO/OPA are well established for generation of mid-IR wavelengths, as they provide tunability and flexibility in pulsed and CW regimes. The output performance of such systems such as power, efficiency, tuning range and spectral content is directly dependent on the conversion setup as well as the available pump source.

The development of the nanosecond source discussed in section 4.3 was focused on providing a source for pumping nonlinear frequency conversion in addition to the other applications. In order to optimize the performance of the system for OPO and DFG, a theoretical understanding of the nonlinear processes is critical. In this section the process will be described.
including with phase matching, DFG and OPO schemes and choice of nonlinear material for mid-IR generation.

5.2.1 Nonlinear Polarization and Coupled Wave Equations

When an electric field is incident upon a medium, a polarization density is induced due to the dipole moment induced on the molecules of the medium. The total induced polarization density $\tilde{P}(t)$ for a given medium can be approximated in a Taylor series in terms of the strength of the applied electric field $\tilde{E}(t)$ as [143]

$$\tilde{P}(t) = \varepsilon_0 \left[ \chi^{(1)} \tilde{E}(t) + \chi^{(2)} \tilde{E}^2(t) + \chi^{(3)} \tilde{E}^3(t) + \cdots \right]. \quad (25)$$

In the case of interaction between multiple waves, the induced polarization can oscillate at different frequency as compared to input. This is due to the nonlinear nature of the dipole moment induced. For example, if the input beams are $E(\omega_1)$ and $E(\omega_2)$, the induced polarization at the frequency $\omega_3$ is given as

$$P(\omega_3) = \varepsilon_0 \chi^{(2)} (\omega_3; \omega_1, \omega_2) E(\omega_1) E(\omega_2). \quad (26)$$

In the equation above, $\varepsilon_0$ is the vacuum permittivity and $\chi^{(2)}$ is the nonlinear susceptibility tensor. The nonlinear coefficients of a material are generally represented in the form of a nonlinear tensor $d$ which can be reduced to $d_{eff}$. The equation for induced polarization becomes

$$P(\omega_3) = 2\varepsilon_0 d_{eff} E(\omega_1) E(\omega_2). \quad (27)$$
To obtain the wave equations for three wave mixing, the electric field and polarization can be represented as

\[ E_j(z, t) = \frac{1}{2} E_j(z, t) e^{i(kz - \omega_j t)} + c.c. \quad (28) \]

and

\[ P_j(z, t) = \frac{1}{2} P_j(z, t) e^{i(k_{nl}z - \omega_j t)} + c.c. \quad (29) \]

In the above equations, the indices \( j = s, p, \) and \( i \) stand for signal, pump and idler waves. Starting with the Maxwell’s Equations, and considering a dielectric medium, the plane wave equation obtained is

\[ \Delta^2 E_j - \frac{1}{c^2} \frac{\partial^2 E_j}{\partial t^2} = \frac{1}{\varepsilon_0 c^2} \frac{\partial^2 P_j}{\partial t^2}. \quad (30) \]

Considering the slowly varying envelope approximation and simplifying, the equation above reduces to

\[ \frac{\partial \varepsilon}{\partial z} + \left( \frac{n}{c} \right) \frac{\partial \varepsilon}{\partial t} + \frac{\alpha}{2} \varepsilon = i \mu_0 \omega_c \frac{\partial}{\partial t} P_{NL} e^{i(k_{NL} - k)z}. \quad (31) \]

In the equation above, \( \alpha \) is the loss term which is often negligible. In addition, the term \( \left( \frac{n}{c} \right) \frac{\partial \varepsilon}{\partial t} \) can be ignored for long pulse durations.

Consider three waves interacting in a \( \chi^2 \) media, the three waves are signal \((\omega_s)\), pump \((\omega_p)\), and idler \((\omega_i)\) which are related by the relation

\[ \omega_p = \omega_s + \omega_i. \quad (32) \]
Here the equation can be reduced to the following three wave equations

\[
\frac{d}{dz} \mathcal{E}(z, \omega_p) = i \frac{\omega_p}{n(\omega_p)c} \tilde{d}^{(2)}_{\text{eff}} \mathcal{E}(\omega_s) \mathcal{E}(\omega_i) e^{i\Delta k z}, \tag{33}
\]

\[
\frac{d}{dz} \mathcal{E}(z, \omega_i) = i \frac{\omega_i}{n(\omega_i)c} \tilde{d}^{(2)}_{\text{eff}} \mathcal{E}(\omega_p) \mathcal{E}^*(\omega_s) e^{-i\Delta k z}, \tag{34}
\]

and

\[
\frac{d}{dz} \mathcal{E}(z, \omega_s) = i \frac{\omega_s}{n(\omega_s)c} \tilde{d}^{(2)}_{\text{eff}} \mathcal{E}(\omega_p) \mathcal{E}^*(\omega_i) e^{-i\Delta k z}. \tag{35}
\]

These equations are considered as the basic equations governing all the three wave $\chi^2$ interactions including SHG, DFG, and OPG. These simplified equations assume the wavelengths are far from the resonances i.e. Kleinman symmetry is assumed. In the above equations, the phase term $\Delta k$ is given as

\[
\Delta k = k_s + k_i - k_p. \tag{36}
\]

Efficient conversion can be obtained only when phase matching is satisfied i.e. $\Delta k = 0$. This can be verified by first finding an approximate solution for the generated idler signal. First of all equation can be simplified for crystal of length $L$. The equation is integrated for $z=0$ to $z=L$. The equation is then multiplied by its conjugate and normalized to find the term for optical intensity. Skipping a few intermediate steps, the final term for intensity is found to be

\[
I_i(L) = I_i^{\text{max}} \left[ \frac{\sin(\Delta k L)}{\Delta k L/2} \right]^2. \tag{37}
\]
This equation gives the generation of the idler field assuming that signal and pump do not vary significantly over the length of the crystal.

### 5.2.2 Phase Matching

The concept and significance of phase matching is understood by solving the Equation 37. The figure below shows the effect of the phase mismatch term on the generated signal.

Figure 62: The generated nonlinear signal (I(L)) is plotted against the position (L) as given in Equation (45) for different values of phase mismatch term $\Delta k$.

Figure 62 shows the buildup of the nonlinear signal intensity with crystal length for different phase matching conditions. It can be seen that any phase mismatch reduces the conversion efficiency and leads to back conversion for a particular coherence length, given by

$$ L_{coh.} = \frac{2\pi}{\Delta k}. $$

(38)
As seen, the maximum output intensity is obtained for zero phase mismatch. The phase mismatch term can be represented as

\[ \Delta k = \frac{n_s \omega_s}{c} + \frac{n_l \omega_l}{c} - \frac{n_p \omega_p}{c}. \]  

(39)

The refractive indices for the three wavelengths need to be matched precisely in order to minimize the mismatch term. In the above choice of wavelengths, \( \omega_p > \omega_s > \omega_l \) assumption is made.

Unfortunately, material dispersion is such that different wavelengths have different refractive index which cannot be easily matched. For accurate phase-matching, material birefringence can be used. There are three common types of phase matching employed: critical phase matching (CPM), non-critical phase matching (NCPM) and quasi phase matching (QPM).

**Critical Phase Matching**

Birefringent crystals exhibit different refractive indices depending on the crystal axes. The most common type of crystals used is uniaxial crystal where the crystal geometry is such that light polarized parallel to the optic axis (called ordinary ray (o-ray)) sees the ordinary refractive index. In a uniaxial crystal, light polarized perpendicular to the optic axes will see different value of refractive index which is defined as the extraordinary refractive index.

Depending on the angle the incoming ray makes with the optic axis, the refractive index can vary from \( n_o \) (ordinary refractive index) to \( n_e \) (extraordinary refractive index) depending on the relative projection of the laser polarization onto the ordinary and extraordinary axes. If the angle \( \theta \), which the propagation vector makes with the optic axis, is chosen correctly the three
waves can be phase matched. An example of the phase matching conditions is shown in Figure 63 for ZGP cut at $\theta$ of 57.5$^0$. It is clear that with the change $\theta$, the crystal can be phase matched for a variety of wavelengths shown in Figure 64.

Figure 63: Phase matching curves for ZGP crystal at angle ($\theta$) of 57.5 degrees at 293 K. The pump, signal wavelengths are 1985 nm, 3215 nm and 5188.4 nm respectively. This is an example of type I phase matching with signal and idler polarized along the extraordinary axis and pump polarized along the ordinary axis.
In addition to the phase matching condition, the effective nonlinear coefficient, $d_{\text{eff}}$, for a particular crystal at a particular phase matching condition determines the conversion efficiency. The output obtained scales as the square of $d_{\text{eff}}$. The $d_{\text{eff}}$ for ZGP, which is a positive uniaxial crystal (since $n_e > n_o$) belonging to the class of $\overline{4} 2 \ m$ (tetragonal crystal), is given as [75]

$$d_{\text{eff}}^{eoo} = -d_{14} \sin(\theta) \sin(2\varphi), \quad (40)$$

and

$$d_{\text{eff}}^{eoo} = d_{14} \sin(2\theta) \cos(2\varphi). \quad (41)$$

In the above equations, $\theta$ is the phase matching angle, $\varphi$ is the azimuthal angle measured from x axis and $d_{14}$ is the element from the Kleinman d-tensor matrix [75]. In the above equations, the
phase matching is type I when the two lower frequency waves involved in the mixing have the same polarization and type II otherwise. The angles $\theta$ and $\phi$ must be chosen depending on the operating conditions and the involved frequencies.

CPM nonlinear conversion efficiency is fundamentally limited by the spatial walk-off for the extraordinary beam. The direction of energy transfer is along the Poynting vector, whereas the direction of the signal is along the propagation vector. For ordinary waves, the direction of propagation vector and Poynting vector are the same but for extraordinary wave, they are at an angle. This angular difference between the propagating wave and the energy transfer is the spatial walk-off angle [143]. This is a limitation strongly affecting all kinds of nonlinear conversion processes and shows stronger impact for shorter pulses due to small temporal overlap. There are methods to improve the walk-off degraded efficiency; for example tilting beams [172] or using two crystals with inversed orientations [173].

**Non critical Phase Matching**

Non critical phase matching (NCPM) is employed when the propagation direction is fixed along the optical axis. The refractive index is fixed along the propagation direction and hence fine tuning of the phase matching is obtained by varying the refractive index by changing the temperature. Since the beams are not at an angle with respect to the optic axis, there is no walk off, and higher efficiencies can be obtained. But the temperature induced damage of the crystal and coatings are the limiting factors and usually the phase matching curve covers smaller bandwidth range.
Quasi Phase Matching

There are cases in which only isotropic crystals are available or the birefringence is insufficient for phase matching. These cases can benefit from a third kind of phase matching, referred to as quasi phase matching (QPM) [143]. Fundamentally, this technique works on the principle of reversing the crystal orientation thereby reversing the sign of $d_{eff}$ after each coherence length. The generated nonlinear signal moves with a phase mismatch with respect to the pump signal. However, whenever the coherence length is reached, i.e. a phase mismatch of $\pi$ radians, this phase is reversed such that the signal sees a continuous increase in amplitude. This process is evident in Figure 65.

![Figure 65: The buildup up of intensity in A perfect phase matched case of $\Delta k = 0$, B QPM case (for Coherence length = period of polarization reversal = $\Lambda = 2.09$), and no phase matching case C. Here the grey arrows indicate the direction of crystal orientation of the QPM material.](image)

The most widely used QPM materials are ferroelectric materials like LiNbO$_3$ and KTiOPO$_4$, which can be periodically poled by applying a periodic electric field on the crystal.
during growth to alternate the crystal domains. Wang et al. [174] have grown mm thick PP-KTP crystals with ~3 µm period. But the typical ferroelectrics used in this technique are not transparent beyond 6 µm wavelength. For mid-IR generation, a semiconductor like gallium arsenide (GaAs) is optimal as it shows very high nonlinear coefficient (d_14=90 pm/V) and wide transparency (~1 to 17 µm) [75]. However, it is not possible for GaAs and other semiconductors to be electrically poled. As a consequence, these structures are either stacked together or grown epitaxially with alternating domains. The crystal growth technique involving hydride vapor phase epitaxy (HVPE) in addition to epitaxially grown GaAs/Ge/GaAs template provides high quality OP-GaAs crystal [175-177].

The OPGaAs crystal used in the scope of this thesis was provided by BAE Systems with dimensions of 1.4 mm x 6 mm x 16.4 mm, structure period of 60.5 µm and QPM layer thickness of 600 µm. Since the QPM period for a given crystal remains constant, wavelength tuning of the signal/idler requires either varying the pump wavelength or the temperature of the crystal. The phase matching curve for this crystal for two different pump wavelength, 1985 nm and 1965 nm, as a function of crystal temperature obtained from SNLO [178] as shown in Figure 66. Figure 67 shows the tuning obtained by keeping the temperature of crystal constant and tuning the pump wavelength from 1850 nm to 1990 nm. This corresponds to the typical tuning range of the thulium based MOPA developed in section 4.3.
Figure 66: The temperature tuning curve for OPGaAs crystal with grating period 60.5 µm for pumps 1965 and 1985 nm. The temperature was tuned from 290 K to 550 K. SNLO software was used for the calculations.

Figure 67: The tuning curve for OPGaAs crystal obtained by varying the pump from 1850 nm to 1990 nm at crystal temperatures of 300, 350, 400 and 450 K. SNLO software was used for the calculations.
Once the phase matching conditions are satisfied in the three wave mixing process, the mid-IR wavelengths can be generated using techniques like DFG, OPG, OPO, or OPA. In the context of this thesis, the focus is set to DFG and OPO.

### 5.2.3 Difference Frequency Generation (DFG)

DFG is a three wave mixing process in which the pump wavelength is considered to be stronger than the signal. The mixing process generates an idler wave at a frequency corresponding to the difference of the frequency of the input beams.

![DFG Diagram](image)

The Figure 68 shows the schematic for this process. As this is a single pass mixing process, it has low efficiency (< 1 %), but this process can be used to achieve extremely broad idler wavelength tuning with narrow linewidth.

Solving the three wave mixing equations, the value for DFG efficiency considering an infinite plane wave and no effects of absorption, walk off, dispersion etc. is given as [179]

\[
\text{Conv. Eff. } \eta = \frac{p_i}{p_p} = \frac{8\pi^2 d_{eff}^2 L^2 I_p}{\epsilon_0 n_p n_s n_i c \lambda_i^2} \left[ \frac{\sin(\frac{\Delta k L}{2})}{\frac{\Delta k L}{2}} \right]^2.
\]  

(42)
In the above equation, $L$ is the length of the crystal, $I_p$ is the input pump intensity, $n$ is the refractive index where the subscripts $p,s$ and $i$ represent signal, pump and idler respectively. From the above equation, the term $d_{\text{eff}}^2/n^3$ is used as a nonlinear figure of merit (FOM) for a given nonlinear crystal where $n$ is the average refractive index. In order to accurately calculate the output pulse energies for most laser pumps, the three wave mixing equations have to be solved considering Gaussian beams. In addition, it is necessary to consider effects such as absorption in the crystal, divergence of the beams, walk off, diffraction (severe diffraction effects take place for far IR wavelengths which are of the order of pump waist), and group velocity mismatch (for sub-ns pulses). SNLO has been used in the context of this thesis for the calculations, which implements a split step approach to include pump depletion, transverse beam profiles, absorption, diffraction effects and walk off effects for all the three interacting waves [178, 180].

5.2.4 Optical Parametric Oscillator (OPO)

Optical parametric generation (OPG) is a quantum mechanical effect where a pump photon incident in a nonlinear medium, is spontaneously split into two lower energy photons [137]. Upon incidence of a pump photon, the idler and signal build up from noise (random vacuum photons fluctuations) for the photon wavelengths that satisfy the phase matching conditions.

If a cavity is built around such an OPG setup where feedback is provided for the signal and/or the idler wavelengths, an OPO is formed. This oscillator is similar to a laser resonator
where the oscillation starts when the gain exceeds the cavity losses. This optical parametric process is instantaneous and incapable of storing energy like a lasing medium.

Two main types of OPOs exist: singly-resonant oscillator (SRO) and doubly-resonant oscillator (DRO) as shown in Figure 69 (a) and (b). In the DRO case, the mirrors are designed to provide feedback for both signal and idler wavelengths. In the SRO configuration, either of signal or idler has feedback. The DRO configuration has a lower threshold condition than SRO, since the three waves are coupled and transfer energy to each other. On the other hand, the DRO has an inherent stability problem of mode hopping. Small mechanical instabilities and thermal variations change the cavity length, thereby altering the cavity resonant mode frequencies. In a DRO, this drift in cavity modes for signal and idler wavelengths occurs in the opposite direction of the spectrum resulting in mode hopping [179]. In a SRO, this mode hopping is suppressed since only one wavelength is resonant. The tentative thresholds are given by [179]

\[
\frac{I_{th(SRO)}}{I_{th(DRO)}} \approx \frac{2}{(1-Re^{-\alpha L})}. \tag{43}
\]

In the above equation, the R is the reflectivity for both the mirrors (for the wavelength not resonated in SRO case), α is the absorption coefficient and L is the effective crystal length. For example, if the mirrors are 98 % reflective, SRO threshold is ~100 times the DRO threshold.
Figure 69: OPO cavities. a) Doubly resonant oscillator (DRO), b) Singly resonant oscillator (SRO), c) Singly resonant ring oscillator (SRRO), and d) Doubly resonant ring oscillator (DRO).

For an infinitely plane wave, the threshold for DRO and SRO output is given as [179]

\[
I_{P,th(DRO)} = \frac{\varepsilon_0 n_2^2 n_p c \lambda_0^2}{2 \pi^2 d^2 e f f L^2 (1 - \delta^2)} \left( 1 - R_s e^{-\alpha_s L} \right) \left( 1 - R_t e^{-\alpha_t L} \right)
\]  

(44)

and
The degeneracy factor is given by the term \( \delta = (\omega_s - \omega_i) / \omega_p \). As seen in DFG, higher FOM (i.e. \( d_{eff}^2 n^3 \)) results in a lower threshold. Unfortunately, no simple analytical solutions can be obtained for the output of signal and idler intensities. Once the equations are solved using real 2-dimensional beams and all the associated parameters like walk off, dispersion as well as beam focusing are inculcated, the equations do not lead to analytical solutions. Typically, software packages, such as SNLO \([178]\), are utilized for solving the equations numerically for a given OPO geometry.

Figure 69 shows several OPO configurations schematically. In the ring oscillator configuration (Figure 69 (c) and (d)), the signal and idler propagate unidirectionally in the OPO cavity. This improves the efficiency by reducing losses via SFG of signal and idler to the pump wave when backward propagating in the cavity. Another effect contributing to lower efficiency in DRO cavities is the phase mismatch unless the OPO cavity round trip time is directly matched to the longitudinal modes (i.e. the round trip time) of the input laser cavity. This degradation is seen when a pump with multi-longitudinal modes is used \([181]\). These factors must be considered for the design of an efficient, high power and stable OPO cavity.

**5.2.5 Mid-IR Crystal Considerations**

The majority of nonlinear crystals used for near-IR generation, such as lithium niobate (LiNbO\(_3\)), potassium titanyl phosphate (KTP), potassium titanyl arsenate (KTA) and rubidium titanyl (RTA) are opaque for wavelengths longer than ~ 5 \( \mu \)m. Thus, for the generation of longer
wavelengths it is necessary to use materials such as zinc germanium phosphide (ZGP), silver germanium selenide (AGSe), silver germanium sulphide (AGS), cadmium germanium arsenide (CGA), gallium selenide (GaSe) and gallium arsenide (GaAs), which have transparencies ranging beyond 5.5 µm.

Table 2: Comparison of linear and nonlinear properties of commonly available crystals for frequency-conversion into the mid-IR regime [75, 182]

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Transparency range (µm)</th>
<th>d_{eff} (pm/V)</th>
<th>Avg. refractive index (n)</th>
<th>NLO FOM (d_{eff}^2/n^3) (w.r.t. PPLN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPLN</td>
<td>0.4-5.5</td>
<td>22.3</td>
<td>2.13</td>
<td>1.00</td>
</tr>
<tr>
<td>PPKTP</td>
<td>0.35-4.3</td>
<td>10.8</td>
<td>1.80</td>
<td>0.95</td>
</tr>
<tr>
<td>PPKTA</td>
<td>0.35-5.3</td>
<td>10.3</td>
<td>1.80</td>
<td>0.87</td>
</tr>
<tr>
<td>AGS</td>
<td>0.47-13.0</td>
<td>12.0</td>
<td>2.40</td>
<td>0.5</td>
</tr>
<tr>
<td>AGSe</td>
<td>0.71-19.0</td>
<td>33.0</td>
<td>2.65</td>
<td>2.80</td>
</tr>
<tr>
<td>ZGP</td>
<td>0.74-12.4</td>
<td>75.0</td>
<td>3.13</td>
<td>8.80</td>
</tr>
<tr>
<td>GaSe</td>
<td>0.62-20.0</td>
<td>54.0</td>
<td>2.73</td>
<td>6.80</td>
</tr>
<tr>
<td>CGA</td>
<td>2.40-18.0</td>
<td>236.0</td>
<td>3.60</td>
<td>57.00</td>
</tr>
</tbody>
</table>

Table 2 compares several mid-IR nonlinear crystals relative to the FOM for periodically poled lithium niobate (PPLN) crystal. It is evident from the table that the CGA crystal has a superior FOM and is transparent up to 18µm; however, we were not able to investigate CGA crystals experimentally as this requires pump with wavelength of >2.4 µm which was not available to us. The crystal utilized for the mid-IR generation experiments carried out in this
dissertation is ZGP (and future work is expected using OP-GaAs) since it allows using the 2 µm source for pumping (as does OP-GaAs). In addition, the FOM is ~ 7 times larger than PPLN and the transparency extends to > 8 µm.

5.3 Experimental Results: Nonlinear Frequency Generation

The following section describes nonlinear generation experiments conducted as part of this dissertation, and is divided into two sub sections: DFG generation and OPO generation.

5.3.1 Difference Frequency Generation (DFG)

DFG typically provides mid-IR wavelengths with superior linewidth and stability as compared to OPG as determined by controllability of input signal and pump laser sources. Mid-IR DFG sources have been used extensively in trace gas concentration measurements where a narrow linewidth and low noise are required [183].

Fine control and stability of the input lasers lead to stable, narrow linewidth and broad wavelength tunability for the generated idler making it a useful tool for spectroscopic applications. Periodically poled RTA (PPRTA) and periodically poled KTA (PPKTA) crystals were used to generate µW level tunable cw mid IR (3.4 – 4.5 µm) from tunable Ti: sapphire (0.71 – 0.72 µm and 0.847 – 0.915 µm) and Nd:YAG or diode laser (1.064 µm and 1.45 – 1.55 µm) as driving source, respectively [183, 184]. But these pump sources could only drive mid-IR generation ranging till 5 µm whereas the molecular fingerprint region lies at longer wavelengths.

Much wider and longer wavelength tunability (6.8 – 20.1 µm) was demonstrated by Vodopyanov et al. in 1998 using a ZGP OPG pumped CdGeAs$_2$ crystal [73]. In this
configuration, the input for DFG was the signal (5 µJ, 90 ps pulses, 4 – 5 µm) and the idler (1.5 µJ, 90 ps pulses 6.5 – 9.5 µm) from a Cr:Er:YSGG laser (2.8 µm) pumped ZnGeP₂ OPG. GaSe is another crystal capable of broadly tunable mid IR generation. Wei Shi et al. used Nd:YAG laser pumped BBO-OPO output (~0.73 – 1.8 µm) and the Nd:YAG laser output to demonstrated ns, multi-kW peak power DFG extending beyond the transparency range of GaSe (2.7 – 28.1 µm) [185]. The result shown is the widest mid-IR wavelength band which was covered in DFG experiments. The effect of operating beyond the transparency range of GaSe (~20 µm) is greatly diminished DFG signal due to absorption.

This section has gone briefly describing the implementation of long wavelength mid-IR DFG generation scheme. We have worked on > 5µm DFG generation using two tunable picosecond laser systems. Unfortunately, these experiments and the obtained results were part of an industrially sponsored research project covered by a non-disclosure agreement and cannot be described here.

5.3.2 Optical Parametric Oscillator (OPO)

As seen in section 5.2.5, ZnGeP₂ (ZGP) is one of the most commonly used CPM crystals for mid-IR generation. It is well suited for high average and high peak power frequency conversion to >5 µm wavelengths due to its high nonlinear coefficient (75 pm/V), damage threshold (~1-2 J/cm²) and thermal conductivity (~35 W/mK) [75]. The transparency decreases rapidly below 1.9 µm but nevertheless, can be pumped around 2 µm.

History and State of the Art

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The majority of early demonstrations of ZGP OPOs were pumped with the output from a 1.06 µm-pumped OPOs. For example, Vodopyanov et al. used 1.064 µm light to pump a PPLN OPO, and the signal from this OPO (2.55 µm) in turn pumped a type I ZGP OPO [77]. Haidar used similar 2 step mid-IR OPO, using a KTP crystal in the first OPO [186] stage. In both the cases, the beam quality was non-optimum with $M^2 > 4$ due to the relatively poor beam quality of signal from the first OPO. Furthermore, beam quality degradation at higher powers (> 2 W) was also observed due to thermal lensing in ZGP OPO by Hemming et al. [72]. The best performances demonstrated to date was achieved by Lippert with $M^2 \sim 1.4$ and 22 W average power using a V-shaped 3 mirror ring resonator [187] using a Ho:YAG pump laser with $M^2 \sim 1.1$.

The primary alternative to ZGP for nonlinear mid-IR generation is OP-GaAs (Section 5.2.5). OP-GaAs has the advantages of no walk-off and broader transparency range (~3 - 12 µm) as compared to ZGP (~3-8 µm). Recently, >50 % slope efficiency has been demonstrated with 46.5% conversion efficiency in Ho:YAG ns laser pumped OP-GaAs OPO cavity [188]. However, the input pump pulse energies of 305 µJ (~2 J/cm² fluence) induced surface damage due to restrictions on the spot size (~100 µm 1/e² diameter) associated with the 450-µm thickness of the orientation patterned region. Alternatively, an optical parametric amplifier (OPA) can provide better conversion and can be used for pulse durations from the ultrafast to CW. For example, French et al. demonstrated an OPO-OPA scheme which generated signal pulse energies of 48 µJ, ~5 times higher energy for signal and idler than a single OPO cavity for the same pump source [189].
Due to the restriction on damage threshold for OP-GaAs, ZGP crystal is practically a better choice for generation of high energy pulses at mid-IR wavelengths. Our experimental ZGP-OPO results are discussed in the next section.

**ZGP-OPO Experiments**

The Tm:fiber MOPA system (section 4.3.4) was used as pump source for a mid-IR OPO. The ZGP crystal used has dimensions of 5 x 4 x 12 mm$^3$, cut at 57.5 degrees and is provided by BAE systems.

![Figure 70: The experimental setup shows the MOPA system where a 10/130 SMF fiber is used in the Q-switched oscillator. The output seeds a flexible-Tm:PCF amplifier through a pulse picker/slicer. The output is passed through a second pulse picker/slicer and a 400 mm focusing lens focusses it into a nonlinear crystal (ZGP) enclosed in an OPO cavity. The output is collimated by a parabolic mirror and sent to beam diagnostics through a mid IR band-pass filter.](image)
The OPO experimental setup and the pump laser schematic is shown in Figure 70. The flat-flat DRO-OPO cavity consisted of two flat mirrors establishing a resonator around the crystal, where the pump was input through a dichroic mirror that was HR in 3 - 5 µm wavelength range and HT for 2 µm. The output coupler was 50% reflective for 3 - 5 µm and HT for 2 µm. In order to maximize the number of passes the signal/idler makes through the OPO during the pump pulse; the mirror separation was set to the minimum value (~2 mm) that allowed angle tuning of the crystal. The pump light was focused to ~330 µm (full width at 1/e² diameter) on the crystal using a 200 mm focusing lens. A gold-coated parabolic mirror collimated the output beam and a ZnSe filter (HT > 2.5 µm) filtered out the residual pump light. The output was measured using a power meter and the spectrum was measured using a combination of monochromator (Cornerstone 130, Oriel, Inc.), MCT detector and lock-in amplifier (SRS Systems, Inc.).
Figure 71: Obtained spectrum from the DRO-ZGP cavity. The signal wavelength is around 3.5 µm and the idler is at 4.58 µm. The broad random wavelength profile is typical of a non-stabilized DRO cavity.

The OPO generated mid-IR wavelengths centered at ~3.58 and ~4.48 µm for the signal and idler, respectively, as shown in Figure 71. For these experiments, the Tm:MOPA produced ~3.64 W average output power at 20 kHz repetition rate. The pulse duration was ~6 ns and the wavelength was centered at 1985 nm with spectral FWHM of ~1 nm. After correcting for losses induced by the filter, the combined output power with respect to the input pump power is shown in Figure 72. The slope efficiency of the combined output power was 28.2 %. The output power of 600 mW (signal + idler) corresponds to 16.35% conversion efficiency.
Figure 72: Measured corrected output power, slope efficiency and the corresponding conversion efficiency for pumping at 1985 nm and 20 kHz.

The beam quality of the combined output was measured to have an $M^2 < 1.2$ as shown in Figure 73. This beam quality was enabled by the excellent beam quality from the MOPA system ($< 1.15$).

Figure 73: Measured beam quality and the beam profile of the mid-IR output (signal + idler combined) signal.
Discussion

The OPO-threshold value for the input pump pulse energy was ~87 µJ corresponding to a peak intensity of ~33 MW/cm². This threshold is lower than the 2 µm pumping threshold stated in reference [82]. However, the DRO-OPO thresholds are in the range of 3 - 5 MW/cm² when pumping with Ho:solid-state lasers in the 2.05 - 2.1 µm wavelength range and 20 - 40 ns pulses [187, 190, 191] due to the longer time available for the buildup of the signal/idler. Using direct pumping with a TDFL, a threshold of 14 MW/cm² (~30 ns pulses) was observed by Creeden et al [82] and ~26 MW/cm² for ~30 ns pulses (36 % slope efficiency) by Simakov et al in [72]. Although both the cases used curved-curved OPO cavity with similar spot sizes, in the latter case, the pump spot size was not matched to the signal and idler fundamental mode size causing higher threshold. The OPO threshold can be reduced in a flat-flat OPO cavity using a larger pump beam diameter, which has better mode overlap with the OPO cavity mode.

Figure 74: a) The slope efficiency of ZGP-OPO with respect to input pump power at 20 kHz, and b) The OPO Threshold at pulse durations of ~7 ns and ~100 ns with different repetition rate of the pump.
A 400 mm focal length focusing lens was used to verify the impact of the beam waist in the crystal for a flat-flat cavity performance. The new focus spot was measured to be ~450 µm (1/e² diameter). The threshold decreased for ~7 ns pulse duration to 10 - 14 MW/cm² as shown in Figure 74 (b). Increasing the pulse to ~100 ns duration further lowered the thresholds to 3 - 4 MW/cm² in agreement with the results in [82].

Creeden et al. [82] saw effects of thermal lensing for incident average power density beyond ~45 kW/cm². Using the larger spot size, it should be possible to pump our OPO to average power levels up to ~70 W before any deleterious thermal lensing effects become prominent. No signs of thermal lensing were observable in our experiments to date.

In order to enable tunability of the idler to wavelengths > 5 µm, it is necessary to employ a SRO cavity. For an SRO-OPO, as shown in section 5.2.4, the threshold increases ~4 times (assuming 50 % output coupler and a HR input coupler), corresponding to ~ 400 µJ threshold. The slope efficiency of the OPO can be further improved by implementing SRRO cavity design.

5.4 Summary and Outlook

The work shown in this section proves the utility of the developed thulium fiber MOPA system for generation of mid-IR wavelengths. Broadening in ZBLAN fiber was achieved using 20 kW, ~5 ns pulses. This incoherent SCG benefits from the thulium wavelength and dispersion properties of silica and ZBLAN fibers. The same source was used to generate 3 - 5 µm wavelengths using a ZGP OPO cavity. This gave ~600 mW of mid-IR output (signal + idler) with good beam quality (M-square < 1.2). The background work for reducing the OPO threshold
and improving slope efficiency (and hence optical conversion efficiency) is given. SRO cavity which can generate wavelengths > 5 µm is the next stage of development.

The good beam quality and high pulse energies obtained from the OPO can be used for material processing in the mid-IR. Polymers like polyethylene and polypropylene display strong absorption features around 3.3 µm [192, 193]. Although their machining using a CO₂ laser has been investigated by Caiazzo et al.[194], the absorbance at ~3.3 µm is more than an order higher than at 10.5 µm. Hence, the average power required for effective ablation could be significantly reduced. Similarly, an SRO-OPO could be used as a source for tissue ablation at ~6.5 µm.
CHAPTER SIX: SUMMARY AND OUTLOOK

TDFLs have the beneficial properties of long emission wavelength, large bandwidth (~1.8 – 2.1 µm), high efficiencies (~60 %), and high power output levels both cw and pulsed operation. Applications like remote sensing, materials processing, and mid-infrared generation benefit from high peak power thulium laser sources. Pulsed TDFL systems have developed rapidly during the last five years. This dissertation describes the development of PCF based novel nanosecond pulsed TDFL systems with record high peak power levels in order to pump nonlinear mid-infrared generation.

We have investigated two types of Tm:PCF for high peak power generation. The first is a ~1000 µm² MFA thulium-doped flexible-PCF and the second is a ~2500 µm² thulium-doped PCF-rod. In comparison, commercially available SI-LMA fiber has a MFA of ~415 µm². The flexible-PCF is inherently single-mode by design whereas the PCF-rod can guide six modes but can support fundamental mode operation. The PCFs have higher laser thresholds and lower slope efficiencies than SI-LMA fibers. To date, the CW slope efficiency for the flexible-PCF (34 – 37 %) was below the Stokes limit (40 %). For the PCF-rod, the slope efficiency obtained was even lower (~28 %). In comparison, Tm:SI-LMA fiber lasers demonstrate slope efficiencies of >50 %.

The larger mode area of the PCFs in comparison to SI-LMA fiber results in strong pump absorption and higher nonlinear/damage thresholds. These higher limits in combination with higher stored energy and lower levels of ASE make PCFs extremely attractive for high peak power, pulsed operation.
When used in a Q-switched oscillator, the flexible-PCF enabled ~9 kW peak pulse power generation. When used as an amplifier in a MOPA system, the flexible-PCF-based power amplifier was able to produce ~100 kW peak power with sub 10 ns pulses at 1 kHz repetition rates. Further increase in the peak power was achieved using an additional amplifier stage based on the PCF-rod. This system was able to generate record level ~0.9 MW peak powers. The spectral width was maintained <1 nm, and there was no indication of nonlinear pulse degradation.

Mid-IR generation by nonlinear frequency conversion via ZGP crystal based OPO was investigated. The Tm:PCF MOPA system was used as the pump for the OPO. This system generated signal and idler at 3.6 and 4.6 μm respectively. The optical conversion efficiency was more than 16%. A combined signal and idler average power of ~0.6 W was produced when pumped with the MOPA output of 3.64 W. Further power and energy scaling is possible, as neither thermal roll-off nor damage effects were seen. The Tm:PCF MOPA system is an effective pump for generating high peak powers at mid-IR wavelengths.

The availability of high energy/peak power output at 2 μm wavelength is also useful for novel applications benefiting from the longer wavelength. Silicon backside machining is one of the applications we have explored using the above mentioned MOPA source. This work has potential applications in solar cell and microelectronics manufacturing. Other applications based on thulium Q-switched oscillator systems which were investigated are LIBS of copper and polymer welding. All these applications have been demonstrated as a proof-of-concept and require further study and optimization for practical usability.
The work shown in the scope of this dissertation opens up the prospect for reaching extremely high peak power and pulse energy in TDFL systems. The inherent advantages of the longer thulium wavelength over the shorter wavelengths corresponding to ytterbium and erbium are in the realization of larger MFDs, higher threshold for nonlinear effects, and higher threshold for optical damage. Advanced Tm:PCF designs based on comprehensive simulations can lead to the realization of MFDs in excess of 200 µm. These ultra-large MFD fiber designs with highly increased energy storage capability could lead to generation of peak power and pulse energy levels not yet realized in fiber laser systems. They can further find application in generation of mid-IR pulse energies which until now are possible only with solid state laser systems.
APPENDIX A:
NOVEL APPLICATIONS BASED ON CW THULIUM FIBER SOURCES
The tunable thulium wavelength around 2 µm is particularly interesting for applications close to or in the mid-IR. The broad bandwidth of the thulium emission covers unique absorption/transmission features of water vapor, CO₂, polymers and chalcogenide glasses. Applications based on the above properties are studied in this section. The explored applications are highly novel and not fully exploited since the focus of this dissertation is laser development rather than laser applications.

**Absorption Spectroscopy**

The thulium wavelength range (~1.8-2.1 µm) spans over spectral signatures of water vapor [195] and CO₂ [196]. The entire thulium bandwidth can be utilized by using Tm-fiber as an ASE source. It gives an incoherent broadband source with several 100 mW average power which can be used as a research tool for water vapor/CO₂ sensing. CO₂ sensing using a thulium ASE source is demonstrated in this section.

![Diagram of CO₂ absorption spectroscopy setup](image)

Figure 75: The setup for the CO₂ absorption spectroscopy consists of the Tm:LMA fiber based ASE source (Section 3.1), gas cell, vacuum system and optical spectrum analyzer (OSA) for detection [154].

The ASE source employed for spectroscopy experiments is described in detail in Section 3.1. The ASE source was based on ~2 m Tm:SI-LMA fiber with 25/400 µm core/cladding. A 35
W and 790 nm laser diode (DILAS GmbH) was used as pump source. The system generated broadband ASE output with more than 200 mW. However, only ~35 mW average power was necessary for the experiments. The ASE output spanned from ~1870 – 2030 nm as shown in Figure 17. The setup for the single pass absorption spectroscopy consisted of a ~1 m long gas cell. Infrasil glass windows were installed at two ends of the cell for the probing signal to pass through the CO$_2$ gas (in the cell) maintained at the required gas pressure. The ASE output after passing through this cell was then collected with an optical spectrum analyzer (Yokogawa AQ6375). This OSA covers the wavelength range from 1200 to 2400 nm with resolution of ~50 pm and dynamic range of 55 dBm in optimum configuration.

![Figure 76: The CO$_2$ absorption coefficient measurements with CO$_2$ pressure in the gas cell maintained at 760 Torr [154].](image)

The ASE spectroscopic setup (Figure 75) was used to examine the absorption band features for CO$_2$ in the wavelength span of 1870 – 2030 nm. The vacuum system first generated a vacuum of less than $10^{-3}$ Torr. Then CO$_2$ gas was filled and maintained in the cell at desired pressure level. The weak harmonics of asymmetric stretch absorption band (at 4300 nm) for CO$_2$
were confirmed to be centered at 1960 nm and 2010 nm (Figure 76). The observed band structure was verified to be in accordance with High Resolution Transmission (HITRAN) simulation. The result confirmed the usability of this system for CO$_2$ spectroscopy applications.

The absorption coefficient was calculated for a given pressure of CO$_2$ from the given path length by comparing the signal measurements with and without CO$_2$ (with vacuum maintained at $<10^{-3}$ Torr). The change in the absorption coefficient was verified with a change in the pressure. The value of absorption coefficient was then analyzed with respect to the concentration of the molecules (in moles/m$^3$). The concentration was estimated for a given pressure value by using the ideal gas equation and considering the volume of the gas cell. The results are shown in Figure 77 and they show linear dependence of the coefficient as one would expect for linear absorption regime.

![Absorption Coefficient vs Wavelength](image1)

![Absorption Coefficient vs CO$_2$ Concentration](image2)

Figure 77: a) The absorption coefficient for CO$_2$ with marked peak at 2003.94 nm and b) the linear dependence of absorption coefficient on the CO$_2$ coefficient [154].

The good results prove that the used setup and source can be used as simple, easy to install system for CO$_2$ concentration measurements. The system was not able to trace
atmospheric CO$_2$. The limitation of this system was the low spectral power density of the ASE which is $\sim 2.3$ µW/nm average and $\sim 6.1$ µW/nm maximum. Another limitation is the relative lack of strong absorption resonances in CO$_2$ within this wavelength range. Atmospheric concentration of CO$_2$ was detected using an ultrashort laser system which showed improved spectral power density of the signal by at least 20 times ($\sim 50$ µW/nm average and $\sim 127$ µW/nm maximum). The results are reported in [154]. This system has the potential to be expanded for trace gas detection of water vapor, ozone, ammonia, and methane (from HITRAN data).

**Thermal Lensing in Chalcogenide**

Development of high power laser sources requires the understanding of thermal effects introduced in the optical components like lens, polarizers, isolators etc. Thermal lensing in these components at high average powers a major concern and is partially studied here. Components operating at 1 µm center wavelength are well developed and offer minimal absorption values. Development is still in progress for efficient low absorption components for wavelengths $>2$ µm. Characterization of the mid-IR materials like chalcogenide glasses, ZnSe and semiconductors (Si,Ge) is required for high power operation. This section shows the characterization of thermal lensing effects in Chalcogenide glasses and comparison against the well characterized near-IR materials using a TDFL system.
The TDFL oscillator was based on 25/400 µm core/cladding non-PM LMA fiber shown in section 3.2.2. The fiber length was \(~3.2\) m and the pump diode was fiber coupled with up to 200 W at 790 nm installed in a co-propagating configuration. The total output power was considered for this experiment including output from the cladding since the only requirement for the source is to ‘heat’ the sample. The slope efficiency for the total output power was measured to be 58.2 % and is shown in Figure 78 (a). The laser beam was send through the sample according to the thermal lensing measurement setup shown in Figure 78 (b). The probe laser was centered at 1080 nm with up to 100 mW emerging the single-mode fiber (Qphotonics, LLC). The output of the probe was collimated using a 10 cm lens to \(~1.5\) cm diameter beam. This beam was then passed through the sample and the resulting waveform was measured using a Shack-Hartmann wavefront sensor (Imagine Optic, Inc). The wavefront sensor is capable to measure distortions down to \(\lambda/100\) due to its 32 x 46 pixel array and a 3.6 mm x 4.6 mm surface area.
The thermal lens in Fused Silica was investigated and showed a focal length of 47.5 m (at 44 W), and 11.2 m in BK7 (at 45 W) as shown in Figure 79 (a) and (b) [198]. The absorption coefficient in BK7, which is an order of magnitude higher as compared to Fused Silica, is the major contributor for this effect. A sample of As$_2$Se$_3$ ~5 mm thick and 2.5 cm in diameter was deployed in the setup to find the induced thermal lensing. The thermal lensing in As$_2$Se$_3$ was ~0.9 m at 0.46 W, as shown in Figure 79 (c).

![Figure 79: Thermal lensing measurements for a) BK7 glass, b) Fused Silica, and c) Chalcogenide sample (As$_2$Se$_3$). The samples show significantly different thermal lensing characteristics hence the scales are different [197].](image)

The focal length due to thermal effects is due to induced refractive index change due to the change in temperature given by the following equation [148]

$$f = \frac{K}{P_{\alpha}} \left( \frac{1}{2} \frac{dn}{dT} + \alpha C_{r,\phi} n_0^3 + \frac{\alpha r_0 (n_0 - 1)}{L} \right)^{-1}. \quad (46)$$

In the above equation, $f$ is the induced focal length, $K$ is thermal conductivity, $P_{\alpha}$ is absorbed power, $dn/dT$ is the change in refractive index due to temperature, $\alpha$ is the thermal coefficient of linear expansion, $C_{r,\phi}$ describes elasto-optical coefficients, $n_0$ is the undistorted material refractive index, $r_0$ is the sample radius, $L$ is the sample length, and $A$ is the sample cross-sectional area. This is a general equation which can be applied to all materials given the
values of the involved parameters are known. The parameters for Fused Silica, BK7 and As$_2$Se$_3$ are listed in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>$\text{dn/dT (K}^{-1}\text{)}$</th>
<th>Refractive Index</th>
<th>CTE (K$^{-1}$)</th>
<th>$\alpha$ (cm$^{-1}$)</th>
<th>Thermal Conductivity (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fused Silica</td>
<td>$10 \times 10^{-6}$</td>
<td>$1.43$</td>
<td>$4 \times 10^{-6}$</td>
<td>$0.002$</td>
<td>$1.35$</td>
</tr>
<tr>
<td>BK7</td>
<td>$2.8 \times 10^{-6}$</td>
<td>$1.51$</td>
<td>$8.6 \times 10^{-6}$</td>
<td>$0.06$</td>
<td>$1.11$</td>
</tr>
<tr>
<td>As$_2$Se$_3$</td>
<td>$32 \times 10^{-6}$</td>
<td>$2.81$</td>
<td>$20.7 \times 10^{-6}$</td>
<td>$0.9$ (est.)</td>
<td>$0.24$</td>
</tr>
</tbody>
</table>

The parameter values were dependent on the glass type, but not all the parameters were available especially for the new Chalcogenide family. As a consequence, the above equation was simplified to give one relevant term which is

$$\text{Thermal lensing factor} = M^{-1} = f \ast P_{in} \quad (47)$$

The three samples have been characterized using the thermal lensing factor. The values obtained were $4.34\times10^{-4}$, $2.15\times10^{-3}$, and $2.31$ for fused silica, BK7 and As$_2$Se$_3$ respectively. The larger the lensing factor, stronger is the lensing obtained. The strong lensing in As$_2$Se$_3$ sample was due to higher numbers for $\text{dn/dT}$, CTE, and absorption as compared to fused silica and BK7 (Table 3).

The thermal lensing characterization of Chalcogenide glass was, to the best of our knowledge, reported for the first time [197].

**Polymer Welding**
The following experiment used the thulium-wavelength absorption characteristics for polymers. This work was done by Fabian Weirauch and Ilya Mingareev. The thulium wavelength range has about 20 - 40% absorption for 1.6 mm samples of polymers with low and high density polyethylene (PE-LD, PE-HD), polymethylmethacrylate (PMMA), polypropylene (PP), polyoxymethylene (POM) and glycol modified polyethyleneterephthalate (PETG) [95]. These low absorption values allow enough penetration depth of the 2 μm beam in the material as well as sufficient heat accumulation. Hence, the source was ideally suited for on-surface or transmission welding experiments of these polymers.

![Figure 80](image)

Figure 80: a) The pulse duration and corresponding pulse energies obtained in the non-PM LMA Q-switched oscillator system at 20 kHz PRF and b) the cw performance. The lower slope in cw performance (typically >50 %) were due to the reason that the cw lasing was off the 1st diffraction order from the AOM which inculcated additional ~35% loss in the cavity.

The laser system used in the configuration described in section 4.2.1 with the small difference of using a non-PM LMA fiber and removed the polarization optics. This laser system was used in both cw as well as Q-switched operation and the characteristics are shown in Figure
The pulse energies obtained were ~400 µJ with ~140 ns durations. The CW operation allowed ~27 W maximum output power limited by the pump source.

Figure 81: The setup for a) butt-welding and b) transmission-welding [95].

After initial trails with the pulsed system, for most of the experiments, the laser was used in cw mode. The butt-welding experiments (Figure 81 (a)) with this laser showed promise with the 2 µm system with comparatively lower welding power as compared to 1 µm systems. The weld joint of PE-LD and PE-HD samples (butt-welding) demonstrated tensile strength of >80 % of the full material strength. The transmission welding experiments were performed with similar and dissimilar polymers in upper and lower levels (Figure 81 (b) part A and part B). Two different welding characteristics were identified as ‘material’ joint and ‘form’ joint. The interesting results achieved were published in optics and laser technology [95].
APPENDIX B:
DISPERSION AND SOLITONS
Dispersion

Chromatic dispersion in a bulk material arises due to the wavelength dependence of refractive index. This dispersion imparts a spectral change in a pulse travelling in such a media. A given pulse travelling in a linear dispersive media will experience spectral phase change given in the form of Taylor expansion terms as [132]

\[ \beta(\omega) = \frac{n(\omega)\omega}{c} = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2i} \beta_2(\omega - \omega_0)^2 + \frac{1}{3i} \beta_2(\omega - \omega_0)^3 + \cdots \quad (48) \]

Where

\[ \beta_m = \frac{\partial^m p}{\partial \omega^m}|_{\omega=\omega_0}. \quad (49) \]

The first derivative, \( \beta_1 \) gives the inverse group velocity and the second term \( \beta_2 \) \((s^2/m)\) gives the group velocity dispersion (GVD). Another constant which is largely used in telecommunication industry is dispersion constant \(((\text{ps/nm})/\text{km})\) given by

\[ D_\lambda = -\frac{2\pi c}{\lambda^2} \beta_2. \quad (50) \]

In an optical fiber, two additional dispersion components are present, waveguide and modal dispersion. The waveguide dispersion is determined by the frequency dependence of mode propagation constant. The modal dispersion is a manifestation of the difference in group velocities of different propagating modes in a multimode fiber. The net dispersion experienced by a given mode at a given frequency is the sum of these three dispersions.

Dispersion influences both the phase velocity and group velocity of an optical pulse traveling in an optical fiber. Different frequency components of a pulse travel with different
velocities owing to dispersion hence they experience different delays. This effect of pulse broadening is called as frequency chirping of the pulse.

The wavelength ranges where $\beta_2 > 0$ and $\beta_2 < 0$ are referred to as normal and anomalous dispersion regime respectively. The sign of dispersion plays a significant role in the propagation dynamics in the presence of nonlinearities. The wavelength corresponding to $\beta_2 = 0 \beta_2 = 0$ is called zero dispersion wavelength (ZDW). This zero dispersion wavelength is an essential feature as it is the exact wavelength at which the propagating pulse will travel without acquiring chirp due to dispersion.

**Solitons**

SPM process in an optical fiber will induce a nonlinear positive chirp on a propagating laser pulse [132]. If the anomalous dispersion regime is chosen for operation, the pulse is chirped negatively due to dispersion. These two processes can be combined together in such a way that very stable or periodic evolving soliton pulses are generated. Soliton solution can be obtained by solving the Nonlinear Schrodinger Equation (NLS) where the fiber losses and higher order dispersion terms are ignored

$$i \frac{\partial A}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 A}{\partial T^2} - \gamma |A|^2 A .$$

In the above equation, $A(z,T)$ is the amplitude of the field envelope, $\beta_2$ is the GVD parameter and $\gamma$ is the nonlinear parameter responsible for SPM. The above equation can be solved using inverse scattering method to give soliton solution [132]. The soliton order is defined as the parameter $N$, where
\[ N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|} \]  

The dispersion length \( L_D = T_0^2 / |\beta_2| \) and nonlinear length \( L_{NL} = (\gamma P_0)^{-1} L_{NL} = 1 / \gamma P_0 \) give the length scales where the dispersive and nonlinear effects become significant for pulse evolution. Here, \( T_0 \) is the pulse width and \( N \) gives the soliton order.

First order soliton (\( N=1 \)) is known as the fundamental soliton since its temporal and spatial profile remains unchanged during propagation. It is basically a hyperbolic secant pulse with an existing inverse relation between its amplitude and width. Higher order solitons (\( N>1 \)) exhibit periodic spectral and temporal evolution.

The solitons are an important pulse profiles which can propagate in anomalous dispersion region without broadening, thus enabling stable, ultrashort fiber lasers at wavelengths longer than ZDW in silica. These soliton pulses are extremely stable because the fundamental mode is sustained even for small amounts of peak power mismatch, chirp addition or even perturbations.
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