Applications Of Volume Holographic Elements In High Power Fiber Lasers

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APPLICATIONS OF VOLUME HOLOGRAPHIC ELEMENTS IN HIGH POWER FIBER LASERS

by

APURVA JAIN
M.S., University of Central Florida, 2009

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Major Professor: Leonid B. Glebov
ABSTRACT

The main objective of this thesis is to explore the use of volume holographic elements recorded in photo-thermo-refractive (PTR) glass for power scaling of narrow linewidth diffraction-limited fiber lasers to harness high average power and high brightness beams.

Single fiber lasers enable kW level output powers limited by optical damage, thermal effects and non-linear effects. Output powers can be further scaled using large mode area fibers, however, at the cost of beam quality and instabilities due to the presence of higher order modes. The mechanisms limiting the performance of narrow-linewidth large mode area fiber lasers are investigated and solutions using intra-cavity volume Bragg gratings (VBG) proposed. Self-pulsations-free, completely continuous-wave operation of a VBG-stabilized unidirectional fiber ring laser is demonstrated with quasi single-frequency (< 7.5 MHz) output. A method for transverse mode selection in multimode fiber lasers to reduce higher order mode content and stabilize the output beam profile is developed using angular selectivity of reflecting VBGs. By placing the VBG output coupler in a convergent beam, stabilization of the far-field beam profile of a 20 μm core large mode area fiber laser is demonstrated.

Beam combining techniques are essential to power scale beyond the limitations of single laser sources. Several beam combining techniques relevant to fiber lasers were compared in this study and found to be lacking in one or more of the following aspects: the coherence of the individual sources is compromised, the far-field beam quality is highly degraded with significant power in
side lobes, spectrally broad and unstable, and uncertainty over scaling to larger arrays and higher power. Keeping in mind the key requirements of coherence, good far-field beam quality, narrow and stable spectra, and scalability in both array size and power, a new passive coherent beam combining technique using multiplexed volume Bragg gratings (M-VBGs) is proposed.

In order to understand the mechanism of radiation exchange between multiple beams via these complex holographic optical elements, the spectral and beam splitting properties a 2\textsuperscript{nd} order reflecting M-VBG recorded in PTR glass is experimentally investigated using a tunable single frequency seed laser. Two single-mode Yb-doped fiber lasers are then coherently combined using reflecting M-VBGs in both linear and unidirectional-ring resonators with >90% combining efficiency and diffraction-limited beam quality. It is demonstrated that the combining bandwidth can be controlled in the range of 100s of pm to a few pm by angular detuning of the M-VBG. Very narrow-linewidth (< 210 MHz) operation in a linear cavity and possibility of single-frequency operation in a unidirectional ring cavity of the coherently combined system is demonstrated using this technique. It is theoretically derived and experimentally demonstrated that high combining efficiency can be achieved even by multiplexing low-efficiency VBGs, with the required diffraction efficiency of individual VBGs decreasing as array size increases. Scaling of passive coherent beam combining to four fiber lasers is demonstrated using a 4\textsuperscript{th} order transmitting M-VBG. Power scaling of this technique to 10 W level combined powers with 88% combining efficiency is demonstrated by passively combining two large mode area fiber lasers using a 2\textsuperscript{nd} order reflecting M-VBG in a unidirectional ring resonator.
High energy compact single-frequency sources are highly desired for several applications – one of which is as a seed for high power fiber amplifiers. Towards achieving the goal of a monolithic solid-state laser, a new gain medium having both photosensitive and luminescence properties is investigated – rare-earth doped PTR glass. First lasing is demonstrated in this new gain element in a VBG-stabilized external cavity.
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CHAPTER 1: INTRODUCTION

The laser, as the name suggests, is based on the phenomena of stimulated emission of radiation proposed by Albert Einstein in 1917 [1]. A laser consists of three main components as shown in the schematic of Figure 1-1 – the resonator, the laser medium, and the pump. The pump excites the laser medium to higher energy states resulting in population inversion and subsequent de-excitation via emission of radiation, a portion of which is trapped in the resonator and undergoes amplification [2,3].

Laser research and development has come a long way since the first demonstration of the ruby laser by Theodor Maiman in 1960 [4,5]. In the 1960s, the focus was on demonstrating laser action in new mediums and several of the most relevant lasers were invented in the span of just a few years including the He-Ne and CO$_2$ gas lasers [6,7], the Nd-doped solid state laser [8], and the GaAs semiconductor laser [9]. Back then laser was considered a solution looking for an application, but today it is the applications that drive the high demand for new laser sources. The search for higher powers, new wavelength regimes, and diffraction-limited beam quality has been the inspiration for the next generation of laser development.

Figure 1-1 Schematic of a laser
1.1 The Quest for Higher Powers

Laser output can either be continuous-wave (CW) or pulsed. CW lasers are generally used for applications requiring power-on-target for long periods of time ($\gg 1 \mu s$, high average powers), while pulsed lasers are generally desired for applications requiring power-on-target for very short durations of time ($\ll 1 \mu s$, high peak powers). For CW lasers, the definition of high powers depends on the context of applications considered – for example for machining applications several kilowatts are considered high powers while laser pointers are classified as high power at just a few hundreds of milliwatts. The most important performance metrics for most applications is the combination of power and beam quality – i.e. brightness. The brightness of a laser beam is defined as the optical output power ($P$) per unit area ($A$) per unit solid angle ($\Omega$):

$$B = \frac{P}{A \cdot \Omega} \left( \frac{W}{cm^2 \cdot sr} \right)$$  \hspace{1cm}  \ldots (1.1 - 1)

Good beam quality is essential for long distance propagation (i.e. good collimation) and for delivering maximum power on target (i.e. good focusability). Thus, a high brightness ensures that the power generated by the laser is useable whereas low brightness indicates that the power generated by the laser diverges quickly. For many applications a narrow spectrum is also of great importance, and in such cases the spectral brightness is used to characterize the laser performance:

$$B = \frac{P}{A \cdot \Omega \cdot \Delta \lambda} \left( \frac{W}{cm^2 \cdot sr \cdot nm} \right)$$  \hspace{1cm}  \ldots (1.1 - 2)

That is, the brightness per unit bandwidth. Thus, a high spectral brightness laser requires high average power in a narrow spectral linewidth with good beam quality.
The focus of this thesis is on the development of CW laser technology with high average power and high spectral brightness. Such laser sources are very useful for free-space optical communication [10–12], material processing [13,14], directed energy [15], defense [16,17] and high-energy scientific [18,19] applications among others.

There are several issues related to thermal management, damage thresholds, and size that must be considered for a high average power laser system. High electrical to optical efficiency is of utmost importance for a kW-class laser system. Low efficiency would not only result in wastage of electrical power, but also make the system bulkier as more power supplies will be needed to achieve the desired optical output. Moreover, a large part of the unconverted pump energy manifests itself as heat in the laser gain medium leading to several deleterious effects such as degradation of gain medium, mechanical instabilities, thermal lensing, and even melting. Other optical components such as mirrors and lenses having even slight absorption at the lasing wavelength can also heat up significantly at such high powers. Thus, quick and efficient removal of heat from the gain medium and other components is crucial and the laser design, including the choice of gain medium and optical components, must take this into account. In addition to heating, high optical intensities in the cavity can also compromise laser operation by causing optical damage and triggering nonlinear effects. The mechanism and thresholds of these effects are specific to the laser type and will be discussed in more details for fiber lasers in later chapters.
Excellent reviews of the state-of-the-art high power laser technology are available in literature [5,13,14,16,20]. Gas lasers, which include carbon dioxide (CO₂), chemical, and excimer lasers, are typically capable of generating the highest output powers in a single beam. CO₂ lasers are by far the most popular among gas lasers, typically emitting up to 10 kW output power in the 10 μm wavelength region with ~10% wall-plug efficiency. These lasers currently account for about 35% of the laser market for the material processing industry [21]. Prototypes of CO₂ laser with output powers of 100 kW and above have been demonstrated for defense applications in the lab, however, scaling of power required scaling in size and the long wavelength operation required huge optics making it a massive, complicated and impractical system. Chemical lasers like hydrogen fluoride (HF, 2.6 – 3.3 μm), deuterium fluoride (DF, 3.5 – 4.2 μm) and oxygen-iodine (COIL, 1.3 μm) are all technologically mature and successfully demonstrated megawatt-class laser weapons. However, these lasers never found use in other applications and interest has decreased even for defense application because of problems in storing the reactive fuels and disposing the harmful by products, and due to their large sizes, huge costs, and complex designs.

Direct diode lasers have high electrical to optical efficiency (up to 65%), are compact, reliable and low cost. However, single edge emitting diodes are limited to powers levels in the range of 10 W. Higher output powers are achievable by combining several emitters in diode bars, which are capable of generating several 10s or 100s of watts. Further power scaling to kilowatts of CW power is achieved by stacking several diode bars (2D array of single emitters) and by superimposing the individual outputs to form a single beam either by using beam shaping optics
or by coupling into high NA fibers. However, these high power diode bars and stacks come at the cost of beam quality – the poor beam quality renders these sources useless for a majority of applications. The main application for the high power fiber-coupled diodes is to pump other solid-state, fiber, or gas lasers.

Diode pumped solid state (DPSS) and fiber lasers are fast gaining popularity for industrial materials processing, defense, and other high power applications [17,22,23]. With diode pumping, rare-earth doped crystals like Nd:YAG with sharp absorption lines can be efficiently pumped to obtain kW level outputs. Although fairly efficient, the main challenges with the DPSS technology (rod and disks) are thermal management, poor beam quality, and complicated free-space resonators. Rare-earth doped fiber lasers solve a lot of these issues.

Fiber lasers have many inherent benefits over other laser mediums due to its unique geometry. The 2-D wave-guiding nature and cylindrical symmetry of fibers allow it to support Gaussian-like modes and make it possible to obtain diffraction limited beams. The long lengths and small cross-section of fibers result in several benefits as well. For one, the long interaction lengths enable high gain and high output powers, while heat is distributed over the entire length. This coupled with the high surface area to volume ratio results in extremely effective thermal management compared to other laser mediums. Another major advantage for making high power sources comes from the ability to efficiently pump a dual clad fiber using low brightness diode lasers to generate a high brightness output beam. Some fiber laser systems also have the added
advantage of all-fiber architectures requiring no free-space alignment – thus resulting in highly robust, compact, and efficient sources for use in high shock and vibration environments. A comprehensive review of high power fiber lasers will be presented in chapter 3.

1.2 Scope of this Thesis

The focus of this work is on the investigation of new approaches to high average power fiber lasers and their scalability to 100 kW level outputs. An attempt is made to review the state-of-the-art fiber lasers and recognize the key mechanisms that limit the high power performance of these sources. In chapter 3 we discuss several of these limiting factors and experimentally investigate techniques to eliminate, or at least mitigate, some of the key issues. The main contributions of this thesis in this regard are towards transverse mode selection in large mode area fiber lasers and in elimination of self-pulsations in narrow linewidth fiber lasers.

Our proposed solutions are based on fiber laser design using volume holographic elements in photo-thermo-refractive (PTR) glass. The PTR glass technology and various volume holographic elements recorded in it are described in detail in chapter 2. An important contribution of this thesis is the development of multiplexed volume Bragg gratings (M-VBG) and experimental investigation of its unique properties. The work was done in close collaboration with researchers at Photoinduced Processing Laboratory (PPL) at the College of Optics and Photonics in University of Central Florida and OptiGrate Corporation, who performed development and study of photosensitive glass and volume Bragg gratings used in this research.
As we will see in chapter 3, fiber lasers like all other sources, have limitations to power scaling as well. In order to scale the output powers beyond the limitations of a single laser, beam combining techniques must be adopted. These techniques will be reviewed and compared in chapter 4. Perhaps the most significant contribution of this thesis is towards the development of a new passive coherent beam combining technique using M-VBGs. Chapter 5 details the proposed technique and demonstrates high efficiency combining along with channel and power scaling.

Apart from the contributions mentioned above, the author of this thesis has participated in several other projects during his PhD career at CREOL. One of the more exciting projects, and closely but not directly related to this thesis, was the development of rare-earth doped PTR laser. This promising development is a first step towards the goal of developing high power monolithic single-frequency solid state lasers which are desired for a range of applications including seed for high power fiber amplifiers. The key results of this work are included in chapter 6.

Chapter 7 summarizes the accomplishments of this thesis and provides some motivations for future work in this area.
CHAPTER 2: VOLUME HOLOGRAPHIC ELEMENTS

Optical elements for manipulation of high power beams in applications such as beam steering, wavelength selection, and beam shaping are highly desired. Such elements must have very low absorption and scattering, and robust thermal and mechanical properties for efficient performance at high powers. Photo-thermo-refractive (PTR) glass has been proposed as a suitable material for holographic recording of diffractive optical elements that meet all these requirements and functionalities [66,67].

2.1 Photo-Thermo-Refractive (PTR) Glass

Photo-thermo-refractive (PTR) glass is a photosensitive silicate glass that develops a refractive index change after exposure to photoionizing radiation and thermal treatment. PTR glass is a complex multicomponent silicate glass doped with silver, cerium, and fluorine (15Na₂O-5ZnO-4Al₂O₃-70SiO₂-5NaF-1KBr-0.01Ag₂O-0.01CeO₂). Permanent refractive index change as high as 10⁻³ (1000 ppm) occurs in PTR glass after exposure to UV radiation followed by thermal development. While being photo-sensitive in the UV, PTR glass offers high transmittance in the near-IR and visible parts of spectrum from 350 to 2700 nm. The history of the study of photo-thermo-refractive process and its parameters from the point of view of hologram recording are summarized in surveys [25,26]. The ability to control refractive index change in PTR glass allows fabricating volume holographic elements and recent improvements of PTR technology has resulted in creation of volume phase holograms (Bragg gratings) with low losses and
extremely high diffraction efficiencies exceeding 99% [27,28]. PTR glass has excellent thermo-
mechanical properties with thermal stability of a hologram up to 400°C, refractive index
practically independent of temperature \((dn/dT=5\times10^{-7} \text{ K}^{-1})\), coefficient of thermal expansion
8.5\times10^{-6}/\text{K}, and thermal conductivity 0.01 W/cm\,\text{K}. Laser damage threshold of 10 J/cm\,\text{2}
for 10 ns pulses, and tolerance to CW laser radiation in the near IR region at least up to several tens of
kilowatts per square centimeter, make PTR-glass holograms attractive for high-power laser
applications. Doping of PTR glass with rare-earth ions has recently been achieved allowing it to
be used as a gain medium for lasers. More details of research in this direction are presented in
CHAPTER 6: .

2.2 Volume Bragg Gratings (VBGs) in PTR Glass

Both reflecting and transmitting volume Bragg gratings have been recorded in PTR glass. The
phenomena of diffraction from a periodic crystalline structure was first discovered and proposed
by William L. Bragg and William H. Bragg in 1913 [29], and the thorough coupled wave theory
of Bragg diffraction by thick hologram gratings was developed by Kogelnik in 1969 [30]. The
theory was further developed and a simplified matrix approach of Kogelnik’s coupled wave
theory formulated in [31]. In this report we focus much of our attention to reflecting VBGs (R-
VBGs), however, similar analysis for transmitting VBGs is readily available as well.

Volume Bragg gratings have the property of diffracting almost the entire incident light satisfying
the Bragg condition to a single diffracted order. The Bragg condition is given by:
2d \sin \theta = \lambda_B

where ‘d’ is the periodicity of the grating, \theta is the angle of incidence in the medium, and \lambda_B is the wavelength of incident light. The VBG functions like a mirror for the wavelengths satisfying the Bragg condition, while for all other wavelengths it is simply a piece of transparent glass (Figure 2-1).

![Figure 2-1 R-VBG as a wavelength selective mirror](image)

The peak diffraction efficiency (\eta_0), spectral selectivity (\Delta \lambda^{HWFZ}) , and angular selectivity (\Delta \theta^{HWFZ}) of a VBG depends on its thickness (t), refractive index modulation (\delta n) and the angle of incidence in the medium (\theta_m).

For a reflecting VBG (R-VBG), the peak diffraction efficiency is given by [31],

\[ \eta_0 = \tanh^2 \frac{\pi (t \cdot \delta n)}{\lambda_0 |\cos \theta_m^*|} \]  

...(2.2 - 1)

The half-width first-zero spectral width can be calculated as,

\[ \Delta \lambda^{HWFZ} = \frac{\lambda_0^2 \left(\text{atanh} \sqrt{\eta_0} \right)^2 + \pi^2}{2 \pi \cdot n_{av} \cdot t |\cos \theta_m^*|} \]  

...(2.2 - 2)
Finally, a relationship between the angular and spectral selectivity can be derived from the Bragg condition expressed in differential form to be,

\[
\Delta \theta_{\text{HWFZ}} = \left( \tan^2 \theta^* + \frac{2 \cdot \Delta \lambda_{\text{HWFZ}}}{\lambda_0} \right)^{\frac{1}{2}} + \tan \theta^* \quad \ldots (2.2 - 3)
\]

For normal incidence (\( \theta^*_m = 0 \)) these equations simplify to:

\[
\eta_0 = \tanh^2 \left( \frac{\pi (t \cdot \delta n)}{\lambda_0} \right) \quad \ldots (2.2 - 4)
\]

\[
\Delta \lambda_{\text{HWFZ}} = \frac{\lambda_0 \left( (t \cdot \delta n)^2 + \lambda_0^2 \right)^{\frac{1}{2}}}{2 \cdot n_{av} \cdot t} \quad \ldots (2.2 - 5)
\]

\[
\Delta \theta_{\text{HWFZ}} = \left( \frac{\left( (t \cdot \delta n)^2 + \lambda_0^2 \right)^{\frac{1}{2}}}{n_{av} \cdot t} \right)^{\frac{1}{2}} \quad \ldots (2.2 - 6)
\]

Using the above three equations, an R-VBG can be designed for the desired diffraction efficiency and angular selectivity. For instance, if the desired R-VBG output coupler is:

Design wavelength, \( \lambda_0 = 1 \mu \text{m} \)

Peak diffraction efficiency, \( \eta_0 = 99.9\% \)

HWFZ spectral selectivity at normal incidence, \( \Delta \lambda_{\text{HWFZ}} = 100 \text{ pm} \)

The required thickness and refractive index modulation is:

\( t = 5.6 \text{ mm} \)

\( \delta n = 237 \text{ ppm} \)

HWFZ angular selectivity at normal incidence, \( \Delta \theta_{\text{HWFZ}} = 13.5 \text{ mrad} \)

Figure 2-2 shows the spectral and angular response of the above R-VBG.
Custom designed R-VBGs with any desired diffraction efficiency and spectral bandwidth (as narrow as 50 pm) recorded in PTR glass are commercially available [32]. Using the PTR glass technology, volume holographic elements for various applications including spectral narrowing in laser resonators, beam deflection, stretching and compression of laser pulses, and spectral beam combining has been developed [33].

### 2.3 Multiplexed Volume Bragg Gratings

In general, multiple VBGs can be recorded in the same volume to realize a 1:N splitter [34–36]. VBGs can be multiplexed in several ways and for several applications. Here we are interested in angularly multiplexing VBGs such that it behaves like a splitter for an incident beam. In other words, all the VBGs multiplexed in the volume share a common bisector along which the Bragg condition is satisfied for all the VBGs simultaneously by the same incident beam. Figure 2-3 shows the 1:2, 1:4, and 1:8 multiplexed VBG (M-VBG) splitters realized by recording 2, 4, and 8 identical high diffraction efficiency VBGs symmetrically in the same PTR glass sample.
In this section, we develop the coupled-wave theory for multiple thick holograms recorded in the same volume using the formulation outlined in [31]. Similar analysis for multiply exposed volume holographic media has been presented earlier by various groups including Case [34] and Yum [37]. However, a detailed analysis of the spectral and angular detuning properties of these complex holographic elements has not been presented before. The theoretical model is developed particularly for reflecting M-VBGs and is confirmed with experimental measurements of a double reflecting M-VBG.

### 2.3.1 Coupled-Wave Theory for Reflecting M-VBGs

Figure 2-4 shows the case for two thick reflecting gratings that are incoherently recorded in a volume of thickness $L$. We denote the common reference beam as ‘F’ and the two recording beams which are symmetrical with respect to the reference beam as ‘A’ and ‘B’ respectively. Considering a lossless medium with two VBGs of refractive index $n(z)$ such that,
\[ n(z) = n_o + n_{AF} \cdot e^{i(\vec{q}_{AF}z + \varphi_{AF}(z))} + n_{BF} \cdot e^{i(\vec{q}_{BF}z + \varphi_{BF}(z))} \]  \hspace{1cm} (2.3 - 1)

Here \( n_o \) is the real constant refractive index of the medium, \( n_{AF} \) and \( \varphi_{AF} \) are slowly varying amplitude and phase of the index modulation corresponding to the VBG formed by the interference of \( A \) and \( F \) waves respectively, and \( n_{BF} \) and \( \varphi_{BF} \) are those corresponding to VBG formed by the \( B \) and \( F \) waves.

Figure 2-4  Two thick reflecting gratings symmetrically recorded in a volume of thickness \( L \)

We will consider only TE polarized electric fields, which can be defined as follows along the three directions:

\[ E_F(z) = F(z)e^{i\vec{k}_F \cdot \vec{r}}, \quad E_A(z) = \frac{A(z)}{\sqrt{\cos \theta_A}}e^{i\vec{k}_A \cdot \vec{r}}, \quad E_B(z) = \frac{B(z)}{\sqrt{\cos \theta_B}}e^{i\vec{k}_B \cdot \vec{r}} \]

Solving the Maxwell’s equations under the assumption of slowly varying amplitudes for these fields in homogenous media, results in a set of coupled differential equations commonly referred as the Takagi equations. For a more detailed derivation the reader is referred to [31]. Adding a
wavelength detuning term to account for incidence of broadband radiation on the VBGs, the Takagi equations can be written in the following form;

\[
-\frac{i(\omega - \omega_0)}{v_{gr}} A - \frac{\partial A}{\partial z} = i\kappa_{AF} F \\
-\frac{i(\omega - \omega_0)}{v_{gr}} B - \frac{\partial B}{\partial z} = i\kappa_{BF} F \\
-rac{i(\omega - \omega_0)}{v_{gr}} F + \frac{g_{F}}{\partial z} = i\kappa_{AF}^* A + i\kappa_{BF}^* B
\]  

...(2.3 - 2)

Here \(\kappa_{AF}\) and \(\kappa_{BF}\) are the coupling coefficients from wave ‘A-to-F’ and wave ‘B-to-F’ respectively and are calculated as:

\[
\kappa_{AF} = \frac{n_{AF}\omega}{2c\sqrt{\cos \theta_A}} e^{i\phi_{AF}}, \quad \kappa_{BF} = \frac{n_{BF}\omega}{2c\sqrt{\cos \theta_B}} e^{i\phi_{BF}}
\]  

...(2.3 - 3)

The above set of coupled differential equations can be represented in matrix form,

\[
\frac{\partial}{\partial z} \begin{pmatrix} A \\ B \\ F \end{pmatrix} = \hat{\mathbf{V}} \begin{pmatrix} A \\ B \\ F \end{pmatrix}
\]  

...(2.3 - 4)

where, \(\hat{\mathbf{V}} = \begin{pmatrix} -i\Delta & 0 & -i\kappa_{AF} \\
0 & -i\Delta & -i\kappa_{BF} \\
i\kappa_{AF}^* & i\kappa_{BF}^* & i\Delta \end{pmatrix}\)

Where, \(\Delta = \frac{(\omega - \omega_0)}{v_{gr}}\), is the wavelength detuning term. The analytical solution to such differential equations is formulated as [31],

\[
\begin{bmatrix} A(L) \\ B(L) \\ F(L) \end{bmatrix} = \hat{\mathbf{M}} \begin{bmatrix} A(0) \\ B(0) \\ F(0) \end{bmatrix}
\]  

...(2.3 - 5)

Here, \(\hat{\mathbf{M}} = e^{\hat{\mathbf{V}} L}\), and can be calculated using the Lagrange formula for the function of a matrix,
\[
\bar{M} = e^{\nu L} = e^{\lambda_1 L} \frac{\hat{\nu} - \lambda_2 \hat{I}}{(\lambda_1 - \lambda_2)(\lambda_1 - \lambda_3)} + e^{\lambda_2 L} \frac{\hat{\nu} - \lambda_3 \hat{I}}{(\lambda_2 - \lambda_3)(\lambda_2 - \lambda_1)} + e^{\lambda_3 L} \frac{\hat{\nu} - \lambda_1 \hat{I}}{(\lambda_3 - \lambda_1)(\lambda_3 - \lambda_2)}
\]

\[\ldots (2.3 - 6)\]

Where, \(\lambda_1, \lambda_2, \text{and} \lambda_3\) are the eigenvalues of the matrix \(\hat{\nu}\). The eigenvalues of matrix \(\hat{\nu}\) can be found by setting the following determinant to zero and solving for \(\lambda\),

\[|\hat{\nu} - \lambda \hat{I}| = 0\]

Which gives,

\[\lambda_1 = -i \Delta, \quad \lambda_2 = \sqrt{|\kappa_{AF}|^2 + |\kappa_{BF}|^2 - \Delta^2}, \quad \lambda_3 = -\sqrt{|\kappa_{AF}|^2 + |\kappa_{BF}|^2 - \Delta^2}\]

\[\ldots (2.3 - 7)\]

It is useful to define the grating strength, S, and the detuning parameter, X, as:

\[S = |\kappa| \cdot L, \quad X = |\Delta| \cdot L\]

\[\ldots (2.3 - 8)\]

Knowing the matrix M, relation (2.3-5) can be expanded to,

\[\begin{bmatrix} A(L) \\ B(L) \\ F(L) \end{bmatrix} = \begin{bmatrix}
M_{00} & M_{01} & M_{02} \\
M_{10} & M_{11} & M_{12} \\
M_{20} & M_{21} & M_{22}
\end{bmatrix} \begin{bmatrix} A(0) \\ B(0) \\ F(0) \end{bmatrix}\]

\[\ldots (2.3 - 9)\]

Using the relations 2.3-3 through 2.3-8, the system of equations in 2.3-9 can be solved for three boundary conditions shown in Figure 2-5. These three scenarios are the degenerate (or common) Bragg conditions for the two VBGs.
Figure 2-5 Multiplexed VBG splitter considered for the 3 cases of incidence along (a) the bisector of the two grating normal (wave F), (b) the conjugate angle for one of the gratings (wave A), and (c) conjugate angle for both gratings (in-phase waves A and B)

Case 1: Incidence along wave F (1x2 Splitter)

We consider the case when only wave F is incident on the M-VBG at $z = 0$ (Figure 2-5a). The boundary conditions for this case are hence,

$$ F(0) = 1, \quad A(L) = 0, \quad B(L) = 0 $$

The matrix relation (2.3-8) can be solved under these conditions to calculate the fields $A(0), B(0),$ and $F(L)$.

$$ 0 = M_{00} \cdot A(0) + M_{01} \cdot B(0) + M_{02} $$

$$ 0 = M_{10} \cdot A(0) + M_{11} \cdot B(0) + M_{12} $$

$$ F(L) = M_{20} \cdot A(0) + M_{21} \cdot B(0) + M_{22} $$

Which leads to,

$$ A(0) = \frac{M_{11} \cdot M_{02} - M_{01} \cdot M_{12}}{M_{10} \cdot M_{01} - M_{00} \cdot M_{11}} $$

$$ B(0) = -\frac{M_{00}}{M_{01}} A(0) - \frac{M_{02}}{M_{01}} $$

$$ \ldots (2.3 - 10) $$
Case 2: Incidence along wave A (1x3 Splitter)

We consider the case when only wave A is incident on the M-VBG at $z = L$ (Figure 2-5b). The boundary conditions for this case are hence,

$$F(0) = 0, \quad A(L) = 1, \quad B(L) = 0$$

The matrix relation (2.3-8) can be solved under these conditions to calculate the fields $A(0), B(0),$ and $F(L)$. Going through the same steps as in case 1, we get;

$$A(0) = \frac{M_{11}}{M_{00} \cdot M_{11} - M_{10} \cdot M_{01}}$$

$$B(0) = -\frac{M_{10}}{M_{11}} A(0)$$

$$F(L) = M_{20} \cdot A(0) + M_{21} \cdot B(0)$$

.... (2.3 – 11)

Note that the case for incidence along only wave B is exactly the same for symmetrical and identical gratings.

Case 3: Incidence along both wave A and wave B (Combiner)

We consider the case when both waves A and B (in-phase) are incident on the M-VBG at $z = L$ (Figure 2-5c). The boundary conditions for this case are hence,

$$F(0) = 0, \quad A(L) = 1, \quad B(L) = 1$$

The matrix relation (2.3-8) can be solved under these conditions to calculate the fields $A(0), B(0),$ and $F(L)$. Solving the three equations, we get;

$$A(0) = \frac{M_{11} - M_{01}}{M_{00} \cdot M_{11} - M_{10} \cdot M_{01}}$$
\[ B(0) = \frac{M_{10} - M_{00}}{M_{11} - M_{01}} A(0) \]

\[ F(L) = M_{20} \cdot A(0) + M_{21} \cdot B(0) \] .... (2.3 – 12)

2.3.2 Measured Spectral and Angular Response of Reflecting M-VBGs

Two symmetric VBGs are recorded in a single PTR glass sample at angles ±3.3° with respect to sample surface. Each VBG has high peak diffraction efficiency (~99%) and a FWHM bandwidth of 210 pm around 1065.7 nm for incidence along their respective grating vectors.

2.3.2.1 Spectral Properties

The spectral response of this M-VBG was measured for the degenerate cases shown in Figure 2-5 and compared with the simulated plots obtained from the equations above. The measurements are made using three detectors and a tunable laser as shown in Figure 2-6.

Figure 2-6 Setup for MVBG alignment using a tunable laser source
Case 1: Incidence along wave F (1x2 Splitter)

For incidence along the axis bisecting the two VBGs (Figure 2-5a), the M-VBG acts as a 50:50 beam splitter for a narrow spectral band around the degenerate Bragg wavelength of 1064.0 nm and is transparent at wavelengths outside of the grating bandwidth. Figure 2-7a shows the simulated spectral response using equation set (2.3-10). Figure 2-7b shows the measured spectral response for the case when the incidence is exactly along the bisector of the two grating normal. The splitting is almost 50:50 but not exact probably due to some imperfections in the recording process. The two diffracted beams make angles of $\pm9.6^\circ$ relative to the input beam. The asymmetry in the measured response is due to the 2nd order inhomogeneity in background refractive index of glass along the recording direction. Angular detuning of the M-VBG around this position will be discussed later.

Figure 2-7  Simulated (left) and measured (right) spectral response of MVBG for Figure 2-5a
Case 2: Incidence along wave A (1x3 Splitter)

For incidence at the conjugate angle of ±9.6 degrees and the same degenerate Bragg wavelength of 1064.0 nm, the M-VBG acts as a three-way splitter (Figure 2-5b). The incident wave is diffracted by its respective VBG (and does not interact with the other VBG for which Bragg condition is not satisfied at this angle of incidence). The diffracted wave is along the bisector of the two VBG normal and, as it propagates through the sample, it is partially re-diffracted by both gratings, since the Bragg condition is satisfied in this case. Note that the beams split in the ratio F:A:B = 50:25:25 near the degenerate wavelength. The simulated (using equation set 2.3-11) and measured spectral response for this case is shown in Figure 2-8.

Figure 2-8  Simulated (left) and measured (right) spectral response of MVBG for Figure 2-5b
2.3.3 Combining of Two Coherent Beams

Case 3: Incidence along both wave A and wave B (Combiner)

It is intuitive that the M-VBG, being an efficient splitter, should act as an efficient beam combiner if the beams in Figure 2-5a are reversed. To measure the response of the case of Figure 2-5c and evaluate the performance of the M-VBG as a beam combiner, we tested the M-VBG in a Michelson interferometer like setup (Figure 2-9).

The output from a tunable laser is linearly polarized and split equally using a beam splitter. The two split beams are combined again at the M-VBG, and the combined beam is observed in the far field using an IR camera to ensure perfect overlap of the diffracted beams from the two gratings. A 5 mm thick piece of silica glass is inserted in one of the arms. Thermal tuning of this glass provides relative phase change between the two arms.

Figure 2-9 Experimental setup to test M-VBG as a coherent beam combiner, Figure 2-5c
The tunable laser was set to the degenerate wavelength of 1064.0 nm and had a maximum output power of 4 mW. After the beam splitter, beam 1 and beam 2 (in Figure 2-9) had 2.04 mW and 1.94 mW respectively. The M-VBG is first aligned with respect to beam 1 so that the split beams correspond closely to the ratio at 1064 nm in Figure 2-8; i.e. 50:25:25. Beam 2 is then aligned so that the diffracted beams are in perfect overlap.

The two beams are combined along the bisector of the two gratings. Figure 2-10 shows the power in the combined beam as a function of relative phase change. The silica glass was heated from 29.9 °C to 32.6 °C to provide a π phase change. Figure 2-11 shows the pictures as seen from the IR camera of the two individual beams, the combined beam corresponding to constructive interference, and the combined beam corresponding to destructive interference. Figure 2-12 shows the simulated (using equation set 2.3-12) and measured spectral response (averaged over several scans) measured when the combined power was close to maximum, i.e. the two beams were almost in-phase. The fluctuation in the measured signals is attributed to the random atmospheric and thermal perturbations in the interferometric system over the course of the scan.

![Figure 2-10](image.png) Measured and theoretical power in the combined beam as a function of relative phase difference
Figure 2-11 The individual beams (top) and the combined beams (bottom) for constructive and destructive interference at M-VBG

Figure 2-12 Simulated (left) and measured (right) spectral response for Figure 2-5c

2.3.4 Angular Detuning

The MVBG is first aligned using a tunable laser and three detectors in a setup shown in Figure 2-6. For rough alignment, the tunable laser is first set to the degenerate wavelength of 1064.25 nm and the MVBG angularly aligned so that two diffracted beams are observed. Precise alignment is achieved by scanning the wavelength of the tunable laser about the degenerate
wavelength (1064 nm – 1064.35 nm) while making small adjustments to the MVBG angular alignment. Slight angular detuning of the M-VBG around this angle shifts the spectral response of the two individual VBGs in opposite directions. As the angular detuning is increased, the two VBGs become more and more independent of each other and finally act as single VBGs at their respective Bragg angles. Figure 2-13 shows the spectral response of the M-VBG at small angular steps around the degenerate condition. It is an interesting observation that the two VBGs move away from each other upon angular detuning until they do not interact at all. In other words, bandwidth of degeneracy (where the Bragg conditions for both VBGs is simultaneously satisfied) is largest when the input beam is incident exactly along the common bisector, and gradually decreases with angular detuning.
Figure 2-13 Angular detuning of the M-VBG at small steps around the degenerate angle of incidence
2.3.5 Scalability of Reflecting M-VBGs

The theory for two multiplexed reflecting volume Bragg gratings developed in section 2.3.1 can be extended to analyze ‘N’ number multiplexed VBGs under the same assumptions. In general, for N multiplexed gratings there will be (N+1) coupled differential equations resulting in an (N+1)-th order matrix and (N+1) eigenvalues. Such systems of equations can be easily solved using readily available programming tools. Since there is only a finite amount of refractive index change available in PTR glass (~1x10⁻³), multiplexing high diffraction efficiency VBGs for large values of N can get challenging. Thus, it is of great interest to calculate the minimum diffraction efficiencies of individual VBGs required for achieving efficient M-VBG operation – i.e., the M-VBG performs as a perfect splitter and combiner with no losses. Case 3 of section 2.3.1 was solved, this time for N multiplexed VBGs for N= 2, 4, 8, and 16, and values of individual DE were determined that resulted 99% power in the combined beam. Figure 2-14 shows the calculated values of individual DE required versus the number of multiplexed VBGs. It is fairly straightforward to derive an analytical expression for this behavior, and it is interesting to note that the required strength, S, of the individual gratings scales as $\frac{1}{\sqrt{N}}$,

$$DE_{\eta=99\%} = \left[\tanh\left(\frac{3}{\sqrt{N}}\right)\right]^2 \times 100$$

... (2.3 - 13)

A direct consequence of this equation is that a highly efficient 1:N splitter can be fabricated by recording N low efficiency VBGs, thus allowing scalability to large values of N.
Figure 2-14  Required diffraction efficiency of individual VBGs to achieve 99% combining efficiency as a function of the number of VBGs multiplexed

2.4 Summary

Photo-thermo-refractive glass is a multi-component silicate glass doped with photosensitive agents capable of developing a permanent refractive index change upon exposure to UV light and subsequent thermal development. This allows holographic recording of Bragg gratings in the volume of PTR glass. The PTR glass and all VBGs were made by our collaborators at OptiGrate Corporation.

The properties of multiplexed volume Bragg gratings are studied in detail in this work. The use of M-VBGs for beam splitting and passive coherent combining of lasers beams is proposed; specifications for such gratings are developed and provided to the holographic group where the M-VBG splitters are recorded in PTR glass for the very first time. The spectral response of the M-VBG for the degenerate Bragg conditions is theoretically and experimentally studied. It is
experimentally shown that a double reflecting M-VBG is an ideal 50:50 beam splitter with a tunable bandwidth. Control of spectral window for beam combining by angular detuning of M-VBGs is proposed and studied. Moreover, the M-VBG is capable combining coherent in-phase beams with high efficiency. Insight on scaling this technology to higher order splitters is provided. The M-VBGs developed in this chapter will be used in chapter 5 for coherent beam combining of fiber lasers.
CHAPTER 3: HIGH POWER NARROW-LINEWIDTH FIBER LASERS

3.1 Introduction

Although fiber lasers were first proposed and demonstrated in 1961 [38,39], the real interest in fiber technologies was triggered by the developments in the telecommunication industry in the 1990s. The simultaneous investments and improvements in various enabling technologies such as efficient high brightness fiber-coupled diode lasers, fiber geometries including the development of double-clad [40] and large mode area (LMA) fibers, and development of various fiber-optic components, have tremendously accelerated the development and growth of the fiber laser technology. This growth is evident from the exponential increase in the output power from single fiber lasers in the last decade (Figure 3-1) [41].

Figure 3-1  Power scaling of diffraction-limited and near diffraction-limited fiber lasers in the last decade. All Yb-doped fiber lasers since 1999. [41]
3.1.1 Common Architectures for Fiber-based Laser Sources

The most common architectures for high power narrow linewidth fiber sources are shown in Figure 3-2 and can be classified as all-fiber, linear external cavity, ring resonator, and master oscillator power amplifier (MOPA). In the all-fiber architecture of Figure 3-2a, fiber Bragg gratings (FBGs) spliced to either one (with other end straight cleaved for ~4% feedback) or both ends of the active fiber eliminates the need for any free space alignment making it a very robust and easy to use system. FBGs also provide wavelength selective feedback, and depending on the design such lasers can generate relatively narrow linewidth outputs. FBGs can also be recorded over the entire length of the gain fiber to make distributed feedback (DFB) fiber lasers to generate single-frequency radiation. Pump signal combiners are used to efficiently couple several pump diodes. Output powers from such fiber laser designs are usually limited to a few watts mainly due to the onset of nonlinear effects, spatial-hole burning (SHB) in narrow linewidth standing wave resonators, thermal instabilities of the FBGs, and the short lengths of gain fibers in some cases [23].

In the external-cavity architecture of Figure 3-2b, feedback is generated from external bulk optical elements. As we will see in later sections, several high power system designs and beam combining techniques require external-cavity fiber lasers to overcome the limits of thermal load and optical damage thresholds of the fiber. Such fiber laser designs have been able to achieve CW operation up to several kW of output powers. Additionally, in some cases an external cavity allows for unique opportunities of engineering the feedback mechanism to force the fiber laser to
operate under certain desired regimes. Such fiber laser resonators will be demonstrated later in the chapter using volume Bragg gratings.

In contrast to the linear laser cavities described above where radiation is repeatedly bouncing back and forth between resonator mirrors, a ring cavity can be designed where the radiation travels in clockwise and counterclockwise directions. The ring cavity shown in Figure 3-2c can also be implemented in either all-fiber or external cavity. An isolator is usually included inside the ring cavity to ensure unidirectional operation. This design has often been used for single-frequency laser design as it suppresses spatial-hole burning. External cavity ring lasers will also be explored in this thesis for high power fiber laser design.
Finally, Figure 3-2d shows a very commonly used architecture for high power fiber sources – the master oscillator power amplifier (MOPA). MOPA is not a fiber laser, but provides highly coherent and diffraction-limited high power beams by amplifying a single frequency seed laser over multiple fiber amplifier stages. MOPAs have demonstrated a few kW level output powers, and their diffraction-limited single-frequency operation makes them very attractive for several applications. The main drawbacks of the MOPA architecture are that it requires several high power isolators and it depends on a single frequency seed which limits power scaling due to the onset of nonlinear effects.

There are several textbooks that describe the longitudinal and transverse mode characteristics of fiber lasers, properties of rare-earth dopants used for gain, and the dynamics of laser action in fiber [3,42]. The focus of discussion here will be on state-of-the-art high power lasers and the mechanisms that limit performance and power scaling.

3.1.2 State of the Art

Several articles have been published reviewing the current state of high power fiber lasers [16,20,41,43–46]. HPFLs in the 1 μm region have scaled from 100 W power levels in 1999 [47], to over kW in 2004 [48]. IPG Photonics has demonstrated 3 kW in 2006 [49] and more recently to 6 kW in 2008 [50] from single broadband fiber lasers with diffraction limited outputs.
As we outlined in the previous section, the requirements for many high average power laser applications is that of narrow linewidths while maintaining diffraction-limited outputs for long propagation distances. The state-of-the-art high power sources mentioned above are all either broadband or multimode, or both. Achieving high powers in a narrow linewidth emission is the next goal proposed by the Defense Advanced Research Projects Agency (DARPA) in the Revolutions in Fiber Lasers (RIFL) program [51]. Although fiber lasers are very well suited to meet all of these requirements, the technology is very young and there are still several hurdles to overcome in the development of narrow linewidth HPFL sources.

3.1.3 Fundamental Mechanisms Limiting HPFL Performance

Over the last decade, as the output powers from single fiber lasers have reached the kW levels, several factors that could limit further power scalability have come to light. The most important are optical damage, thermal damage, and non-linear effects [42,46,52].

3.1.3.1 Fundamental Damage Thresholds

**Optical Damage:** High optical intensities can cause ionization of atoms and molecules in materials leading to dielectric breakdown. Optical breakdown is most common at fiber ends, where the pump and signal intensities are focused. The optical damage threshold for silica fiber is believed to be 30 W/μm² [53].
Thermal Damage: Thermal heating in fibers is caused by two main effects – quantum defect and non-radiative relaxations. The heat accumulation over time can be roughly estimated as,

\[ \Delta Q = P_p (1 - \eta) \Delta t, \]

where \( P_p \) is the coupled pump power and \( \eta \) is the optical-to-optical conversion efficiency. The most common effect of thermal heating in fibers is thermal lensing and melting. Usually the polymer coating around the fiber has lower melting point and melts first. Even in fibers where the surface to volume ratio is high, efficient removal of heat becomes necessary when dealing with very high pump powers.

3.1.3.2 Threshold for Nonlinear Effects

The primary nonlinear effect that degrades narrow-linewidth fiber laser performance is stimulated Brillouin scattering (SBS) [44,46,54]. SBS results from the interaction of light with acoustic phonons in the laser medium. The acoustic phonons are initially thermally generated and subsequently sustained by a process called electrostriction – wherein the high electric fields present in the material pulls the molecules into the high field area, producing a intensity-dependent travelling change in refractive index. The diffraction of the optical wave from this grating creates a Doppler-shifted wave, resulting in loss of efficiency and degradation of the laser signal. The threshold for SBS is given by,

\[ P_{th} = \frac{21 A_{eff}}{g_B \cdot L_{eff}} \]

... (3.1 - 1)

Where, \( P_{th} \) is the power of the laser signal, \( A_{eff} \) is the effective mode area, \( L_{eff} \) is the effective length, and \( g_B \) is the Brillouin gain coefficient (typical value of \( g_B \) for SiO2 glasses is about 0.05
m/GW at 1 μm). Equation (3.1-1) is often simplified to reflect that the threshold for SBS is directly proportional to the effective mode area and laser linewidth, and inversely proportional to the effective length,

\[ P_{th} \propto \frac{A_{eff} \cdot \Delta \lambda}{L_{eff}} \]  

...(3.1 – 2)

Other nonlinear effects such as stimulated Raman scattering (SRS), self-phase modulation (SPM) and photo-darkening can add to performance degradation to some extent at high powers. However, the threshold for SRS is higher than SBS and SPM and photo-darkening are usually not a concern for CW lasers. These effects are therefore not of major concern and will not be discussed further.

A simple estimate using equation (3.1-1 or 3.1-2) can show that the SBS thresholds in typical fiber lasers can be very low, even on the level of a few hundred watts. Thus, SBS is the most immediate limitation for power scaling, whereas the optical damage limit of 10 kW (for ~20 μm core) seems to be the ultimate limit for single fiber lasers [44].

3.1.4 Fiber Designs for High Power Operation

Optical fibers have often been referred to as efficient brightness converters and mode converters. This is due to the unique waveguide geometry of fibers which allows light to be highly confined in the core. Figure 3-3 shows a typical double-clad fiber (DCF) cross section with the signal core (usually doped with rare-earth ions for providing gain), the inner cladding (pump core), the outer
cladding, and the protective jacket. The V-number of the fiber is an important design parameter that determines the number of allowed transverse modes in the fiber core.

\[ V = \frac{\pi \cdot a}{\lambda} \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2} = \frac{\pi \cdot a}{\lambda} NA \quad \cdots (3.1 - 3) \]

Here, ‘a’ and NA are the diameter and numerical aperture of the fiber core respectively. For single mode operation, \( V \leq 2.405 \). For example, the maximum core diameter which will still permit single transverse mode operation at 1 \( \mu \)m in a typical fiber with core NA of 0.06 is \( \sim \)12.7 \( \mu \)m (core area of \( \sim \)127 \( \mu \)m\(^2\)).

![Double-clad fiber (DCF) cross-section](image)

Figure 3-3 Double-clad fiber (DCF) cross-section

A direct consequence of equation (3.1-2) is that for high power capabilities, fibers with large mode areas (LMA) and short lengths are desired. This means fabrication of highly doped cores (to enable high gain over shorter lengths) with large core sizes, while at the same time allowing single transverse mode operation. It is evident from equation (3.1-3) that the only way to maintain single mode operation in a DCF with increased core sizes is by decreasing the core NA, which is currently limited by fabrication tolerances to \( \sim \)0.06 (corresponding to a core diameter of \( \sim \)12.7 \( \mu \)m). Fibers with core diameters larger than single-mode limit are being commonly used.
for high power applications, even though the output consists of several transverse modes that deteriorate the beam quality.

A fundamentally different approach for increasing the effective mode area has led to the development of microstructured or photonic crystal fibers (PCFs). As a result of their design, PCFs have extremely small core NAs – values as low as 0.01 with effective core diameters of up to 100 μm have been demonstrated [55]. With such high core diameters, and even larger cladding diameters, PCFs are typically no longer physically flexible and behave as rod-fibers. PCFs have many more benefits over traditional fibers which have not been discussed here and the reader is referred to the following references for an overview of this technology [56–58]. PCFs have already shown great promise as mediums for high power lasers and are expected to become the technology of choice for HPFLs. Although this report only deals with double-clad fibers, all theoretical and experimental results presented are independent of the choice of fiber type and can be directly applied with PCFs as well.

An important aspect of fiber design is doping the core with rare-earth ions. There have been huge improvements in the techniques for making highly doped fibers making it possible to use shorter lengths even for high gain applications. The dopant is chosen depending on the desired wavelengths of operation. Popular dopants are neodymium (Nd) for 1.06 μm, ytterbium (Yb) for 1 – 1.1 μm, erbium (Er) for 1.52 – 1.58 μm, and thulium (Tm) for 1.7 – 2.0 μm. *All the*
experiments in this work use Yb-doped fibers for operation around 1.06 μm; however, the techniques and results presented are applicable to all fiber lasers in general.

The attractive features of Yb-doped fibers, such as broad emission band and small quantum defects, have generated a lot of interest and as a result been an active topic of research for high power fiber lasers and amplifiers [59–64]. The absorption and emission spectra of Yb-doped silica fiber is shown in Figure 3-4. Yb-doped fibers are usually pumped at either 915 nm (for broadband pumps) or 976 nm (for higher absorption and smaller quantum defect) for laser generation in the vicinity of 1 μm. Obtaining narrow-linewidth high power emission in the vicinity of 1064 nm is highly desirable for several reasons – the primary being high atmospheric transmission and for second and third harmonic generation (green and UV lasers at 532 nm and 355 nm respectively).

Figure 3-4 Absorption and emission cross-section of Yb in silica glass
There are several other important developments in the area of fiber fabrication, suppression of nonlinear effects, and laser design for high power applications that are not reviewed here. Readers are referred to the following texts and articles where these topics are covered in-depth [42,46,65].

3.1.5 Spatial and Temporal Instabilities

There are several other mechanisms that have been found to impact double-clad LMA fiber laser performance. We will discuss here two that we believe demand most attention for high power and narrow linewidth sources: beam instabilities and self-pulsations.

**Beam Instabilities:** A direct consequence of using LMA fibers is the deterioration of beam quality due to the presence of multiple transverse modes (Figure 3-5a). Single-mode operation of such multimode fibers is an active area of research and several techniques including special doping profiles, special fiber design, fiber alignment techniques and fiber bending are being proposed [66–70]. Bending the fiber to induce losses in higher order modes (HOMs) is by far the most commonly employed. As shown in Figure 3-5b for a 20 μm core 400 μm cladding fiber, the modal index of the fundamental LP_{01} mode is higher than that for the next higher order LP_{11} mode for the entire range of an Yb-doped laser [70]. Thus, by bending the fiber higher order modes are stripped out at a larger coil diameter than the fundamental mode. The fact that the bend induced losses are greater for higher order modes makes it possible to find an optimal coil diameter such that only the fundamental mode is supported. To effectively filter HOMs with all
polarities (for example the vertical and horizontal polarities of the LP\textsubscript{11} mode), it is necessary to use two coils oriented in orthogonal directions [68]. Single mode operation in LMA fibers with core diameters of up to 40 \(\mu\text{m}\) (area \(\sim 1256 \mu\text{m}^2\)) has been demonstrated using this technique. Although effective to a large extent, this technique gets harder to implement for shorter gain fibers (not enough fiber to coil) and larger core diameters (harder to bend). Moreover, this technique inevitably induces some losses for the fundamental mode as well. It has been shown that coiling the fiber also causes field deformations leading to decreased overlap of the fundamental mode with the gain profile, and thus adding further losses in the laser.

![Figure 3-5](a) LP modes of a step index LMA fiber [71]; (b) Modal index difference for a 20 \(\mu\text{m}\) core, 40 \(\mu\text{m}\) cladding fiber [70]

Recently, threshold type beam instabilities have been discovered in high power LMA fiber lasers [72–74]. These modal instabilities are shown to appear at a certain threshold power level depending on the fiber and cavity design, below which the output beam is seemingly stable and single-mode. Although the origin of instabilities is not clear, it has been largely attributed to the
formation of long period gratings due to the interference between the fundamental mode and one or more higher-order modes via resonantly induced index change or the thermo-optic effect. In any case, the root cause of these instabilities is the presence of some fraction of HOMs in the multimode fibers and the suppression of these HOMs should increase the threshold of these modal instabilities [74].

Thus, techniques for transverse mode selection in LMA fiber lasers are highly desired for diffraction-limited power scaling.

Self-Pulsations: Dynamic intensity instabilities in the form of self-pulsations have been widely reported in continuous-wave rare-earth doped fiber lasers for various fiber designs and cavity configurations [75–80]. Although the dynamics of self-pulsations depend largely on the specific of the laser resonator design and gain fiber used, Figure 3-6 shows the typical behavior of the instabilities as observed using a fast detector. The pulse durations are usually a few microseconds with a repetition rate of a few hundred kHz. The microsecond pulses have finer modulation related to the cavity round-trip time, usually a few MHz for fiber lasers. The main mechanisms initiating self-pulsations, especially in Yb-doped fibers, have been attributed to a combination of: 1) relaxation oscillations and nonlinear dynamics of population inversion near threshold operation; and 2) saturable absorption due to an under-pumped section of gain fiber. Furthermore, it has been experimentally observed that in certain cavity configurations (depending on fiber length, lasing linewidth, etc.), these pulsations arising from relaxation
oscillations are amplified due to either stimulated Brillouin scattering (SBS) or stimulated Raman scattering (SRS) [79–81]. The intensities of these pulses can be high enough to cause damage to the fiber and other optics, and trigger other nonlinear effects.

Several groups have investigated self-pulsations for rare-earth doped fiber lasers and proposed techniques for its suppression. These include methods to suppress relaxation oscillations either by electronic feedback to the pump laser [82] or by auxiliary pumping near the signal wavelength [83]. Both of these techniques have only been demonstrated for Er-doped fibers, add to system complexity and work in a limited range of pumping levels. In [84], Guan et. al. demonstrated that relaxation oscillation dynamics are changed by increasing the length of the laser cavity leading to suppressed pulsations. By adding a long section of passive fiber (~2.35 km), they were able to suppress self-pulsations at all power levels for a dual-clad Yb-doped fiber with single-mode core. Although effective, this technique requires very long cavity lengths which may not be suitable for all applications such as single-frequency laser sources. Other
techniques to suppress pulsations have focused on bi-directional pumping or using short active fibers to achieve uniform pumping and eliminate saturable absorption as an initiation mechanism [77,79]. In section 3.2.3, we experimentally show that though using short gain fibers is effective to some extent for stabilizing broadband lasers, it is not enough for narrow-linewidth standing-wave laser resonators. In [78], Hideur et. al. investigated self-pulsations for various cavity configurations and found that a unidirectional ring cavity is capable of suppressing pulsations at all pump levels citing that back-scattered Brillouin and Raman waves cannot be generated in such a cavity. Suzuki et. al. showed that such a unidirectional ring cavity greatly improves the performance of a single-frequency distributed feedback (DFB) fiber laser by simultaneously eliminating self-pulsations and narrowing the laser linewidth compared to the conventional linear cavity [85]. However, DFB fiber lasers are limited to only mW-level output powers.

3.2 High Power Fiber Lasers using VBGs

Volume Bragg gratings have been extensively used for spectral narrowing and stabilization of diode lasers, solid state lasers, optical parametric oscillators, and fiber lasers [86–92]. For fiber lasers, the use of fiber Bragg gratings (FBGs) has been by far more common due to the key benefit of making robust all-fiber alignment-free systems. However for certain applications requiring high spectral brightness, volume Bragg gratings can offer many unique benefits.
As mentioned earlier, a high spectral brightness laser requires high average power in a narrow linewidth with a good quality output beam. Here we describe the development of VBG stabilized tunable narrow-linewidth LMA fiber lasers produced in this work. Injection locking of several fiber lasers to the same narrow linewidth spectra using a single VBG is demonstrated. Self-pulsations-free stable CW operation with tunable narrow linewidths and the possibility of single-frequency operation using a VBG in a unidirectional ring cavity is achieved. Finally, a new technique for transverse mode selection in LMA fiber lasers based on the angular selectivity of reflecting VBGs is proposed and demonstrated.

3.2.1 Spectral Stabilization, Narrowing, and Tunability

Two fiber lasers are constructed, each with ~3.3 m of Yb-doped panda-type PM LMA fiber with 25 μm core and 250 μm cladding (Figure 3-7 shows the fiber cross-section). Each laser is pumped using two 915 nm laser diodes with 4 W maximum power via a (6+1)x1 pump-signal combiner with matched fibers.

![Cross-section of 25 μm core and 250 μm cladding PM fiber](image)
The fibers are loosely coiled with a diameter of ~12 cm on the optical table, output end of the fibers are angle cleaved to ~6°, the rear feedback end is straight cleaved, and aspheric lenses with 8 mm focal lengths and 0.5 NA are used for beam collimation on both ends. External polarizers and half wave-plate are used for polarization control. The external cavity is formed by a highly reflective (HR) broadband dielectric mirror in the back and a broadband or narrowband output coupler in the front end. A 30% reflective dielectric mirror is used as the broadband output coupler. The narrowband output coupler is realized by using a high diffraction efficiency reflecting VBG in combination with the 30% dielectric mirror as shown in Figure 3-8. The VBG used in this case had a peak diffraction efficiency of 98% and FWHM spectral selectivity of 300 pm. Due to the finite apertures of the optics used, the minimum angle of diffraction in this folded cavity is ~4°.

![Figure 3-8 Experimental setup for external cavity VBG-stabilized tunable fiber laser](image)

The performance of both lasers is individually tested in an external cavity setup. The results obtained were similar for both and will be presented for one of them in the following discussions, say laser channel 1. Linearly polarized output with a slope efficiency of about 34%
with respect to absorbed pump power was achieved in both cases (Figure 3-9a). Figure 3-9b compares the output spectra for the two choices of output couplers at 6 W of launched pump power (~4.5 W absorbed power). The measurements are made with an Ocean Optics spectrometer with a resolution of 220 pm. The laser with the broadband output coupler operated simultaneously at several wavelengths and fluctuated with time and power. On the other hand, the VBG stabilized laser operated at a single resolution-limited peak that was stable at all pump levels.

Continuous tunable operation over 15 nm (4.5 THz) is obtained by simply rotating the VBG-mirror combination. The angular selectivity of this VBG limited further tunability to lower wavelengths while maintaining the same power levels. Figure 3-10 shows several resolution-limited peaks between 1060 – 1065 nm.

Figure 3-9 (a) Slope efficiency with 30% output coupler and (b) Output spectra for the broadband and the VBG-stabilized cavity
The output beam profile was observed to be multimode and constantly changing with time and very sensitive to any movement of the fibers. To stabilize the beam profile and suppress higher order modes, a compact fiber platform was designed as shown in Figure 3-11. This platform is designed to integrate the orthogonal coiling technique to facilitate fundamental mode operation as described in [68]. Two coils each with a diameter of 6 cm are orthogonally oriented. Fiber clamps are used to maintain a little tension for securing the fibers and preventing the coils from unspooling. About 130 cm of the gain fiber is coiled in each spool (~7 coils per spool). The platform also shrinks the laser footprint on the table and secures the fibers to minimize any movement and vibrations. Beam quality measurements could not be made at the time, but the output beam showed tremendous visible improvements and looked like pure fundamental mode. The profile was also very stable showing no signs of fluctuations from HOMs. Performance of the fiber lasers, in terms of slope efficiency and spectrum, was not sacrificed compared to the initial setup with loosely-coiled fiber.
Figure 3-11 Fiber laser platform with orthogonal coiling

### 3.2.2 Injection Locking of Fiber Lasers

Many applications desire an array of lasers that are locked to the same wavelength. Fiber laser arrays locked to a narrow linewidth spectrum can find a wide range of applications – for example for pumping other fiber and solid state lasers or for passive coherent beam combining in tiled aperture arrays (more details in the next chapter). We demonstrate a scalable technique for injection-locking of several fiber lasers using a few R-VBGs.

#### 3.2.2.1 Injection Locking in Symmetric Architecture

Figure 3-12 shows the experimental setup for injection-locking of two fiber lasers in the symmetrical architecture – i.e. the two lasers are symmetrically placed on the same side of the VBG. The two fiber lasers constructed in the previous section are used. The VBG used has a
peak diffraction efficiency of ~ 50% and FWHM spectral selectivity of ~ 90 pm at ~4° incidence angle.

The output of each laser in Figure 3-12 is incident partially diffracted by the VBG at a small angle. The diffracted radiation is coupled into the other channel, thus creating a common cavity and effectively locking the two channels. Spectral selectivity of the VBG provides strong mode selection and spectral narrowing of the output signal. Both the lasers are operating at 1062.9 nm (resolution limited to 220 pm) as shown in Figure 3-13a. Spectral measurement with a scanning Fabry-Perot interferometer revealed a number of longitudinal modes oscillating under an envelope of 2.5 pm FWHM (Figure 3-13b).

Figure 3-14 shows the power in the two outputs corresponding to laser 1 and laser 2 as a function of absorbed pump power in each. Note that the slope efficiency is actually slightly higher compared to the individual laser operation of Figure 3-9a. The two output signals are interfered using a beam splitter cube and the interference fringes are observed with a CCD camera (Figure
The maximum contrast was about 96% and the average contrast was about 67%, indicating a significant coherence between the two beams.

Figure 3-13 Spectra of the two injection locked lasers: (a) Left: OSA measurements reveal common spectra for the two lasers resolution limited to 220 pm; (b) Right: Measurements with scanning Fabry-Perot interferometer

Figure 3-14 Output powers of the two injection locked LMA fiber lasers

Figure 3-15 Observed fringes from interfering the two outputs
3.2.2.2 Injection Locking in Asymmetric Architecture

Figure 3-16 shows the experimental setup for injection-locking of two fiber lasers in the asymmetrical architecture – i.e. the two lasers are asymmetrically placed on the opposite side of the VBG.

The same fiber lasers of Figure 3-12 are re-aligned in the asymmetric architecture of Figure 3-16. The mirrors M1 and M3 are 50% output couplers and the mirrors M2 and M4 are high reflection feedback mirrors. VBG-1 is the same used in the symmetrical architecture with a peak diffraction efficiency of 50% and a FWHM linewidth of 90 pm. VBG-2 has a high diffraction efficiency (~95%) with the central Bragg wavelength matched to VBG-1 and having a slightly broader FWHM linewidth of 120 pm. This ensures that the entire bandwidth of VBG-1 within the bandwidth of VBG-2. This cavity is more complex than the symmetrical architecture as it is a combination of 3 cavities – 1st for laser channel 1 formed by M1-VBG2-VBG1-M2; 2nd for laser channel 2 formed by M3-VBG1-M4; and 3rd for a common-cavity formed by M1-VBG2-M3.
The emission spectra of the locked lasers were again identical and resolution limited to 220 pm. Further measurements reveal that the results are similar to the previous case – linewidth of ~2.5 pm, similar output powers as in Figure 3-14, and fringe visibility of ~95%.

3.2.2.3 Scaling of the Injection Locking Technique

By combining the symmetric and asymmetric architectures, a single VBG element can be potentially used to injection lock up to 4 fiber lasers in the configuration shown in Figure 3-17. The mirrors M2 and M4 of Figure 3-16 are replaced here by two laser channels. It should be noted that VBG-1 is the beam splitter which facilitates radiation exchange and mixing between the four channels. VBG-2 is used only to filter out the ASE from the four channels to prevent parasitic lasing and any other suitable filter can also be used in its place. Thus locking of four lasers is still achieved using a single element. The technique can be further scaled to lock a larger array by employing a tree-like architecture using multiple matched VBG splitters in a chain. Due to unavailability of more pumps and laser channels, scaling of this injection-locking technique to 4 and more fiber lasers could not be experimentally demonstrated during the course of this thesis.
3.2.3 Self-Pulsations Free, Stable CW Operation

External cavity VBG-stabilized LMA fiber lasers have been developed in the previous sections and injection-locking of two such lasers has been demonstrated. The output spectra and average powers were found to be stable for long periods of time. However, when closely analyzed using a fast detector, it is found that fast temporal instabilities in the form of random and chaotic pulses are present. Figure 3-6 show the dynamics of the observed self-pulsations. The dynamics of self-pulsations and some techniques for its suppression were reviewed in section 3.1.5. There is indication that self-pulsations can be initiated due to saturable absorption in under-pumped sections of the gain fiber and be further amplified in lasers with long lengths of active fiber.
In efforts to make the fiber lasers temporally stable (self-pulsation-free), the setup of Figure 3-8 was upgraded with new fibers and pump diodes (Figure 3-18). Highly doped Yb fiber with smaller pump cladding (Liekki Yb1200-20/125-PM) was chosen to allow of shorter lengths and better pump-core overlap for homogeneous pumping throughout the fiber length. To efficiently pump these short gain fibers, high brightness 25 W IPG pump diodes emitting at 976 nm with 4 nm linewidth were chosen. The output of the diode is at 976 nm only at maximum output power; for all other drive currents the diode is heated to shift the emitting wavelength closer to the absorption peak of Yb.

![Figure 3-18](image)

Figure 3-18  Linear fiber laser cavity setup for comparing the dynamics of a broadband versus narrowband output coupler

The experimental setup of Figure 3-18 is used to compare the behavior of a fiber laser in a linear cavity with broadband dielectric output coupler and narrowband reflecting VBG output coupler. In these experiments, a short length (~70 cm) of Yb-doped PM fiber is used to ensure the entire length is well pumped and there is no section of under-pumped fiber acting as a saturable absorber. The pump end of the fiber was straight cleaved and the output end cleaved at ~6°. These fibers were too short to be orthogonally coiled and operated in multimode regime. Aspheric lenses with f = 8 mm were used at both ends to collimate the fiber output, and a highly reflecting dielectric mirror was used in the rear end for feedback. The laser dynamics was
observed for a variety of output couplers with different reflectivity and bandwidths. For broadband output coupler, dielectric mirrors with several 10s of nm bandwidth and reflectivity ranging from 10% – 80% were used. For narrowband output coupler, VBGs having full-width-half-maximum (FWHM) linewidth between 100 – 200 pm and varying diffraction efficiencies from 30% – 80% were used.

Figure 3-19 compares the broadband mirror versus VBG cavity for the case when both are ~30% reflective. The spectrum for the broadband output coupler has several peaks fluctuating over a ~10 nm range centered at 1045 nm, whereas for the VBG output spectrum it is relatively very narrow (<220 pm resolution limited) centered at 1064.5 nm (Figure 3-19a). Although self-pulsations in the broadband cavity were observed near lasing threshold (~900 mW launched pump power), it transitions to CW regime at roughly twice the threshold and maintains stable operation beyond this point. On the other hand, for the narrowband VBG cavity self-pulsations were observed at all pump levels (up to 20 W pump limited). Figure 3-19b shows a snapshot of the observed pulsations at 3 W pumping for comparison.

Figure 3-19: Comparison of broadband and narrowband lasing characteristics for R = 30% and 3 W launched pump power: a) output spectrum, and b) fast temporal dynamics.
Similar behavior was observed for broadband output couplers with different reflectivity – the laser would transition from self-pulsations to CW regime at roughly twice the threshold pump level. Pulsations were always observed at these power levels for narrowband output couplers, however, for high diffraction efficiency gratings the laser transitioned to a quasi-CW regime at high pump powers. Figure 3-20 shows a snapshot of the quasi-CW regime for a ~65% diffraction efficiency VBG at 20 W launched pump power (roughly 20 times the threshold).

![Fast temporal dynamics for VBG output coupler with diffraction efficiency of ~65% at 20 W launched pump power.](image)

These observations give a strong indication that although self-pulsations can be eliminated in broadband cavities for almost all pump levels by using short gain fibers; there are additional mechanisms in a narrowband cavity that prevent stable-CW operation. Given the very narrow lasing linewidth, these instabilities could originate from two possible mechanisms: 1) SBS and 2) spatial hole burning (SHB). If the linewidth is narrow enough and the gain fiber sufficiently long, self-pulses initiated from relaxation oscillations can lead to giant pulses due to SBS as pump is increased [79,80]. In our case the length of the gain fiber is pretty short and the core area large, both of which increase the threshold for SBS and hence making it less favorable. This fact
is supported to some extent by the quasi-CW state of Figure 3-20, which would not be possible in the presence of giant SBS pulses. A more probable cause of instabilities seems to be SHB, wherein narrow-linewidth counter-propagating waves form a standing-wave pattern thereby saturating the gain at the nodes and cause spiking in the laser output [93]. Thus, in addition to using a short gain fiber to suppress saturable absorption and SBS as causes of self-pulsations, the standing-wave pattern must also be suppressed to eliminate SHB in narrow linewidth laser operation.

The unidirectional ring cavity approach is adopted and extended to high CW power single frequency sources using volume Bragg gratings (VBG) in the external cavity. Unidirectional ring resonators with external cavity surface gratings have been previously demonstrated [94], however, no investigation of self-pulsations in VBG stabilized fiber laser cavities has been previously reported. More importantly, this is the first demonstration of watt-level CW single frequency Yb-doped fiber laser achieved using a single reflecting VBG in the external cavity.

A traveling-wave unidirectional ring resonator as shown in Figure 3-21 is implemented for the elimination of SHB. The same gain fiber and pump and collimation optics of Figure 3-18 are used. The VBG (~65% diffraction efficiency, 120 pm FWHM linewidth, centered at 1063.8 nm at normal incidence) is aligned at an angle of ~10°. A free-space optical isolator (1 W maximum power handling capacity) ensures unidirectional operation achieving two key benefits – elimination of SHB; and suppression of any backward travelling SBS waves. Figure 3-22a shows
the fast dynamics of the laser for both unidirectional (with isolator, green line) and bidirectional (without isolator, red line) operation at 4 W launched pump. Self-pulsations similar to those in Figure 3-19b at low powers and Figure 3-20 at higher pump levels are observed for bidirectional operation. For unidirectional operation, completely stable CW output is observed from threshold to 1 W of output power limited by the isolator specification (Figure 3-22b). The output spectrum is shown in the left of Figure 3-23 and is found to be resolution limited to 10 pm by the OSA. Measurements with a scanning Fabry-Perot interferometer (FSR = 1.5 GHz, resolution @ 1 µm ~ 7.5 MHz) revealed single frequency operation (Figure 3-23). Periodic mode hops (every few seconds) and some frequency jitter was observed and the system will need to be further optimized for stable operation. This technique of using a VBG in a unidirectional ring resonator can be attractive for making high power stable CW single frequency fiber lasers.

Figure 3-21 Experimental setup of VBG-stabilized unidirectional fiber ring laser
Figure 3-22  a) Fast temporal dynamics for bidirectional and unidirectional operation; (b) Slope efficiency of the VBG stabilized unidirectional fiber ring laser

Figure 3-23 Linewidth of unidirectional fiber ring laser measured with (Left) Optical spectrum analyzer with 10 pm resolution and (Right) scanning Fabry-Perot interferometer

This technique can be extended for wavelength tunable operation. The proposed schematic is shown in Figure 3-24. The lens and VBG are first mutually aligned at normal incidence using a seed laser. The beam from the output end of the fiber is then aligned to the optical axis of this “lens-VBG module”. Wavelength tunability is achieved by translating the module in the transverse direction and is limited by the aperture of the lens. Collimated output from the fiber is directed on to the VBG by the lens at a certain angle determined by the transverse position of the
beam on the lens. The beam diffracted by the VBG is re-collimated by the same lens and the ring cavity completed with the help of a set of fold mirrors, polarization optics, an isolator and the output coupler. The placement of the output coupler is important as it does not need to be realigned as the laser is tuned – the output beam is not shifted by the tuning process.

In our proof-of-concept experiment, a dielectric mirror with 50% reflectivity is used as the output coupler. A VBG with diffraction efficiency of 99.9% and FWHM spectral linewidth of 0.9 nm for Bragg wavelength of 1029.28 nm at normal incidence is used in combination with a plano-convex lens (f = 50 mm, 20 mm usable aperture). Note that as long as the divergence of the focusing beam is smaller than the angular selectivity of the reflecting VBG, no additional losses are introduced. In this case, the FWHM angular selectivity of the VBG for normal incidence is 60 mrad which is about 3 times greater than the divergence of ~22 mrad (full angle) for the focused beam.

Figure 3-24 Schematic of VBG-stabilized unidirectional fiber ring laser with wide tunability range
By translating the lens-VBG module and the fold mirror together, continuous wavelength tunability is achieved without the need for any realignment. Figure 3-25 demonstrates output spectrum tunability over 5 nm as a function of angle of incidence on the VBG. Tuning is limited in the longer wavelength by the aperture of the fold mirror and in the shorter wavelengths by the aperture of the lens. The FWHM linewidth of laser output varied between 40 – 70 pm. Further linewidth narrowing and single-frequency operation is possible by optimizing the VBG parameters. Also, as will be evident after the next section, the VBG and lens combination can be optimized for filtering of higher order transverse modes as well.

![Emission spectrum of tunable unidirectional fiber ring laser as a function of VBG-lens module translation](image)

Figure 3-25 Emission spectrum of tunable unidirectional fiber ring laser as a function of VBG-lens module translation

### 3.2.4 Spatial Stabilization and Transverse Mode Selection in LMA Fiber Lasers

In section 3.1.5, the issue of poor beam quality in LMA fibers and the modal instabilities in high power fiber lasers were discussed. In the experiments of section 3.2.1, the technique of orthogonal coiling was implemented for a ~3 m long large mode area fiber with core diameter of 25 μm and stable operation in a seemingly fundamental mode was achieved. However, this
technique requires long lengths of fibers to allow for coiling and cannot be applicable to shorter fibers (< 1 m) without incurring huge losses for the fundamental mode as well as mechanically straining the fiber. Thus, for self-pulsations-free stable CW operation and single frequency experiments of the previous section, the fiber lasers with short gain fibers operated in multimode regimes with unstable output beam profiles. Techniques for suppression of higher order modes in multimode gain fibers are highly desired for scaling to higher output powers. Here we propose and demonstrate a promising new technique for transverse mode selection and beam stabilization in multimode fibers using the angular selectivity of reflecting VBGs.

The acceptance angle of any VBG is directly related to the Bragg condition and for reflecting VBGs it manifests itself as an acceptance cone (solid angle) at normal incidence, ideally suited to match the cylindrical geometry of transverse modes in free space resonators based on multimode optical fibers, solid state rods and gas cells. As is evident from the derivations in section 2.2, the angular selectivity of a reflecting VBG can be designed to be anywhere from few tenths of mrad to tens of mrad. On the other hand, different modes of a cylindrical step index fiber have different divergences on exiting the fiber, the exact value of which depends on the fiber design. However, in general, lower order modes have lower divergence than higher order modes and have higher on-axis intensity. Divergence matching of the lowest order or any preferred transverse mode to the solid acceptance angle of the grating can be established by focusing the light onto the grating. These properties of R-VBGs and fiber modes can be utilized to engineer the modal content of LMA fiber lasers.
The divergence of the incident beam can be matched to the angular selectivity of the R-VBG, for instance by using a focusing lens shown in Figure 3-26. By using the imaging equation and simple algebraic manipulations, we can derive for small angles and finite distances:

**Divergence at RBG,** \( \theta_2 = \theta_1 \cdot \frac{d}{f} \)  

... (3.2 -1)

**Minimum lens half-aperture,**  
\[ H = \left( d + f \right) \cdot \tan \theta_1 \]  

... (3.2 -2)

**Distance from lens to new waist,**  
\[ D = f \cdot \left( 1 + \frac{f}{d} \right) \]  

... (3.2 -3)

**New waist,**  
\[ w_2 = \frac{w_1 \cdot D}{d + f} \]  

... (3.2 -4)

As an example, to match a multimode fiber with 20 µm core diameter and 0.07 NA with an R-VBG with \( \theta_2 = \Delta \theta_{HWFZ} = 10 \) mrad using 1/2” optics (70% clear aperture gives \( H \approx 4.5 \) mm), we require a lens with:

\[ f = 56 \text{ mm} \]
\( d = 8 \text{ mm} \)

The new waist diameter will 140 µm be located at ~450 mm from the lens. Figure 3-27 shows the evolution of beam divergence and waist as a function of lens translation distance, \( d \). This simple monochromatic modeling enables designing of resonators with matched beam divergence and solid acceptance angle of an R-VBG for different gain media such as fibers, solid state elements, or cells filled with liquids or gases.

![Figure 3-27 Beam divergence and beam waist as a function of lens translation distance, d](image)

Figure 3-28 shows the schematic of the experimental setup. Output from the LMA fiber (length 0.7 m, core NA = 0.07) is focused onto the reflecting VBG using lens L1 (\( f = 8 \text{ mm, NA = 0.5} \)). The R-VBG used has a FWHM spectral linewidth of 110 pm at 1064.1 nm, peak diffraction efficiency of ~65% for a collimated beam, and corresponding angular selectivity of ~ 10 mrad. Changing the distance (\( d \)) between the fiber and the lens, the divergence of the multimode beam incident on the R-VBG can be tuned in a wide range. As a result, the alignment of the focusing lens L1 and the R-VBG can be optimized so that only the lowest order mode receives enough
feedback to lase, while all other higher order modes incur higher losses and remain below threshold.

Figure 3-28 Schematic of setup used for simultaneous mode selection in LMA fiber lasers. L1: lens with $f = 8 \text{ mm}$ $\text{NA} = 0.5$; L2: re-collimating lens.

The system was first aligned for a collimated beam (i.e. $d = 0$ in Figure 3-28). Lasing was obtained at the Bragg wavelength of 1064.1 nm with a slope efficiency of $\sim 79\%$ with respect to estimated absorbed power (Figure 3-29). Maximum measured output power was a little over 5 W at launched pump power of 11.4 W. The output beam profile was observed using a Spiricon camera and was found to be made up of several constantly changing transverse modes as shown in Figure 3-30 at different instants of time.
The lens L1 was then translated to focus the beam, the R-VBG translated to the new focal position, and lens L2 aligned to re-collimate the beam. The position of lens L1 was optimized until the observed beam profile stabilized and looked like the fundamental mode. Figure 3-31 shows the beam profiles in the far zone of the laser when the R-VBG is placed in this focused beam at different instants of time. The beam is very symmetric, shows no signs of higher order mode content, and is highly stable even when the fiber is vibrated. From threshold all the way up to 5 W of output power, the fiber laser maintained the same beam profile. No decrease in total output power and slope efficiency was observed compared to the alignment of the R-VBG in the collimated beam as discussed above. The R-VBG in this case works as a spectrally and spatially selective output coupler that provides maximum feedback to the fundamental transverse mode lasing in a narrow linewidth satisfying the Bragg condition.

Figure 3-29  Output power versus absorbed power for the laser of Figure 3-28
Figure 3-30 Unstable output beam profile (far-field) for collimated beam (d=0) at different time instants

Figure 3-31 Far-field output beam profile when R-VBG is placed in focused beam for (LEFT) maximum power at different time instants; and (RIGHT) different pumping levels. Beam profile is diffraction-limited and stable.

3.3 Summary

Fiber lasers are well suited for high power and high brightness applications thanks to their wave-guiding nature, high gain, and large surface-to-volume ratio for efficient heat removal. Although average powers in the range of a few kW have been demonstrated from single fiber lasers,
scaling to higher power, especially for narrow linewidth sources, is limited by the onset of nonlinear effects, thermal damage, and ultimately optical damage threshold. Large core fibers are able to increase the threshold for some of these effects, however, at the cost of beam quality. Moreover, LMA fiber lasers are also found to suffer from self-pulsations and modal instabilities at high powers due to the presence of higher order transverse modes.

The original work presented in this chapter offers promising solutions for power scaling of narrow linewidth fiber lasers. Spectrally stable operation of an external cavity VBG-stabilized LMA fiber laser is demonstrated with the capability of wavelength tunability over a wide range of 15 nm. Two such lasers are injection-locked with high efficiency using reflecting VBGs and ways for scaling this technique to higher arrays is shown. Through our experimental findings, the primary cause of self-pulsations in narrow-linewidth resonators with short gain fibers is attributed to spatial hole burning. A unidirectional fiber ring resonator using an R-VBG, which provides stable CW operation in quasi single-frequency regime, is demonstrated. For improving the beam quality, a technique utilizing the angular selectivity of R-VBGs in conjunction with convergent incident beams to provide preferential feedback to the desired fundamental mode is invented. Using this technique an LMA fiber laser with 20 μm core diameter is operated with a very stable and seemingly diffraction-limited beam profile.
CHAPTER 4: BEAM COMBINING TECHNIQUES FOR POWER SCALING FIBER LASERS

Current and future industrial, defense, and scientific applications like machining, directed energy weapons, fusion research, power beaming and laser propulsion, require 100s of kW of power in a single diffraction-limited beam. The previous section discussed that the two fundamental bottlenecks for power scaling of single fiber lasers beyond a few kWs are - (i) the onset of nonlinear effects like SBS, and, (ii) optical damage primarily at fiber end facets. Although new fiber geometries (LMA, PCFs, etc.) are trying to push this boundary by increasing the effective core area, they are again limited in scope by onset of multimode operation, mechanical properties of fibers, and fabrication challenges.

A scalable approach to increasing the effective core area is by using multiple apertures, i.e. distributing the intensities and thermal load over a number of fibers, and then combining their outputs. Thus, beam combining methods provide an alternative way of achieving high average output powers, wherein the outputs from an array of laser sources are combined to have the propagation characteristics of a single beam. Several beam combining techniques have been investigated and can be broadly classified as incoherent and coherent combining (Figure 4-1) [95]. In this chapter, a detailed comparative review of the beam combining techniques most relevant to the power scaling of fiber lasers is presented.
4.1 Incoherent Beam Combining

Incoherent beam combining uses spatially and temporally incoherent beams from several emitters to overlap them either in the far-field or combine them into a single diffraction limited beam (still temporally incoherent but maybe spatially coherent) in the near field. This has been achieved by using far-field beam superposition techniques, polarization multiplexing, and wavelength multiplexing of laser arrays. Combining beams from ‘N’ lasers using these
techniques can at best increase the on-axis far-field intensity by ‘N’ times from that of a single laser.

4.1.1 Far-Field Beam Superposition

In this technique, the outputs of multiple lasers are superimposed (overlapped) at the target without any attempt for matching the relative phases, wavelengths or polarizations. Most commonly, the output ends of the individual lasers are tiled to form the output aperture and the individual beams are steered using actively controlled steering optics so that the far-field spots overlap at the target (Figure 4-2) [96]. In such a scheme, combining $N$ lasers can at best lead to a far-field irradiance $N$ times the irradiance of a single beam. An alternative approach is to couple the output of several lasers into a larger fiber, thus combining the outputs at a single aperture at the cost of beam quality.

Figure 4-2 Incoherent beam combining using far-field beam superposition technique
This technique is relatively inexpensive and straightforward to implement and has been employed by IPG to demonstrate its 30-50 kW fiber lasers with supposedly 25-30% wall plug efficiency [97]. In 2008, the Naval Research Laboratory (NRL) incoherently combined four IPG single-mode fiber lasers with total output power of 6.2 kW over a propagation range of 1.2 km [96].

In [96], simulation results for long distance propagation under atmospheric turbulence are compared for coherent and incoherent combining, and suggest that under typical conditions for directed energy applications the respective propagation efficiencies are nearly identical. The propagation efficiency is defined as the ratio of power on target to total transmitted power, and the simulations are performed for the same aperture size and a target size of 100 cm$^2$. Based on their analysis, the authors claim that there are no inherent advantages to coherent beam combining over incoherent combining for applications requiring long range atmospheric propagation.

Possibly the most important benefit of this technique is that there are no physical factors limiting the number of sources that can be combined. The irradiance at the target largely depends on how accurately the individual beams can be steered and focused to get a small overlapped spot on target. This may require multi-element and large beam steering optics when combining broadband sources or as the number of lasers being combined is increased. As a result of these
complexities, IBC usually results in degradation of the beam quality and ends up having a lower brightness combined spot on target compared to the individual source beams.

4.1.2 Polarization Beam Combining (PBC)

In polarization beam combining (PBC), two beams of orthogonal polarizations are combined using polarization sensitive optics. In the simplest case, two linearly polarized lasers are combined using a polarization beam splitter (PBS) in reverse. PBC is most commonly used to combine two diode lasers for free space pumping of solid state or fiber lasers, as shown in Figure 4-3. This technique preserves beam quality while increasing the power, thus capable of brightness scaling. However, it is very challenging to scale PBC to more than two sources and hence finds very limited application in high power lasers.

Figure 4-3 Polarization beam combining (PBC)

Recently, scalable beam combining using PBS was proposed and demonstrated for two Yb-doped fiber lasers with combined powers of up to 90 W [98]. Although polarization rotators and PBS were used for combining, this technique requires sources at different wavelengths and is closer to spectral beam combining.
4.1.3 Spectral Beam Combining (SBC)

As the name suggests, in spectral beam combining, outputs from an array of sources operating at different wavelengths are superimposed spatially by means of filters or dispersive elements to form a beam with combined power. The technique is similar to wavelength division multiplexing systems employed in communication networks. Whereas in low power communication systems waveguide and fiber approaches are efficient, free space approaches using diffractive optics are usually needed in high power spectral beam combining systems of the kind we discuss here.

Spectral beam combining systems can be classified as either serial or parallel as demonstrated in Figure 4-4. Use of dichroic mirrors to overlap beams of different wavelengths is an example of serial SBC, whereas the use of surface gratings with multiple diffraction orders is an example of parallel SBC. The most common approaches to spectral beam combining use diffraction gratings as a wavelength multiplexer and several architectures have been demonstrated using both surface and volume gratings [91,99–107]. These approaches can be broadly classified as external-cavity and common-cavity.

Figure 4-4 Spectral beam combining (SBC) in (a) serial, (b) parallel
In an external-cavity configuration, each laser in the array is designed to operate at a specific wavelength and the wavelength spacing between the neighboring lasers is also specified. These seed lasers are usually single frequency lasers or fiber lasers in MOPA architecture. The output of each laser is spatially overlapped using diffraction gratings designed for the given wavelengths and wavelength spacing. Up to 2 kW of combined power with $M^2 = \sim 2$ has been reported by combining 4 MOPA fiber lasers with a dielectric grating \cite{102}. The individual amplifiers were later scaled to a power of 2.1 kW and the combined power scaled to 8.2 kW with $M^2 = 4.3$ (limited by the beam quality of individual amplifiers)\cite{108}. Highly efficient (~92%) SBC of 5 fiber lasers with combined output powers of 770 W and beam quality limited by that of the sources was demonstrated using VBGs recorded in PTR glass \cite{91}. In this experiment, 4 VBGs were used in series for combining the 5 beams as shown in Figure 4-5; however, an architecture using multiplexed VBGs recorded in the same glass substrate was also proposed to reduce the number of combining elements.

Figure 4-5  Five channel SBC using volume Bragg gratings (VBG)
In the common-cavity approach (Figure 4-6) [103], the laser array has a common feedback arm formed by the grating and the output coupling mirror on one end. Radiation from each emitter in the array is incident on the grating at a different angle, depending on its position in the array, which determines the wavelength that the grating directs towards the partial reflector forcing each emitter to operate at a unique position-dependent wavelength. The output is a common beam comprising of all the wavelengths and combining is achieved without the need for externally controlling the wavelengths and linewidths of each emitter.

![Common-cavity SBC setup](image)

Another approach uses wavelength dependent polarizers for combining of beams with different wavelengths [98]. The preliminary demonstration of this technique combined two fiber lasers that were spectrally separated by ~28 nm and scaling to larger arrays is unclear. Some preliminary efforts have been reported of using several spatially incoherent beams operating at different frequencies to generate a single diffraction limited beam using SBS in optical fibers [109]. Two pump beams coupled into a SMF were shown to excite their own separate Stokes beams and produce a single spatially coherent output. This technique allows combination of
lasers without any restriction on its wavelength, as long as they lie in the transmission window of the fiber material. The limitation is in the requirement of very narrow linewidth sources for efficient excitation of SBS and thermal issues in a SMF at high powers.

*SBC techniques are capable of power scaling while maintaining the beam quality, but at the cost of spectral brightness.* There are several factors limiting the power and channel scalability of SBC techniques. SBC techniques require narrow linewidth sources with highly stable wavelengths and controlled spacing – narrow linewidths lead to lowering of non-linear thresholds in fibers, while the wavelength spacing required limits the number of lasers in the array due to limited gain bandwidth of the active medium. In most SBC technique, the number of optical elements in the system scale with the number of lasers in the array, adding to losses in the system, increasing the complexity of alignment, and increasing the system footprint. The large number of optical elements also gives rise to serious thermal management problem as different optical elements in the system heat differently causing unwanted distortions in the combined beam.

### 4.2 Coherent Beam Combining (CBC): Tiled vs. Filled Aperture

In coherent beam combining (CBC) techniques several laser sources are somehow phase locked with respect to each other and are forced to emit mutually coherent radiation. To achieve this, the relative phases, the wavelengths, and the polarizations of the individual sources being combined
must be matched. A number of methods for coherently combining several lasers for high power applications have been proposed and we will discuss these in detail in the following sections.

Coherent beam combining techniques can be either classified as *active* or *passive* depending on how the phase-locking of the array of sources is achieved. In active CBC, the phase of each source is precisely controlled using real-time optoelectronic feedback loops and as such requires complicated electronics and phase measurement equipment. On the other hand, in passive CBC the sources usually share a common resonator and self-organize to emit coherently without any external phase control, thereby making the system much more simple and compact.

The CBC techniques are also classified as either *tiled aperture* or *filled aperture*, based on the resonator design. In tiled aperture, the individual laser sub-apertures are stacked in a 2-D array to form a larger combined aperture. The far-field beam quality is limited by the fill factor of the 2-D array and often results in unwanted side-lobes in the far-field, thus reducing the power in the central lobe. On the other hand, in filled aperture designs, the outputs of the laser sources are usually combined inside some sort of a common resonator and the combined output is extracted from a single output aperture. Diffraction-limited beam quality can easily be achieved in such a design. Apart from differences in the beam quality neither design offers any obvious advantages in terms of the number of elements that can be phase-locked, and both designs have been used to demonstrate active and passive CBC systems.
To appreciate the loss of power to the side-lobes, let us consider a tiled aperture array of fiber lasers arranged in hexagonal geometry as shown in Figure 4-7 for seven sources.

![Hexagonal tiled aperture with 7 sub-apertures of radius 'a', each sub-aperture emits a Gaussian beam with radius $\omega_o$.](image)

We assume that the output of each sub-aperture with radius ‘a’ is a Gaussian beam with normalized amplitude, $A_G(x, y) = \exp \left(-\frac{x^2 + y^2}{\omega_o^2}\right)$, where $\omega_o \ll a$ is the beam radius. In a realistic situation, $\omega_o$ can be the mode field radii of the lowest order mode from the core of a single fiber and ‘a’ the radius of the outer cladding or protective coating of the fiber used. The effective fill factor of such an array can be defined as ratio of the total area of the beams and the area of the full aperture; and for the example of a 7-element array is given by:

$$F_f = \frac{7 \times \pi \omega_o^2}{\pi (3a)^2} \qquad \text{(4.2 - 1)}$$

The far-field intensity distribution of a single sub-aperture with the Gaussian amplitude distribution (and ignoring the finite aperture effects for $\omega_o \ll a$) is then given by the Fourier Transform (FT) relationship,
\[ I_{FF}(x, y; z) = \left( \frac{1}{\lambda z} \mathcal{F}\{A_G(x, y)\} \right)_{u=\frac{2\pi x}{\lambda z}, \; v=\frac{2\pi y}{\lambda z}}^2 \]

It is known that the FT of a Gaussian is a Gaussian and can be written as,

\[ \mathcal{F}\{A_G(x, y)\} = \int \int \exp \left( -\frac{x^2 + y^2}{\omega_0^2} \right) \cdot e^{-i(ux + vy)} \, dx \, dy \]

\[ = \pi \omega_0^2 \cdot \exp \left( -\frac{\omega_0^2}{4} (u^2 + v^2) \right) \]

\[ \therefore I_{FF}(x, y; z) = \left( \frac{\pi \omega_0^2}{\lambda z} \cdot \exp \left( -\frac{\pi^2 \omega_0^2}{\lambda^2 z^2} (x^2 + y^2) \right) \right)^2 \quad \text{... (4.2 - 2)} \]

Now, the 7-element hexagonal aperture can be formulated as the convolution of a single aperture with the shifted Kronecker delta function,

\[ A_{array}(x, y) = \exp \left( -\frac{x^2 + y^2}{\omega_0^2} \right) * f(x, y) \quad \text{... (4.2 - 3)} \]

Where,

\[ f(x, y) = \delta(x, y) + \delta(x - 2a, y) + \delta(x - a, y - \sqrt{3}a) + \delta(x + a, y - \sqrt{3}a) + \delta(x + 2a, y) \]

\[ + \delta(x + a, y + \sqrt{3}a) + \delta(x - a, y + \sqrt{3}a) \]

Considering the output of each sub-aperture is mutually coherent and in-phase, the far-field intensity distribution will be the interference pattern formed by all of these contributions. The far-field interference pattern is simply the Fourier transform of the aperture. Note that the FT of a convolution of two functions is the product of the FT of the individual functions. Using this property and the FT of the shifted delta function, \[ \mathcal{F}\{\delta(x - x_0, y - y_0)\} = e^{-i(x_0 u + y_0 v)}, \]

followed by some simplifications, the FT of \( f(x, y) \) is obtained as,
\[ F\{f(x,y)\} = 1 + 2 \cos(2au) + 4 \cos(au) \cos(\sqrt{3}av) \]

Then, the far-field intensity of the array is simply,

\[
I_{\text{FF array}}(x,y,z) = \left[ \frac{1}{\lambda z} F\{A_0(x,y)\} \times F\{f(x,y)\} \bigg|_{u=\frac{2\pi x}{\lambda z}, \ v=\frac{2\pi y}{\lambda z}} \right]^2
\]

\[
= \left[ \frac{\pi \omega_0^2}{\lambda z} \exp\left\{ -\frac{\pi^2 \omega_0^2}{\lambda^2 z^2} (x^2 + y^2) \right\} \times \left\{ 1 + 2 \cos\left( \frac{4\pi ax}{\lambda z} \right) + 4 \cos\left( \frac{2\pi ax}{\lambda z} \right) \cos\left( \frac{2\sqrt{3}\pi ay}{\lambda z} \right) \right\} \right]^2
\]

\[ \ldots (4.2 - 4) \]

Setting \( x = y = 0 \) in this equation for far-field on-axis intensity, we see that it always scales as \( 7^2 \), i.e. \( N^2 \), irrespective of the fill-factor for a coherent tiled-aperture.

A commonly stated advantage of CBC over IBC is that for apertures of the same size, the on-axis irradiance in the far-field scales as a factor \( N \) for IBC, while it scales as factor \( N^2 \) for CBC where \( N \) is the number of laser sources in the array being combined. This is true when the size of each emitting sub-aperture is kept constant as the number of sub-apertures, i.e. \( N \), is increased (therefore, the size of the total emitting aperture increases in proportion to \( N \) [46]).

This can be easily demonstrated using the model developed for the 7-element tiled-aperture array. If we now consider an array of mutually incoherent lasers, directed to a far-field target, the outputs of different sub-apertures do not interfere with each other and simply super-impose at the far-field. The far-field intensity is then simply given by \( N \) times the intensity of a single aperture (equation 4.2 – 2).
Figure 4-8 compares the far-field intensity distributions of the coherent tiled-aperture array, incoherent tiled-aperture array, and a coherent filled aperture array of equal effective mode area, for values $2a = 125 \, \mu m$ and $2 \cdot \omega_0 = 20 \, \mu m$. Note that the peak intensity for both coherent cases is the same; however, considerable power is lost to the side-lobes in the case of tiled-aperture array compared to filled-aperture. It is easy to calculate that the total power in the central far-field spot considering a Gaussian beam for a filled-aperture array is 86.5% compared to the theoretical limit for the maximum central-lobe power of 70% possible for tiled-aperture architecture with similar size [46]. Also, it must be noted that the net power is equal in all cases; however, in the coherent case more power is concentrated in a smaller central lobe compared to the incoherent case.

Figure 4-8  Far-field intensity distribution for (a) coherent tiled-aperture (red solid curve); (b) coherent filled-aperture with equal mode area (green dashed curve), and (c) incoherent tiled-aperture (blue dotted curve). For tiled-aperture, values $2a = 125 \, \mu m$ and $2 \cdot \omega_0 = 20 \, \mu m$ are used.
4.3 Active Coherent Beam Combining

Active CBC uses real-time optoelectronic feedback to force the amplifier array to emit mutually coherent and in-phase radiation. Figure 4-9 shows a general schematic of an active CBC system based on the MOPA architecture. This system has three key parts – the master oscillator and the front end, the fiber amplifier array, and the active phasing electronics. The front end includes a master oscillator, which is usually a single-frequency low-noise semiconductor laser, and several pre-amplification stages separated with isolators. The output of the front end is equally split and amplified in each of the fiber amplifiers of the array. Care is taken to ensure that the lengths of all the amplifiers in the array are nearly the same. This is critical for two reasons – 1) the length difference must be less than the coherence length of the seed laser so that the amplifier outputs are still mutually coherent; and 2) to match the gain in each amplifier stage so that the output power levels are nearly equal. Fine adjustment of the path lengths to exactly match the phases of the entire amplifier array is achieved via a real-time control mechanism using electronic feedback loops. The in-phase and mutually coherent outputs of the tiled-aperture amplifier array are then collimated using a microlens array and combined in the far-field as described in the previous section.
Several techniques have been proposed for implementing the active control mechanism and the feedback loop. Most commonly, a part of the seed is frequency shifted and mixed with the outputs from the fiber amplifier array at the beam splitter producing heterodyne signals with beat notes at the value of the frequency shift. The phase information of the beat notes from each beam is extracted using a photodetector array and is used to generate the electronic error signals for the
phase controllers. In some systems, multiple active feedback signals are generated to control various aspects of the system such as the relative phases, polarizations, and output power levels. Two detection and signal processing techniques, the locking of optical coherence by single-detector electronic frequency tagging (LOCSET) [110] and stochastic parallel gradient descent (SPGD) [111,112], have been widely used but will not be further discussed in this report. Other active phase-locking techniques not requiring a reference signal have also been developed [113,114].

The tiled-aperture MOPA based active CBC techniques have been used to demonstrate phase locking of large arrays [113,115] and kW level combined powers [116–120]. The current record is for 64 amplifier laser array by J. Bourderionnet et. al. in [113] and 4 kW of combined power from eight 0.5 kW amplifiers by C. X. Yu et. al. in [117]. The technique has also been demonstrated for combining an array of 218 diode lasers with 38.5 W combined output [121].

One of the advantages of the active CBC system described above is its ability to correct for atmospheric perturbations. Systems that uses the back scattered light from the spot on target to generate the feedback signal and thus maximize the intensity at the far field spot in the given atmospheric conditions have been demonstrated [122,123]. Another advantage of this technique is the ability to steer the output beam using the same active control. By changing the relative phases of the array elements the position of the far-field spot can be controlled. One way to look
at this is that changing the phase of one beam in the array changes the interference pattern in the far-field, thus changing the location where the peak intensity occurs.

4.3.1 Limitations of Tiled Aperture Active CBC Technique

The above results indicate that MOPA array based active CBC techniques have been very successful in scaling to larger arrays and higher combined powers. Although the initial results are promising, the technique suffers from several challenges that limit its performance and usability in practical applications.

Some of the drawbacks are obvious – the requirement of several high power isolators, the system complexity, the requirement of precise matching of amplifier path lengths, and the large system footprint. The complexity of the system stems from the requirements of the complicated active control mechanisms that involve the use of sensitive heterodyne detection schemes, several feedback loops, and fast algorithms.

The more serious limitation to power scaling comes from the requirement of an ultra-narrow linewidth master oscillator. Narrow linewidth sources are required to ensure that the coherence length is longer than the path length differences, in order to enable the generation of beat frequencies required for the active phase control process. This requirement lowers the SBS threshold thus limiting the output powers from each amplifier stage. Suppression of SBS in such
laser arrays is an active topic of research and multi-tone approaches have shown some promise [118,124].

Another major drawback common to all implementations cited above comes from the fill factor issue inherent to tiled-aperture arrays as discussed in the previous section. The far-field beam quality is highly degraded and substantial power is lost to the side lobes. For example, in [117] Yu et. al. combined 4 kW total power in a tiled aperture array – off which only 58% was in the central lobe while 42% was lost to the side-lobes in the far-field. Filled aperture active CBC is a high interest area of research and several techniques have been proposed including the use of re-imaging waveguides [125], coherent polarization beam combining [126], and use of surface diffractive optical elements (DOEs) [120,127–130]. Off these the use of DOEs for combining the beams in the near filled seems to be most interesting at present and will be discussed in more detail below. Note that although the filled-aperture techniques solve the issue of far-field side lobes, the capabilities of beam steering and correction for atmospheric conditions are lost.

4.3.2 Active CBC with DOE

To overcome this drawback, Wickham et. al. [128] proposed adding a diffractive optical element (DOE) at the output of the previous setup to overlap each beam from the fiber amplifier array in the near-field as well as the far-field (Figure 4-10). Using this technique, a 5-element fiber amplifier array was phase locked at low power levels (~ tens of mW) demonstrating 91.4% combining efficiency (percent of power in the combined far-field spot relative to the total power
incident on the DOE) and $M^2 = 1.04$. In [129], Redmond et. al. combined an array of five 500 W amplifiers using a surface DOE with an efficiency of 79% with 1.93 kW in the combined beam of $M^2 = 1.1$. This technique was extended to a 2D array of 3x5 amplifiers by multiplexing orthogonal surface profiles on the same DOE to combine 15 amplifiers with an efficiency of ~70% at 0.6 kW [130].

Figure 4-10  General implementation of a filled-aperture MOPA based active CBC system using DOEs
### 4.4 Passive Coherent Beam Combining

Passive coherent beam combining techniques attempt to combine an array of laser sources without any active feedback loops and electronic phase control. The sheer simplicity of the combining architectures makes passive techniques very attractive; in fact Torrey Wagner of the Air Force Research Laboratory (AFRL) called it one of the “holy grails” for power scaling of fiber lasers [131]. Several methods for passive CBC have been proposed and most use some form of a common cavity to achieve self-organized phasing of the laser array. These approaches can be categorized as interferometric and spatial filtering techniques. Spatial filtering techniques can be further classified as Talbot resonator, self-Fourier cavity, and ring resonator methods. These will be discussed in more detail in the following sections.

Apart from those mentioned above, several other methods have been proposed for passive phasing of laser arrays. One method worth mentioning for fiber lasers is based on evanescent coupling of fields in closely spaced emitters. In evanescent coupling, the beams in individual emitters partially spatially overlap with beams of neighboring emitters, thus coupling in the transverse direction. Minden et. al. [132] demonstrated with some success coherent operation of several fiber lasers by developing a closely packed bundled of evanescently coupled fiber ends, cleaved across the narrowest part to form the output aperture and coupler (Figure 4-11). Coherent operation due to strong evanescent coupling over long interaction lengths (~15 m) of a closely packed 7-core multicore Yb-doped fiber has also been demonstrated with 65% slope efficiency [133]. Evanescent coupling by itself may not be effective enough for coherent locking
of larger arrays since the interaction is limited to neighboring elements, however, can prove promising when combined with one of the other spatial filtering methods.

![Diagram of a fiber laser array](image)

Figure 4-11 Evanescent coupling scheme used by Minden et. al.

Before we begin our discussion, it is perhaps important to appreciate that although several CBC techniques have been demonstrated for small arrays and low power levels; a simple, robust, and scalable approach is yet to be demonstrated. Several authors have attempted to theoretically analyze the physical mechanisms responsible for coherent locking in these techniques, and references to these articles will be provided for the more inquisitive reader. Our discussions will be limited to a basic description and understanding of these methods, experimental results, and challenges for scaling in power and array size.

4.4.1 Interferometric Methods

Interferometric techniques for passive coherent beam combining of fiber lasers usually involve placing the individual lasers in a Michelson interferometer, generalized to more than two arms [134]. The interferometer can be implemented using all fiber couplers or free space beam
splitters as shown in Figure 4-12 for two gain elements. Scaling to larger arrays has been achieved by either employing a tree-like architecture or NxN couplers (Figure 4-13). Use of Nx1 diffractive combiners has also been proposed for passive CBC and analyzed theoretically, however only a few experimental demonstrations at low power and small array size have been attempted [34,135].

Figure 4-12 Passive CBC using a free-space (left) and an all-fiber (right) Michelson interferometer

Figure 4-13 Array-size scaling using 2x2 couplers in tree-like architecture (left) and using NxN couplers (right)

Let us consider the simplest case of combining two fiber lasers in the Michelson interferometer setup of Figure 4-12. The outputs from the two gain mediums are interfered at the beam splitter, which separates the two supermodes of the common cavity. Preferential feedback is provided to
only one of the supermodes by placing a feedback element in only of the output arms, while the radiation in the other arm ideally incurs complete losses. The two gain mediums are therefore in a common cavity with the common feedback ensuring mutually coherent operation. On an intuitive level, the coherent operation is explained by simply considering the time reversal property. A beam incident on the 50:50 beam splitter of Figure 4-14a will be split into two beams of equal intensities which are mutually coherent and have a unique phase relationship. Reversing the direction of these beams in Figure 4-14b, two coherent beams with equal intensities and the same phase relationship will be combined into a single beam by this beam splitter.

More insight of the passive locking mechanism can be obtained by considering the longitudinal modes of the resonator. The longitudinal mode spacing for a resonator of effective length $L_{eff}$ is given by: $\Delta v = \frac{c}{2 \cdot n \cdot L_{eff}}$. The superposition of the longitudinal modes of individual lasers leads to the formation of common cavity modes, or “supermodes”, whenever the modes coincide for each of them. These supermodes are preferred as they constructively interfere at the combining element and experience the least losses. In the simplified case of two lasers with
different lengths, the separation of adjacent supermodes is $\Delta v_y = c/(2 \cdot n \cdot \Delta L)$ and the separation between adjacent longitudinal modes within the supermode is $\Delta v = c/(2 \cdot n \cdot L_{avg})$, where $\Delta L$ and $L_{avg}$ are the length difference and average length of the laser array respectively (Figure 4-15).

Any resonator with high gain and low Q-factor will satisfy the multiple resonance condition and excite all these supermodes, which gives it the ability to self-adjust to random changes in path lengths [136].

![Figure 4-15](image)

Figure 4-15  Formation of common-cavity "supermodes" due to coincidental overlap of longitudinal modes of individual lasers [136]

It must be noted that although the supermode theory is a good tool to visualize the locking mechanism, it is only a cold-cavity analysis (no gain and absorption elements) and does not
explain the physical mechanism of coherent self-organization of laser arrays. In practice, the longitudinal modes of individual laser cavities are constantly changing due to perturbations in the gain medium caused by thermally induced effects (change in refractive index, material length, etc.), gain variation, nonlinear effects, and mechanical perturbations.

Several groups have demonstrated coherent locking of fiber lasers using this method. The all-fiber implementation using 2x2 fiber couplers in a tree-like architecture has dominated due to the perceived robustness of the architecture [137–142], with only a few free-space demonstrations [143–145]. In these references, combining of up to 16 fiber lasers have been demonstrated at power levels of a few watt. Vytran has recently claimed to have achieved combined power levels of over 100 W from 2 to 4 fiber laser combinations in an all-fiber configuration, however, details of this experiment including stability and efficiency of combining have not yet been published [146]. It has been reported that the combining efficiency is very sensitive to the amount of feedback from the loss ports, which is hard to suppress in all-fiber implementations depending only on angle-cleaving to prevent reflections [147].

The underlying mechanism of phase locking and scalability of array size of this method are important topics of investigation and several theoretical and experimental studies have been performed in recent years [134,141,148–152]. Although the current state of understanding is very basic at best, certain characteristics seem to be evident relating to combining efficiency, bandwidth requirement, and power stability. Most of the work to date indicate a roll-off in
combining efficiency with increasing array size, falling to below 90% for >5 lasers as shown in Figure 4-16a [141]. Moreover, experimental and simulated data indicates an increase in power fluctuations (instabilities) as a factor of $N^3$ as the array size ($N$) is increased as shown in Figure 4-16b [141].

The reasons for these observations are still under speculation; however, it clearly indicates a decrease in the coherency for larger laser arrays. One of the possible explanations for the roll-off in combining efficiency is based on the supermode theory – the probability of finding an accidental overlap in longitudinal modes of individual lasers decreases as the number of lasers increase. As a consequence, it is widely believed that availability of many longitudinal modes (and hence a broad bandwidth) improves the combining efficiency and is necessary for scaling to larger arrays [138]. Contrary to this theory, Minden et. al. [132] have demonstrated of passive locking of two single frequency fiber sources showing the possibility of coherent locking of very narrow linewidth sources.

Figure 4-16  Array-size scalability for passive CBC using 2x2 couplers (a) combining efficiency, (b) power fluctuations
Another possible explanation, which can explain both the roll-off in combining efficiency and the increased fluctuations in combined power, is the lack of interaction between non-neighbor laser channels. The above investigations adopt a tree-like architecture using several 50-50 splitters for channel scaling. In such an implementation, only the nearest neighbors directly interact with each other. Thus, such a setup selects the local supermode for pairs of lasers and may be incapable of efficiently selecting the global supermode for the entire array. Fabricating 1xN fiber-based splitters for combining large array is rather challenging. *For efficient and scalable passive beam combining it is important to have all the laser channels simultaneously interfere at the same point to generate the mutually coherent feedback for the common cavity.*

A major inherent drawback of the all-fiber architecture is that the combined output is still extracted from a single fiber and hence does not help in power scaling beyond the limitations of a single fiber discussed in chapter 3. The combining efficiency is reported to decrease with increasing pump powers for a two laser system due to the nonlinearities of the fiber [147]. The use of LMA fibers can mitigate this effect to some extent. However, the use of larger fibers (or other waveguides) will deteriorate the beam quality and finally the total combined power will still be limited by the fiber (or waveguide) itself. Thus, *it is important that the combined power is in free-space.*

It is evident that a free-space implementation with the capability of providing simultaneous mutual interaction of all laser channels is critical for interferometric passive CBC technique. One
promising idea is the use of Nx1 DOE combiners for passive CBC [37,135,153,154]. However, only very few demonstrations at very low powers and small arrays have been demonstrated. Leger et. al. used a binary phase grating for phase locking six GaAlAs semiconductor lasers with an efficiency of 68% [154]. Morel et. al. [135] passively combined of 3 Nd-doped single mode fiber lasers using a continuous surface relief grating with combining efficiencies of ~ 70%. In chapter 5, a new scalable technique for interferometric passive CBC will be introduced using volume DOEs.

4.4.2 Talbot Resonator

This method is based on the phenomena of Talbot imaging which is well-known for a coherent field with an infinite 1-D periodicity. Such a field exactly reproduces itself after propagating by multiples of the Talbot distance, $Z_T = 2\Lambda^2/\lambda$, where $\Lambda$ is the periodicity and $\lambda$ is the free space wavelength. For an array of ‘n’ coupled lasers, $n$ supermodes can be defined characterized by different phase steps, $\Delta \varphi = \varphi_l - \varphi_{l-1}$, between neighboring emitters. Each of these supermodes has its own characteristic Talbot distance at which it repeats itself; thus, by placing a mirror at a distance $Z_M = Z_T/2$, the corresponding supermode can be selectively reflected and coupled back into the cavity (Figure 4-17) [155]. This preferential feedback mechanism and the resultant high losses for all other supermodes, enables phase locking of all emitters in the array. This technique is very well suited for phase locking of one dimensional semiconductor diode laser arrays and has been demonstrated previously [156].
In fiber lasers, this technique is most suitable for multi-core fiber structures [155,157–160]. A multicore fiber consists of several doped cores typically arranged in a ring inside a larger pump core. Though the self-reimaging phenomena still exists in this array of coupled emitters, the previous definition of Talbot distance for an infinite 1-D array is no longer directly applicable to this finite 2-D circular array. A more rigorous computation is required to estimate the effective modal reflection coefficients, $\gamma$, as a function of mirror distance $Z_M$ [157].

![Figure 4-17 Schematic of multicore fiber laser in a Talbot resonator](image)

In [155], Wrage et. al. have phase locked 18 Nd-doped emitters arranged in a ring array using a free space Talbot resonator. The authors identified the coexistence of difference supermodes and fabrication fluctuations in multicore fiber as likely causes for low on-axis intensity when the mirror spacing is corresponding to the in-phase mode. In [160,161], passive fibers were spliced to both ends of the 19-core multicore fiber to form an all-fiber highly robust Talbot resonator and selective excitation of the in-phase supermode was demonstrated (Figure 4-18). In [158], the authors have used structured mirrors to simultaneously increase discrimination between the different supermodes and shape the output beam for obtaining high intensity in the central lobe.
The main challenges for scaling of this technique to high power operations seem to be fabrication tolerances in the multicore fibers and suppression of out-of-phase modes and the number of elements increase.

![Passive CBC using an all-fiber Talbot resonator](image)

Figure 4-18  Passive CBC using an all-fiber Talbot resonator

### 4.4.3 Self–Fourier (SF) Cavity

Coherent combining of lasers using a SF cavity is based on the principles of Self-Fourier functions. A SF function has a Fourier transform that is an exact replica of itself (Figure 4-19). The Gaussian and the Comb functions are well known to be their own FT, and under certain conditions can be the exact self-replica [162]. For example, a Gaussian with width ‘a’, \(A(x) = \exp(-x^2/a^2)\) is a SF function if \(a = 1/\sqrt{\pi}\). Similarly, a Comb function with spacing ‘b’, \(B(x) = \sum \delta(x - n \cdot b)\) is a SF function when \(b = 1\). In [163], Corcoran shows that under proper choice of parameters a function obtained by the convolution of a Gaussian with a product of a Gaussian and Comb functions is also a SF function given by:

\[
F(x) = A(x) \otimes [B(x) \cdot C(x)] = \sum_n \{\exp[-(x - n \cdot b)^2/a^2] \exp[-(n \cdot b/c)^2]\} \quad (4.4 - 1)
\]
Where, $A(x)$ and $C(x)$ are Gaussian functions with widths ‘$a$’ and ‘$c$’ ($a < c$) respectively and $B(x)$ is a Comb with spacing ‘$b$’. Figure 4-20 shows an example of this function.

The SF setup of Figure 4-19 can be folded onto itself to form a SF cavity by cutting the lens in half and placing it in contact with a mirror as shown in Figure 4-21. Note that, since now the field travels through the lens twice, to have the same effective focal length $F_L$ the real focal length of the lens is $2 \times F_L$. Now the FT of the field at the input plane, which is at a distance $L = F_L$ from the mirror surface, is superimposed on itself after the round-trip in the SF cavity.
It has been shown that the SF function of equation (4.4-1) has one degree of freedom, and choosing the width of the narrow Gaussian ‘\(a\)’ as the design parameter, the other two parameters must satisfy:

\[
b = \sqrt{F_L \cdot \lambda} \sqrt{1 - \pi^2 \frac{a^4}{(F_L \cdot \lambda)^2}} \approx \sqrt{F_L \cdot \lambda} \quad \ldots (4.4 - 2)
\]

and,

\[
c = \sqrt{F_L \cdot \lambda} \times \frac{b}{\pi \cdot a} \approx \frac{F_L \cdot \lambda}{\pi \cdot a} \quad \ldots (4.4 - 3)
\]

In the SF cavity of Figure 4-21, coherent beam combining can be achieved by arranging a fiber array with output beam widths of individual emitters equal to ‘\(a\)’ spaced with a periodicity ‘\(b\)’ at the input plane. The outputs from the fiber lasers are approximated by a Gaussian shape and can be designed to have a desired width by using a micro-lens array. The parameter ‘\(c\)’ determines the feedback envelope and hence also the number of elements in the array. In a practical system, a trade-off from an ideal SF system (infinite elements, best efficiency) must be made by
truncating the array to a finite size. It is shown that the losses can be limited to less than 2% of the circulating power by choosing the number of elements as [164]:

\[ N \sim 0.8 \times \frac{b}{a} \quad \ldots \quad (4.4 - 4) \]

In this arrangement of ‘\( N \)’ elements at the input plane, the feedback interference pattern formed after the round-trip (which is essentially the same as the output pattern of the array) efficiently couples back into the individual fibers. As a consequence of the Fourier nature of the cavity, the feedback to each element comprises of contributions from all elements which forces lasing to occur in a collective manner. Incoherent part of the output from the individual emitters is not capable of undergoing similar transformations in the SF property of the cavity and suffers extremely high loss, not contributing to the feedback at all. The SF cavity is, thus, known to be an extremely effective mode selector for single cavity mode operation. For a more in-depth description of the SF cavity and analysis of passive phasing, the reader is referred to [164–166].

In [167], Corcoran has experimentally demonstrated a robust phase-locked array of 7 fiber lasers in a SF cavity at low combined output powers of 0.4 W and plans of scaling to 21 fiber laser array with high power operation was presented [168]. Passive combination with a SF cavity has also been studied for multi-core fiber lasers with inherent evanescent coupling [166].

The inherent limitation of the SF cavity is in the output beam quality. The far-field of the output beam from the array of \( N \) elements has \( N \) peaks (Figure 4-20), and suitable aperture-filling techniques are needed to collect the powers from the side lobes into a single diffraction limited
beam, thus adding to the complexity of this system. Another challenge in scaling to larger array sizes can be appreciated directly from equation (4.4-4). To scale the number of elements in the array, the size of the emitters must be decreased or the spacing between them increased – both of which lead to a low fill factor. This technique, like all other passive CBC techniques, is also susceptible to relative path length differences of the array elements. Perfect SF imaging is only possible for in-phase input beams, and any relative phase difference changes the far-field distribution and degrades the coupling efficiency.

4.4.4 Spatial Filtering in Fourier Plane

This passive CBC technique has some similarities with the SF cavity in that spatial filtering is done at the focal plane of a Fourier transform lens but not limited to SF functions. A micro-lens array is used to collimate the output from an array of \( N \) fiber amplifiers arranged in the tiled-aperture architecture at plane S2 as shown in Figure 4-22 [169].

![Figure 4-22 Schematic for spatial filtering in Fourier plane](image-url)
A converging lens is used to project the far-field pattern of this collimated array to the plane S3. When all the outputs of the array are coherent and in-phase, the resultant far field pattern at plane S3 will have the peak of constructive interference occurring at zero degrees. A spatial filter designed to transmit only the central peak can be placed at this plane to generate high loss for out-of-phase modes and achieve phase locking. This technique was scaled to high power and larger arrays using a ring resonator implementation [170–172]. The spatial filtering ring resonator architecture is shown in Figure 4-23. A single mode fiber is used as the spatial filtering aperture and feedback is provided to the amplifier array using a 1xN fiber splitter which completes the ring resonator.

Figure 4-23 Spatial filtering ring resonator for passive CBC [170]
The Fourier transform lens essentially forms the far-field pattern of the amplifier array at its focal plane, where the SMF is aligned along the optical axis. In the case of all in-phase modes, which results in maximum on-axis intensity (see also section 4.2), the coupling efficiency into the SMF is highest compared to all other modes resulting in maximum feedback to the array. The combined ring resonator thus passively chooses the mode which has the highest far-field on-axis intensity. A cold cavity analysis of supermode selection in such a ring resonator has been developed, and the reader is directed to the following references for a more detailed discussion [173,174].

This technique has largely been pioneered by researchers at Northrop Grumman, who also own the patent for this technique [175]. Passive locking of up to 8 fibers in a linear array and 4 fibers in a 2-D array has been demonstrated at both low and moderately high combined powers. Figure 4-24 shows the key results obtained in [171], where each individual laser is operating ~200 W power level and a combined power of 710 W was achieved. However, the lasers were operating over a large bandwidth of ~30 nm.

Figure 4-24 Results of [171]: Bandwidth of each laser (left); power of combined system (right)
Although the initial results show some promise, there are several unanswered questions and inherent drawbacks. As expected from any tiled-aperture technique, significant power in the far-field is lost to side lobes. Even so, the observed far-field Strehl ratio in [171] is much worse than the theoretical limit for an array with same fill factor, which the authors conveniently attribute to design imperfections and thermal issues without further analysis. The degradation in beam quality can also result if the array is not mutually coherent and not in-phase. No tests for establishing coherence are performed. The broad bandwidth (short coherence length) and constantly fluctuating spectrum of the individual lasers is likely to cause instability of the far-field pattern at the SMF, which in turn can result in fluctuations of combined power, efficiency, and beam quality. No measure of the stability of beam combining is reported.

More importantly, there is the inherent issue of only selecting the in-phase modes. As described in section 4.2, the far-field pattern for an incoherent array also has a peak on-axis (at zero degrees). Thus, incoherent radiation from the array is always coupled back into the cavity and complete suppression is not possible. At high pump powers, the feedback received by incoherent and out-of-phase modes can be enough to clear threshold and lase. Another issue is the coupling of off-axis amplifiers into the single-mode fiber (finite NA) can be sufficiently less efficient than the coupling of amplifiers close to on-axis for large arrays. Just by minimizing the losses in the cavity, it is not guaranteed that the in-phase mode will be selected. An analysis by Leger et. al. reveals that the path length sensitivity of such spatial filtering architectures is much worse; and
beyond a certain path-length error the losses for all modes are equal and the resulting far-field pattern is an incoherent super-position of all the modes [176].

### 4.5 Summary & Comparison

High-power lasers are desired for a great number of applications and fiber lasers have been preferred for its high gain, superior beam quality, compactness, and ease of thermal management. Power scaling of single fiber lasers beyond few kW output powers is limited by optical damage, thermal effects and non-linear effects. Much higher output powers (>> 10 kW) are desired for several industrial and defense applications, making beam combining techniques a promising tool.

Several beam combining techniques were reviewed in this chapter. So far incoherent techniques such as beam superposition and spectral beam combining have been most successful in achieving record combined powers. In such techniques mutually incoherent beams from several emitters are simply overlapped by either pointing it to a common target or by using wavelength/polarization multiplexing, thus compromising the spectral and spatial properties of the individual sources. Lasers can also be coherently combined when the relative phase, wavelength, and polarization of each amplifier in the array is matched using either active or passive techniques.
Active CBC techniques implemented using MOPA architecture has achieved much success. Using this technique, C. Yu et. al. combined eight 0.5 kW Yb-doped fiber amplifiers to obtain a 4 kW coherently combined beam. However, since the output fibers were arranged in a 2D grid (tiled aperture), the near-field fill factor resulted in 42% of the power to be in the far-field side-lobes. To avoid far-field side-lobes and obtain a diffraction-limited combined beam, beams can be overlapped in the near-field using surface DOEs. An array of 5 amplifiers was combined with an efficiency of ~90% at mW power levels and ~79% at kW power levels using a DOE with complex surface profile. This technique was extended to a 2D array of 3x5 amplifiers by multiplexing orthogonal surface profiles on the same DOE to combine 15 amplifiers with an efficiency of ~70% at 0.6 kW.

Although active techniques using surface DOEs have yielded promising results and meet most of the requirements off a beam combining system, there are several drawbacks to it. Firstly, active techniques require precise detection schemes to generate feedback signals and complicated electronic feedback loops to control each amplifier in the array. Moreover, it requires a single frequency source with several stages of isolators and amplifiers, and complex modulation schemes to push the threshold for SBS. Passive CBC techniques can avoid many of these complexities and offer the possibility of a highly simple and graceful solution to power scaling.

Owing to these benefits significant effort has been put towards investigating passive CBC techniques, which include techniques based on multi-arm interferometers, Talbot cavity, self-
Fourier functions, and spatial filtering at the focal plane of a converging lens. A comparison of the coherent beam combining techniques is presented in Table 1. All of these techniques, depending on the particular design, suffer from several drawbacks which include one or more of the following:

- Combined power is extracted from a single fiber
- Tiled aperture implementation, thus poor far-field beam quality
- Interaction with only the closest neighbors
- Extremely sensitive to cavity misalignment
- Broadband and unstable output spectrum
- Uncertainty over scalability in array size and power

Although the science of beam combining is not comprehensive yet and it is not yet clear which technique may lead to combining >100 kW of average output powers, based on our review we can at least identify the key characteristics that the ideal coherent beam combining technique must satisfy.

1. **Combined beam in free-space** to overcome the fundamental limitations of a single fiber

2. **Filled-aperture implementation** for diffraction limited beam in near and far field

3. **Stable narrow linewidth operation** for long distance atmospheric propagation with the possibility of wavelength tunability

4. **Scalable passive technique** to avoid complexities of active systems. For scalability to large arrays, we believe it is important that *all channels simultaneously interfere to generate a mutually coherent common-cavity feedback* which is equally redistributed.
Table 1: Summary of beam combining techniques

<table>
<thead>
<tr>
<th>Beam Combining Techniques</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INCOHERENT: Far-Field Beam Superposition</strong></td>
<td>✓ No stringent requirements on wavelength, phase or polarization of individual sources ✓ High power broadband fiber lasers can be used ✓ No fundamental limit to scaling of array size ✓ Far-field intensity distribution not sensitive to elemental failure ✓ Up to 30 kW of combined power demonstrated and 6 kW tested for propagation of ~1 km</td>
<td>× Neither spatially nor temporally coherent output × Requires sophisticated steering optics for each channel to steer and focus the beams × Far-field beam divergence depends on sub-aperture size rather than of the combined aperture</td>
</tr>
<tr>
<td><strong>INCOHERENT: Spectral Beam Combining (SBC)</strong></td>
<td>✓ Common-cavity SBC techniques have no requirements on wavelength, phase, or polarization whereas external-cavity techniques only require wavelength control ✓ Produces spatially coherent beams allowing long-range propagation ✓ Filled-aperture output, diffraction limited beam quality possible with no far-field side lobes ✓ Up to 2 kW of combined power demonstrated</td>
<td>× Degrades the spectral purity of the individual lasers × SBC in external cavity requires accurate control of wavelengths and carefully matched combining elements × Channel scaling is limited by gain bandwidth of active medium → ~2 kW/nm spectral power density required for 100 kW Yb-doped fiber system × Usually limited by absorption and distortions in the combining grating</td>
</tr>
<tr>
<td><strong>ACTIVE COHERENT</strong></td>
<td>✓ Advantage of temporally and spatially coherent output → extended propagation range, integration with other technologies ✓ Large 2-D arrays (~ 50) demonstrated, theoretically scalable to a few 100 elements ✓ Ability to steer output beams and correct for atmospheric conditions ✓ Phase-locking demonstrated for up to kW power levels</td>
<td>× Requires high coherence length, narrow linewidth seed sources → limits power per channel × Complicated phase control electronics and algorithms × Usually tiled-aperture → significant power lost in side lobes × Need for high power isolators</td>
</tr>
</tbody>
</table>

Outputs of multiple lasers are overlapped at the target without any attempt for matching the relative phases, wavelengths or polarizations.
<table>
<thead>
<tr>
<th>Beam Combining Techniques</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PASSIVE COHERENT: Interferometric</strong></td>
<td>✓ Spatially and temporally coherent output &lt;br&gt; ✓ Complicated active phase control electronics not required &lt;br&gt; ✓ All-fiber, robust, and alignment free systems possible &lt;br&gt; ✓ Filled-aperture output, diffraction limited beam quality &lt;br&gt; ✓ No requirements on laser bandwidths &lt;br&gt; ✓ Efficient combining demonstrated for up to 4 channels and 100 W combined power</td>
<td>× Output extracted from a single fiber → scaling still limited by the fundamental limitations of fibers &lt;br&gt; × Supposed lack of interaction between non-neighboring elements in tree-like architecture. &lt;br&gt; × Challenges in fabricating 1xN fiber combiners. &lt;br&gt; × Extent and mechanism of self-organization not clear, current analysis limited to cold cavities &lt;br&gt; × Somewhat sensitive to element failure, still works &lt;br&gt; × Current demonstrations limited to 4 – 8 lasers and theoretical scalability to ~12</td>
</tr>
<tr>
<td><strong>PASSIVE COHERENT: Spatial Filtering</strong></td>
<td>✓ Spatially and temporally coherent output &lt;br&gt; ✓ Complicated active phase control electronics not required &lt;br&gt; ✓ Outputs of all lasers are interfered at the same instant/location (partially true for Talbot cavity) &lt;br&gt; ✓ No requirements on laser bandwidths – phasing over large spectral range (~30 nm) demonstrated &lt;br&gt; ✓ Single transverse mode operation &lt;br&gt; ✓ Compatible with multi-core fibers &lt;br&gt; ✓ Up to 710 W combined power demonstrated for ring resonator approach</td>
<td>× Talbot Resonator: Issue of discrimination from higher order out-of-phase modes for larger arrays and higher powers. Tiled-aperture architecture. Fabrication tolerances of multicore fibers. May not work in case of single element failure &lt;br&gt; × Self-Fourier Cavity: Awkward beam profiles → aperture filling techniques required. Requires in-phase beams at the input of SF cavity for perfect transform/re-coupling. Array scalability requires lower fill factors. May not work in case of single element failure &lt;br&gt; × Ring Resonator: Poor far-field beam quality related to tiled-aperture architecture. Array scalability not clear.</td>
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CHAPTER 5: PASSIVE COHERENT BEAM COMBINING USING M-VBGs

Keeping in mind the characteristics of an ideal coherent beam combining system outlined in the previous chapter, we propose a passive coherent beam combining approach that uses a volume DOE as the combining element in a generalized multi-arm interferometer as shown in Figure 5-1. This approach can be seen as the passive version of the active CBC setup discussed above in Figure 4-10 and similar to the approach presented earlier for semiconductor lasers using binary phase gratings [154]. The key difference is that we propose using volume DOEs over surface DOEs due to its many benefits. Firstly, volume DOEs are more robust, simpler to fabricate and much easier to handle due to their polished surface. Due to the very fine surface profiles and larger effective surface areas of a surface DOE, the scattering and surface absorption losses are higher. Also, surface gratings suffer from losses to higher diffraction orders which limit the theoretical combining efficiencies possible [117]. Volume gratings, on the other hand, enable highly efficient diffraction to a single order and allow for > 99% theoretical combining efficiencies as shown earlier. Finally, several VBGs can be multiplexed in the same volume to make 1:N splitters and phase lock 2D laser arrays.

The properties of multiplexed volume Bragg gratings were studied in detail in chapter 2. In this chapter, we demonstrate a passive coherent beam combining technique using the M-VBG as a coherent combiner.
Passive CBC using reflecting M-VBGs as the combining elements can be implemented in the linear geometry shown in Figure 5-1, which can be generalized to ‘N’ channels for an N-th order M-VBG. Note that in such a scheme there is direct and equal radiation exchange between each fiber laser and locking is achieved using a single element. Although we will primarily be discussing the role of reflecting M-VBGs for passive combining, it should be understood that transmitting M-VBGs can also be used for this purpose.

We use the following definition for calculating the combining efficiency of a given system:

\[
\text{CBC Efficiency (\%)} = \frac{P_{CBC}}{P_{CBC} + P_{LOSS}} \times 100 \quad \ldots (5 - 1)
\]

Here \( P_{CBC} \) is the power in the combined output beam and \( P_{LOSS} \) is the sum of the signal power in the transmitted or ‘loss’ beams. This accounts for any degradation in the combining efficiency due to incoherent processes, misalignments resulting in poor beam overlap and collimation, and any M-VBG induced distortions of the beam. As an example, Figure 5-2 shows the two channel
case for CBC using reflecting M-VBGs and the analogous schematic using a free space Michelson interferometer as discussed previously. In the situation when the two lasers are coherent with respect to each other, the beams produce interference effects at beam splitter and power splitting between output and loss ports depends on the relative phases and intensity of the two beams. In the ideal scenario, all power will be in the output beam and none will be lost ($P_{\text{LOSS}} = 0$), thus making the combining efficiency 100%.

![CBC with Free Space Michelson](image1.png)

![CBC with MVBG](image2.png)

Figure 5-2 Analogy between passive coherent combining of two laser channels using (left) Michelson interferometer and (right) M-VBGs

![Incoherent Laser Beam Combining Free Space Michelson](image3.png)

![Incoherent Laser Beam Combining MVBG](image4.png)

Figure 5-3 Analogy between incoherent combining of two laser channels using (left) Michelson interferometer and (right) M-VBGs
On the other hand, when the two lasers are completely incoherent with respect to each other (different wavelength, and/or polarization, etc.), the beams do not interfere with each other at the beam splitter and power is equally split between output and loss ports (Figure 5-3). In such a case, a combining efficiency of 50% in the output beam can be expected at best.

Note that when using reflecting M-VBGs, radiation produced by amplified spontaneous emission (ASE) from the individual fiber sources is simply transmitted through the very resonant M-VBG and therefore the combined output beam has high spectral contrast. However, the ASE content in the transmitting arms can be substantial and must be subtracted when calculating the combining efficiency. In the current experiments, the power measured in the transmitting arms included ASE content (no filters were used) and hence the actual combining efficiency can be greater than the given estimates.

5.1 Passive CBC of Two Single-Mode Fiber Lasers in Linear Cavity

The goal of the experiments presented in this section using single mode fibers is to validate the passive CBC technique using M-VBGs as proposed in previous sections, and to analyze the phase locking mechanism, stability, and scalability at low power levels before progressing to high power systems.

To achieve this two single mode fiber laser channels were constructed as shown in Figure 5-4. The active medium is 60±5 cm of Yb-doped fiber with 6 μm core and 125 μm cladding. The
fiber is core-pumped using pump-signal combiner with a FBG stabilized single mode diode operating around 974 nm (~4 nm FWHM) with 500 mW maximum output power. The output of the gain fiber is spliced to an inline polarizer to achieve linearly polarized operation. A half wave-plate is used in one of the lasers for polarization matching. Highly reflective broadband dielectric mirrors are used in the rear for feedback. Figure 5-5 shows the performance of both lasers with a 30% dielectric mirror as output coupler.

![Figure 5-4 Schematic of individual laser channel](image)

![Figure 5-5 Slope efficiency of individual laser channels aligned with 30% dielectric mirror output coupler](image)
The common cavity for passive CBC is formed using the M-VBG and output coupler combination to provide equal and mutually coherent feedback to all lasers in the array. A set of fold mirrors are used for aligning the output beams to the M-VBG. An experimental schematic for this passive CBC setup is shown in Figure 5-6.

Figure 5-6 Experimental setup for passive CBC of two single-mode fiber lasers using a reflecting M-VBG

5.1.1 CBC with High Diffraction-Efficiency M-VBG

The MVBG discussed in the previous reports is used for CBC in this experiment. The two VBGs are symmetrically recorded at ± 4.8° in air with 99% diffraction efficiency and 210 pm FWHM
bandwidth. The MVBG performs as a coherent combiner at the degenerate wavelength of ~1064.25 nm.

The MVBG is first aligned using a tunable laser and three detectors in a setup shown in Figure 2-6. The effects of angular detuning of the M-VBG were investigated in section 2.3.2. An interesting observation is that even for a slight angular detuning as in Figure 5-7, there exists a degenerate wavelength where perfect 50:50 splitting is observed. However, in this case the “combining window” (bandwidth over which MVBG performs as a ~50:50 splitter) is narrowed by almost an order of magnitude from ~100 pm to ~10 pm.

With the MVBG alignment locked and the tunable laser tuned to the degenerate wavelength of 1064.25 nm, rough alignment of the fold mirrors is achieved by ensuring maximum coupling into the fiber core at the output end. The pump diodes are switched on at this point and the external resonator completed (back mirrors, half wave-plates, and output coupler alignment) to obtain lasing. Precise alignment of the output beams of the two channels, to ensure perfect overlap of the beams in the M-VBG and single collinear output, is achieved by simultaneously looking at the far-field spot of the common output beam using a high resolution Spiricon camera and maximizing the combined power.
5.1.1.1 Broad Combining Window

In this case the MVBG is aligned for near perfect overlap of the two gratings such that the combining window is approximately 100 pm as shown in Figure 5-7a. Figure 5-8 shows the power distribution between the main output beam and other “loss beams” for individual lasers and the combined system (at 314 mW pump power per channel). The beams are combined with an efficiency of >91% at all measured pump powers and the combined system operates with a slope efficiency of 48.6% with respect to net launched pump power (Figure 5-9). Maximum combined output power measured was ~378 mW at ~910 mW launched pump power (limited by pump availability). The average output power was found to be very stable with a standard deviation < 1% measured over several minutes of operation (Figure 5-10).
Figure 5-8 Power distribution emission in a two-channel system at 314 mW pump power per channel when (a) only laser 1 is incident on the MVBG, (b) only laser 2 is incident on the MVBG, and (c) both lasers 1 and 2 are incident on the MVBG and coherently combined.

Figure 5-9 Slope efficiency of the combined system for the cases of broad and narrow combining windows are essentially the same. Also plotted is the total power in the transmitted loss ports used to compute the combining efficiency.

Figure 5-10 Average output power for the 2-laser system with MVBG aligned for broad combining window.
Figure 5-11 shows the spectra of output beam for the three cases in Figure 5-8 superimposed with the MVBG spectra of Figure 5-7a. The spectra of individual lasers (solid pink and blue for laser 1 and laser 2 respectively) was observed to be placed at different positions with spectral width about 30 pm (equal to spectral resolution of the spectrum analyzer) and stable over time, whereas the output spectra of the combined system showed frequent wavelength jumps within the combining window of the current MVBG alignment (solid green lines are the average spectra over several measurements for 300 mW and 415 mW output power levels). This behavior corresponds to the competition between several common-cavity supermodes. The combined output beam is found to be diffraction limited in the far-field (Figure 5-12).

Figure 5-11  Spectra for broad combining window - (Left) Each laser lases near the peak of its respective VBG when the other is blocked; (Right) The spectrum of the coherently combined beam is always within the combining window, shown here for two different power levels

Figure 5-12 Far-field profile of the combined beam measured using a 500 mm lens and Spiricon camera
5.1.1.2 Narrow Combining Window

The MVBG is now angularly detuned by 135 arc sec (0.65 mrad) to correspond to Figure 5-7b. Figure 5-13 shows the output spectra of the individual lasers and the combined system for the new alignment. Due to the drastically narrowed combining window, the combined system is locked to a very narrow linewidth (limited by the 3 pm resolution of the optical spectrum analyzer).

![Figure 5-13](image)

Figure 5-13 Spectra for narrow combining window - (Left) Each laser lases near the peak of its respective VBG when the other is blocked; (Right) The spectrum of the coherently combined beam is always within the combining window.

Measurements with a free-space Fabry-Perot interferometer (5 cm length, 3 GHz FSR, Finesse ~15 at 1064 nm) revealed that the combined system has a linewidth < 210 MHz, again limited by the resolving power of the interferometer (Figure 5-14a). Each laser channel has an optical length of about 8 m ± 0.2 m, which corresponds to a longitudinal mode spacing of ~20 MHz – i.e. about 10 possible longitudinal modes within the 210 MHz bandwidth. Occasional jumps between two stable ring patterns were also observed and the transverse profiles of these are
plotted in Figure 5-14b. These 1.3 GHz (~4 pm) jumps could correspond to the common-cavity supermode spacing (which in turn correspond to length difference of ~23 cm between channels).

Figure 5-14 (a) Observed ring pattern from Fabry-Perot measurement of the combined beam, and (b) Frequency shift corresponding to the observed jumps in ring pattern

The performance of this system in terms of output power, combining efficiency, and beam profile is very similar to the earlier case of broad combining window with ~47% slope efficiency (Figure 5-9), >90% combining efficiency, and diffraction limited beam quality. Figure 5-15 shows the spectra over a large bandwidth for the combined output and the transmitted loss beams: a signal-to-ASE suppression of 70 dB in the output beam is measured.

Figure 5-15 Spectral measurement over large bandwidth shows high spectral purity of the combined output beam (green) and all ASE in the transmitted loss beams. The MVBG in this case is aligned to have a narrow combining window.
5.1.1.3 Test for Coherence

The coherent operation of the two-channel system implemented above is studied by controlling the relative polarizations of the two channels. This is achieved by rotating the half wave-plate for one of the channels to rotate the polarization with respect to the other channel and recording the powers in all ports (Figure 5-16). For orthogonal polarization, we find that the powers simply add up for all ports and the combining efficiency is ~52%, as expected for incoherent combining. Also, two sets of Fabry-Perot rings are observed (Figure 5-17). This confirms that the two lasers are independently operating at slightly shifted wavelengths and the output is simply an incoherent superposition of the two beams. On the other hand, for collinear polarization we find...
that almost all of the power is in the output port with a combining efficiency of ~90%. This indicates interferometric interaction of the two channels which is only possible when the beams are coherent. Also, only a single set of Fabry-Perot rings are observed confirming that the lasers are coherently combined (Figure 5-14a).

Figure 5-17 Observed ring pattern from free-space Fabry-Perot measurement of the combined beam when the beams are orthogonally polarized

5.1.2 CBC with Low Diffraction-Efficiency M-VBG

In section 2.3.5, the theoretical model developed for reflecting M-VBGs predicted that to achieve 99% combining efficiency the diffraction efficiency of individual VBGs need only be:

\[ DE_{\eta=99\%} = \left[ \tanh \left( \frac{3}{\sqrt{N}} \right) \right]^2 \times 100 \quad \ldots (5.1 - 1) \]

For N = 2 channels, this equation allows the diffraction efficiency of each VBG to be ~94%.
In order to test these claims, low diffraction efficiency VBGs were multiplexed for combining two laser channels. The two individual VBGs recorded symmetrically at ± 8° in air were measured to have ~92% diffraction efficiency at normal incidence (Figure 5-18). The MVBG performs as a coherent combiner around the degenerate wavelength of ~1061.55 nm with tunable combining window ranging from ~20 – 240 pm as shown in Figure 5-19. Note that since the efficiency of each VBG is slightly lower than the target of 94%, there is about 2% transmitting losses in the combining regime and the intersection of the two VBGs is below the 50% mark.

![Figure 5-18](image1.png)

**Figure 5-18** Spectral properties of the individual low-diffraction efficiency VBGs measured at their respective normal incidence

![Figure 5-19](image2.png)

**Figure 5-19** Spectral property of the low-diffraction efficiency M-VBG for incidence along exact degenerate angle and detuning of 0.05° and 0.1° (blue: diffracted-1, pink: diffracted-2, green: transmitted)
Passive coherent beam combining was performed using a setup similar to Figure 5-6. The two laser channels are essentially the same as used in previous experiments – just the active Yb-doped fibers are shortened to 30 ± 5 cm in length. The individual performance of the two laser channels when aligned with a 30% dielectric output coupler is shown in Figure 5-20.

The M-VBG is aligned using the same techniques in a narrow combining window roughly corresponding to 0.05° detuning in Figure 5-19. The common cavity is formed by HR mirrors in the back and the M-VBG plus 30% dielectric output coupler in the front. The combined system operates with a slope efficiency of 37% with respect to net launched pump power as compared to 45% for the sum of individual lasers (Figure 5-21). The drop in efficiency is expected due to the ~4% round-trip losses added by the M-VBG and additional losses due to greater number of optics and longer free-space paths. Figure 5-22 shows the output spectrum of the combined beam, which is resolution limited to 20 pm linewidth. Fast temporal instabilities in the form of
self-pulsations were observed at all power levels. However, the average output power was found to be very stable with an rms standard deviation <0.5% measured over several minutes of operation. The beam was diffraction-limited with an $M^2 = 1.12$ (Figure 5-23).

Figure 5-21  Power in the coherently combined beam compared with the total power in loss ports and sum of individual lasers from figure 5-20

Figure 5-22  Spectra of the combined beam superimposed on the measured M-VBG spectral response for this alignment
The most important result here is that the beams are combined with an efficiency of >90% with respect to power in the loss ports at all measured pump powers. This validates the theoretical prediction that beams can be coherently combined with high efficiency using VBGs with low diffraction efficiencies. This becomes very important in scaling the passive CBC architecture to larger arrays and more VBGs need to be multiplexed in the same volume.

Figure 5-23 Screenshot of the $M^2$ measurement of the combined beam

5.2 Passive CBC in Unidirectional Ring Cavity

Highly efficient passive coherent beam combining of two fiber lasers has been demonstrated in the previous sections using a linear cavity. Although stable output and combining was observed when averaged over long periods of time, self-pulsation instabilities were found to be present
when observed with a fast detector. Self-pulsations can lead to high intensity pulses which can cause optical damage and trigger nonlinear effects as discussed in chapter 3. For passive coherent beam combining systems, self-pulsations in individual lasers can lead to reduced efficiency if the pulses from each channel are not mutually synchronous and have different amplitudes and shapes.

From the results of individual fiber lasers in the previous chapter, we know that a unidirectional ring resonator is capable of eliminating self-pulsations for narrow linewidth lasers with homogenously pumped gain medium. In this section, this approach is adopted for passive CBC by inventing a multi-arm unidirectional ring resonator with a common mutually coherent feedback provided by the M-VBG. Figure 5-24 shows the general schematic of such a setup where the M-VBG is used twice – first for coherent combining of the outputs from the laser array and then for equally distributing the feedback to the array. Other variations of this scheme are also possible – 1) a single M-VBG is used from opposite sides for splitting and combining, 2) M-VBG-2 is replaced by a series of free-space beam splitters, and 3) the feedback arm is all-fiber using 3 dB fiber splitters.

5.2.1 Self-Pulsations Free, CW Operation

Figure 5-25 shows the experimental setup of the multi-arm unidirectional ring resonator with a common mutually coherent feedback provided by the M-VBG for passive CBC of two single-mode fiber lasers. A free-space feedback using a series of broadband beam splitters is used in
this case. Unidirectional operation is achieved by using a free-space isolator in the common feedback path.

The same pumps, fibers, optics, and M-VBG used in the experiments of section 5.1.2 are used here. The system is aligned with the help of a tunable seed laser as indicated in the schematic. The output of the seed laser is coupled into the rear end of the fiber amplifiers through the beam splitter. The outputs of the two amplifiers are then overlapped inside the M-VBG using a set of fold mirrors and aligned to achieve a single collinear diffracted beam along the combined path. The output coupler, half wave-plates, isolator, and the rear beam splitters are then aligned to complete the ring resonator and achieve lasing. Once the resonator is lasing, the seed laser is turned off and the alignment fine-tuned for maximum combined power and least losses. The output coupler used is a dielectric beam splitter with ~50% reflectivity at 45º incidence.
Combining efficiency of >90% is maintained throughout. Most importantly the output is completely stable CW with no self-pulsations at all power levels. Figure 5-26 shows a measurement with the fast detector at 237 mW launch pump power per channel over a temporal window of 200 μs.

Figure 5-26 Fast detector measurement for the combined beam in the setup of figure 5-25 shows self-pulsations-free very stable CW operation
5.2.2 Single Frequency Operation

The M-VBG was aligned for narrow combining window and the spectrum of the combined beam measured with an optical spectrum analyzer with 20 pm resolution. Since the spectrum was resolution limited, a scanning Fabry-Perot interferometer (FSR = 10 GHz, Finesse = 150, Resolution = 67 MHz) was used to further analyze the linewidth of the combined spectrum. Figure 5-27 shows the measured oscilloscope signal at one instant of time indicating single-frequency operation with <67 MHz linewidth. The single-frequency operation however was not very stable with frequent jitters and signs of multiple peaks (longitudinal modes). Though further optimization must be made to stabilize the single-frequency operation, the importance of this result lies in the possibility that an angularly detuned M-VBG can be used as a very narrow filter to passively and coherently lock multiple laser channels in single-frequency regime.

Figure 5-27 Scanning Fabry-Perot interferometer (FSR = 10 GHz, resolution = ~67 MHz) measurements reveal quasi-single-frequency operation
5.3 Channel Scaling

The passive CBC setup using single-mode fibers has been extended to demonstrate combining of four fiber lasers (Figure 5-28). Each channel comprises of about 30±5 cm of single mode Yb-doped polarization maintaining gain fiber core-pumped using a FBG-stabilized single-mode diode emitting at 974 nm with 500 mW maximum output power. Figure 5-29 shows the individual performance of these four laser channels when aligned with a 30% dielectric output coupler.

![Figure 5-28 Schematic for passive CBC of 4 fiber lasers using a transmitting M-VBG](image)

A 4th order transmitting M-VBG combiner is used in this experiment. Two transmitting VBGs are symmetrically recorded at ±2.5° in air and the other two are symmetrically recorded at ±5° in air, such that all four have a common bisector. Light at 1064 nm incident along the bisector is split equally among the four channels at ±5° and ±10° as shown in FIGURE. This was the first
quadruple transmitting M-VBG recorded in PTR glass and the various fabrication parameters were not perfectly optimized, resulting in a transmitting loss of ~8% in this case (Figure 5-30). The transmitting M-VBG has a wide spectral bandwidth of ~ 80 ± 20 nm.

The four channels are aligned in an external cavity with high reflection broadband mirrors in the back, while the M-VBG plus output coupler combination in the output end provides common feedback and hence passive phase locking. Half-wave plates are used to match the relative polarizations of all channels and fold mirrors are used to align the output radiation of each channel with the M-VBG.

Figure 5-29 Slope efficiency of the individual laser channels aligned with a 30% broadband output coupler

Figure 5-30 Schematic of the 1:4 transmitting M-VBG splitter recorded for combining 4 fiber laser channels
A combining efficiency of ~70% (power in combined port compared to total output) is currently achieved. A slope efficiency of combined power is 38.3%; however, the slope efficiency of the total output power is 54.7% comparable to the average slope efficiency of ~54.4% for the individual lasers (Figure 5-31). The power is simply redistributed to the loss ports because of the losses in the M-VBG used. Losses in the M-VBG have a double impact – it introduces losses in both the combining and splitting processes in the round-trip configuration. As pointed out in chapter 2, the method to record high efficiency M-VBGs are well understood and efforts are currently underway in our team for realizing such elements.

![Graph showing combined power comparison](image)

**Figure 5-31** Combined power in comparison with total power (sum of all ports) and sum of individual lasers

Figure 5-32 shows the stability of the combined output power over 20 minutes of operation. In the current setup with a broadband M-VBG combiner and a broadband output coupler, the
combined beam has a ~ 2 nm spectral linewidth that is constantly changing around 1064 nm. The far-field output beam was diffraction limited and stable over the entire duration of operation.

Figure 5-32 Stability of average combined power; spectra of the combined beam at three different instants of time shown in different color; and (inset) profile of combined beam

### 5.4 Power Scaling

Based on the results of section 3.2.3, the unidirectional ring geometry was chosen for the experiments at high power to suppress any pulsations and power fluctuations that may lead to damage of the amplifiers. The schematic of the experimental setup is shown in Figure 5-33. Each channel comprised of 2 – 2.5 m of 25/250 Yb-doped PM fiber pumped using a 30 W IPG pump diode at 976 nm. The fibers are very loosely coiled and both lasers emit multimode beams. The individual lasers, when aligned with a 30% dielectric output coupler in a linear cavity, operate with 45% slope efficiency with respect to launched pump power (Figure 5-34).
Experiment setup used for the high power experiments at AFRL for coherently combining two LMA fiber lasers using a M-VBG. HWP: half-wave plate; PBS: polarizing beam splitter.

The M-VBG used in this experiment has similar parameters to the one studied in section 2.3.2 and used for the low power experiment of section 5.1.1. A single frequency seed tuned to the M-VBG degenerate wavelength (1063.4 nm in this case) is used for initial alignment. The outputs from the fibers are linearly polarized using a polarizing beam splitter and the...
polarizations are mutually aligned using a half-wave plate. The beams are aligned with the M-VBG using a set of fold mirrors. A variable output coupler formed by the combination of a half-wave plate and a polarizing beam splitter is used to extract the output. The output coupling is later optimized for maximum output. A part of the combined beam is used for feedback to the two channels using free-space optical components shown in the figure. An isolator in the common feedback path ensures unidirectional operation.

Initial results at power levels of several watts are in very good agreement with our previous experiments at low power levels. A combining efficiency of ~88% is achieved up to combined power levels of 10 W (Figure 5-35). Further power scaling was limited by pump availability and heating (proper thermal management for pumps need to be designed). The slope efficiency is 33% (~43% with respect to absorbed pump power) compared to the slope efficiency of 45% for individual channels. The drop is expected due to much higher losses in the combined system: 5% losses in the isolator and roughly 4% in the fold mirrors and dichroic mirrors combined. Additional sources of losses are mismatched polarizations in the two channels, long intra-cavity free-space propagation, and mismatch in beam profiles of the two channels. Mismatched beam profiles (leads to poor spatial overlap inside the M-VBG) and polarizations (leads to poor coherent addition) directly harm the combining efficiency and couple more power into the loss ports.
Although some pulsations were observed near threshold, at higher pump powers completely CW operation was obtained (Figure 5-36). The combined spectrum at 9 W of output power was resolution limited to 20 pm centered at ~1063.4 nm (Figure 5-37). Since the outputs of individual lasers are multimode, the combined beam is not diffraction-limited either with a beam quality varying between $M^2 \sim 1.8 - 2.6$. Figure 5-38 shows the profile of the combined beam at 9 W output power after 1.5 m of propagation.
Figure 5-37  Spectrum of the combined beam is resolution limited to 20 pm and stable at all power levels.

Figure 5-38  Screenshot of $M^2$ measurement of the combined beam at 9 W output power measured using DataRay slit beam profiler; and (inset) profile of the combined beam after 1.5 m of free-space propagation.

Researchers at AFRL are currently working on a similar setup with plans of power scaling up to 300 W level of pumping per channel.
5.5 Conclusions

A scalable passive coherent beam combining technique capable of delivering a high power narrow-linewidth combined beam from a filled-aperture in free-space is highly sought after. Ideally the technique will involve simultaneous mixing of all individual beams in the same volume to generate a mutually coherent feedback. In this chapter, a passive CBC technique using multiplexed volume Bragg gratings (M-VBGs) recorded in PTR glass as a coherent combiner is proposed.

M-VBG is shown as a perfect coherent combiner in a cold-cavity setup (no active elements). Two single mode fiber lasers are then combined in an interferometric common cavity with >90% combining efficiency. It is shown that the M-VBG can be angularly tuned to vary the spectral width of the combined beam. Diffraction limited ($M^2 = 1.12$) output with spectral linewidth narrower than 250 MHz is obtained from this passive setup. It is also shown that high efficiency combining can be achieved even when the individual VBGs have << 99% diffraction efficiency.

A unidirectional ring cavity setup for passive CBC is introduced to generate completely CW self-pulsations-free combined beams. It is demonstrated that this setup can also be used for passively locking two lasers to ultra-narrow linewidths and even single frequency (< 67 MHz). Channel scalability to 4 channels using a quadruple transmitting M-VBG and power scalability of a two channel system using LMA fiber lasers to ~10 W levels is demonstrated.
Overall, a promising passive CBC technique using M-VBGs is introduced that meets all the desired requirements – the combined output is in free-space and extracted from a filled aperture, the combined beam is narrow linewidth, all laser channels are simultaneously interfered in the same volume to generate mutually coherent feedback, and the technique is scalable to larger arrays and higher powers.
CHAPTER 6: TOWARDS HIGH-ENERGY MONOLITHIC SOLID STATE LASERS

Compact, alignment free, and robust narrow-linewidth lasers with good beam quality are desired for many applications such as seeds for high power amplifiers, and airborne and space-based laser systems requiring temperature insensitivity and mechanical stability in extreme environments. Distributed feedback (DFB) and distributed Bragg reflector (DBR) semiconductor and fiber lasers are widely used for narrow linewidth applications. Single frequency semiconductor sources are capable of generating mW-level outputs with MHz linewidths. However, power scaling is an issue and there are inherent losses related to fiber coupling. DFB/DBR fiber lasers on the other hand can reach output powers of a few watts with kHz level linewidths. However, it is challenging to store large amount of energy in the typically small lengths of gain fiber used thus limiting the pulse energies. Monolithic solid state lasers are highly desired for generating high average power and high energy ultra-narrow linewidth beams.

6.1 Rare-earth Doped PTR Glass

In a recent study conducted by colleagues at PPL and OptiGrate, PTR glass was co-doped with rare-earth ions such as Er, Yb, and Nd which are commonly used in solid state and fiber lasers as luminescent agents. The doped-PTR samples were fabricated with high homogeneity and in various forms as shown in Figure 6-1. These ions were added in oxide form with 1 wt% concentration. Note that this is 100 times higher concentration than the photosensitive agents (silver and cerium) and moreover both the luminescent and photosensitive agents are transitional
elements with similar chemical properties. As a result, addition of such high concentration of rare-earth ions has the possibility of disturbing the delicate chemistry of PTR glass.

To test for photosensitivity, stripes were recorded in doped-PTR samples by UV exposure and consequent thermal development. Figure 6-2 shows the interference pattern of a recorded stripe in Yb:PTR sample. It was found that rare-earth ions will have only a mild impact on the photosensitive properties of PTR glass. Moreover, the level of refractive index change achieved in these glasses (shown for Figure 6-3) is enough to record high efficiency volume Bragg gratings.

Figure 6-2 Interference pattern of an irradiated and developed stripe in Nd:PTR glass sample recorded in a shearing interferometer.
The luminescence properties of the doped-PTR glasses were also measured and were found to be very similar to that of other doped-silicate glasses. The study of the absorption and luminescence properties of a rare-earth doped PTR glass requires measuring three different parameters. The first one is the absorption spectrum, the second one is the luminescence spectrum of a rare-earth ion, and the third one is the lifetime of this luminescence. The measurement of the absorption spectra of PTR glass was performed using a commercial dual-beam spectrophotometer (Perkin Elmer Lambda 950) that can measure transmission over the range from 200 nm up to 3200 nm (Figure 6-4). One can see the band of cerium +III with maximum at 305 nm appears undistorted; confirming that photoionization of cerium ions is possible. Then, multiple absorption bands can be seen in Nd, Yb and Er doped glasses, including the bands at ~808 and 880 nm in Nd-doped PTR glasses and the bands at ~976 nm in Yb and Er-doped PTR glasses commonly used for diode pumping of lasers based on the ions.

The measurement of the luminescence spectra of rare-earth doped PTR glass was made by illuminating the samples with a 100 W Xenon lamp with broad spectrum emission and collecting...
the emission light in an arbitrary direction using a fiber. The collected light is analyzed using an optical spectrum analyzer and is plotted for each sample in Figure 6-4. Finally, the luminescence lifetime \( \tau_{\text{rad}} \) was measured for each dopant in PTR glass (~800 µs for Nd:PTR and 2.8 ms for Yb:PTR glass). The measured luminescence spectra and the emission lifetime were used to calculate the emission cross section \( \sigma_{\text{em}} \) with the following formula:

\[
\sigma_{\text{em}}(\lambda) = \frac{\lambda}{8\pi n^2 \tau_{\text{rad}}} \times \frac{I(\lambda)}{\int I(\lambda) d\lambda}
\]

... (6.1 - 1)

The emission cross sections of Nd:PTR and Yb:PTR glasses are plotted in Figure 6-5.
It was also shown experimentally that the luminescence spectra and lifetimes are constant over the UV exposure and thermal development cycles for holographic recording in PTR glass (shown in Figure 6-6 for Nd:PTR glass sample).

As described in the previous sections, PTR glass was successfully doped with Er, Yb, and Nd ions and the absorption cross-sections and lifetimes were measured for each of these. Based on the availability of appropriate pump source and laser optics, we focused on making a laser using Nd-doped and Yb-doped PTR samples. Table 2 gives a summary of the key parameters of these samples, the available pump sources and laser cavity optics.

Figure 6-4 and Figure 6-5 show the absorption coefficients and emission cross sections that have been measured using a UV lamp to excite samples that are doped with 1 wt.% of active ions. The fluorescence decay time has also been measured and is 0.8 ms for Nd-doped PTR glass samples.
and 2.8 ms for Yb-doped PTR glass. The samples doped with Yb show spectra typical for a quasi-3 level system and the maximum of the emission spectrum coincides with the low energy shoulder of the absorption, Nd doped glass shows a clear separation of absorption and emission and considerably larger absorption and emission cross sections.

Table 2: Key parameters for doped PTR glass and available pump source and optics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Nd:PTR</th>
<th>Yb:PTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption, ( \alpha )</td>
<td>1.32 cm(^{-1}) @ 808 nm</td>
<td>0.31 cm(^{-1}) @ 976 nm</td>
</tr>
<tr>
<td></td>
<td>0 cm(^{-1}) @ 1064 nm</td>
<td>0.0023 cm(^{-1}) @ 1058 nm</td>
</tr>
<tr>
<td>Lifetime, ( \tau )</td>
<td>0.8 ms</td>
<td>2.8 ms</td>
</tr>
<tr>
<td>Emission cross-section, ( \sigma_{em} )</td>
<td>1.35 ( \times ) 10(^{-20}) cm(^2) @ 1058 nm</td>
<td>2.1 ( \times ) 10(^{-21}) cm(^2) @ 1010 nm</td>
</tr>
<tr>
<td>Sample Dimensions, ( l \times w \times h )</td>
<td>250 mm ( \times ) 250 mm ( \times ) 2 mm</td>
<td>250 mm ( \times ) 250 mm ( \times ) 2 mm</td>
</tr>
<tr>
<td>AR Coating on doped PTR</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Cavity mirrors R1, R2</td>
<td>1, 0.99 @ 1064 nm</td>
<td>1, 0.99 @ 1064 nm</td>
</tr>
<tr>
<td>Max. Pump Power</td>
<td>30 W @ 808 nm</td>
<td>25 W @ 976 nm</td>
</tr>
<tr>
<td>Pump Delivery Fiber</td>
<td>400 ( \mu )m, 0.22 NA</td>
<td>200 ( \mu )m, 0.22 NA</td>
</tr>
</tbody>
</table>

6.2 Modeling and Design of PTR-Laser

To demonstrate lasing in glasses described in the previous section, we decided to use a longitudinal pumping scheme and a simple Fabry-Perot laser cavity as shown in Figure 6-7. That way, the samples can be excited by high power diode lasers at 808 nm or 976 nm with relatively good beam quality that are available in our laboratory. For the first experiments flat plane mirrors were used, relying on thermal lensing in the sample to achieve sufficient overlap of the pump beam with the cavity mode.
The lasing threshold in general can be estimated as follows:

\[ P_{pr} = \frac{(\Delta N_t) h \nu_p V}{\eta \tau} \]  

...(6.2 – 1)

where \((\Delta N_t)\) is the threshold populations inversion of the working transition level, \(h \nu_p\) is the quantum of energy of pump light, \(V\) is the active area volume, \(\eta\) is the net pumping efficiency coefficient, and \(\tau\) is the lifetime of upper level in lasing transition.

\((\Delta N_t)\) can be expressed as:

\[ (\Delta N_t) = \frac{\gamma_t}{\sigma_{em}} \]  

...(6.2 – 2)

where \(\gamma_t\) is the threshold gain coefficient (in cm\(^{-1}\)) for which the gain in the active material is equal to all losses in the cavity. The equation for threshold for absorbed pump power then becomes:

\[ P_{pr} = \frac{h \nu_p A[2\alpha d - \ln(R) - 2\ln(1 - L')]}{2\eta_q \sigma_{em} \tau} \]  

...(6.2 – 3)

Here, \(\alpha\) (in cm\(^{-1}\)) is the (re)absorption coefficient at the lasing wavelength, \(d\) the length of the lasing medium, \(L'\) the roundtrip cavity loss including Fresnel reflections from the uncoated glass,
and R the mirror transmission loss. The emission cross-section, $\sigma_{em}$ and the spontaneous decay lifetime $\tau$ were measured for all the rare earth-doped PTR glass samples and are summarized in Table 2 for Yb-doped and Nd-doped PTR glasses.

For longitudinal pumping the effective area $A$ can be approximated by $\frac{\pi (\omega_p^2 + \omega_s^2)}{2}$ where $\omega_p$ and $\omega_s$ are the radii of the pump and lasing mode and the lasing threshold becomes:

$$P_{pl} = \frac{\hbar \nu_p \pi (\omega_p^2 + \omega_s^2) (A + R + L)}{4\sigma_{em} \tau \eta_q}$$

where $R$ and $L$ are the logarithmic roundtrip losses as defined above. The absorbed pump power depends on the length of the medium:

$$P_{ABS} = \eta_F P_{IN} \cdot \left(1 - e^{-\alpha d}\right)$$

where, $\eta_F$ is the pump transfer efficiency, $P_{IN}$ is the launched pump power, $\alpha$ is the absorption coefficient at the pump wavelength, and $d$ the length of the gain medium.

Beam divergence for a given pump beam parameter $M^2$ limits the radius of the pump beam and the smallest possible pump beam waist for a given sample thickness $d$ is given by:

$$\sigma_p = \frac{M^2 \lambda_p d}{2n\pi}$$

with the length of the active medium equal to the Rayleigh length of the focused beam. Using equations 6.2-4 and 6.2-6 the length of the gain medium can be optimized to obtain the right lasing conditions.
To estimate the threshold as a function of sample thickness in Yb-doped PTR glass, we first calculated the spectrum of the lasing threshold given the known absorption and emission spectra of the Yb-doped glass. Figure 6-8 shows that the threshold is expected to be lowest around a wavelength of 1010 nm for samples up to 5 cm of length. The graph shows the absorption and emission spectra of the glass together with the ratio of total emission cross section for several different cavity losses.

Figure 6-8  Emission and absorption spectra of Yb doped PTR glass and calculated lasing threshold (in arbitrary units) as a function of wavelength.

Next, we have calculated the estimated lasing threshold as a function of the sample thickness and plotted it together with the maximum available absorbed power for, 1058 nm lasing in Nd-doped PTR glass and 1010 nm lasing in Yb-doped PTR glass in Figure 6-9. For simplicity, pump and lasing mode are assumed to be of equal size. Comparing this with the actual available pump power (black line) gives an indication if the lasing threshold can be achieved in these samples with the available pump diodes.
It is clear that lasing is achieved easier in Nd doped samples using the pump diodes at hand. Yb doped samples with the given doping level have lower absorption, lower emission cross sections, and show the effect of re-absorption at the lasing wavelength. While it should be possible to observe lasing with the given doping concentration and pump diodes, the possible thickness range of the sample is limited and the expected overall efficiency is relatively low due to the small absorbed power. We plan to demonstrate lasing in antireflection coated thin samples in the future but for our first experiments we choose Nd-doped PTR glass. Actually, Figure 6-9b shows that the available pump power is sufficient to overcome the lasing threshold for short gain medium lengths of up to several cm even without AR coating and cavity losses up to several percent.
6.3 Lasing in Rare-Earth Doped PTR Glass

Figure 6-10 shows the experimental setup that was designed and assembled. Based on the above calculations, a 2 mm thick Nd-doped PTR glass slab was used as the gain medium. In order to match the Rayleigh length to the sample thickness, a 808 nm pump light should be focused to a diameter of 600 μm. The combination of a 50 mm focal length lens and a 75 mm focal length lens was used to image the output from the 400 μm fiber to a 600 μm spot inside the sample.

![Experimental setup for Nd:PTR laser]

The Nd-doped PTR glass as gain medium was placed close to the 100% reflective flat mirror. The overlap between the pump and laser beam was achieved using a 45° dichroic mirror. The output coupler at the front end was separated by about 50 mm from the back mirror, completing the laser cavity. The Nd-doped PTR glass sample was not actively cooled in these experiments. The pump source was operated in a quasi-CW regime with a pulse width of 1.5 ms, slightly longer than the measured lifetime, and a repetition rate of 100 Hz to keep thermal effects low and maintain low average power.
The transmitted pump power was found to be linearly proportional to the input power. Figure 6-11 shows the pump absorbed power versus the launched pump power. We observe a linear absorption of about 23% which corresponds well to the initially measured absorption coefficient of 1.32 cm$^{-1}$.

Lasing was observed above a threshold of about 4.4 W of incident or ~ 1 W of absorbed power. Compared to the estimated threshold pump power this corresponds to a cavity loss between 1% and 3%. We have observed a lower divergence of the lasing beam compared to the pump beam. While we have not yet characterized the lasing beam completely, we estimate that the lasing mode waist is at least a factor of 1.5 smaller than the pump beam. The temporal characteristic of the pump and lasing pulses are plotted in Figure 6-12 which shows the spiking behavior characteristic for Nd doped glasses.
A slope efficiency of 21% and maximum output pulse energy of 0.8 mJ or 0.5 W of steady state power was obtained for the 99% mirror output coupler (Figure 6-13). At higher power levels, the lasing efficiency dropped which we tentatively attribute to uncontrolled thermal lensing.

The lasing spectrum was distributed around 1058 nm and about 10 nm wide. In order to narrow the spectrum we replaced the 99% output coupler by a volume Bragg grating with a diffraction efficiency of ~ 99% and a bandwidth of FWHM linewidth ~230 pm (Bragg wavelength of
~1065.3 nm at normal incidence). Figure 6-14 compares the laser output spectra for the mirror and VBG output couplers. A FWHM laser linewidth of 23 pm was measured for the case of VBG output coupler using a 0.01 nm resolution spectrum analyzer.

![Figure 6-14 Lasing spectra of Nd: PTR glass laser with mirror and VBG output couplers](image)

### 6.4 Conclusions

A recently developed rare-earth doped photo-thermo-refractive glass, which has been shown to be a new and promising laser material, was used in our experiments for the first demonstration of lasing in this photosensitive material. A diode pumped Nd:PTRG laser in an external cavity formed with two broadband dielectric mirrors emitted at 1058 nm with >5 nm spectral width and >20% slope efficiency. The use of a reflecting VBG narrowed Nd:PTRG laser emission down to ~23 pm FWHM linewidth centered at ~1065.3 nm. The combination of large optical gain, low loss, and the possibility to write distributed reflectors directly into the active material open a plethora of new possible laser structures that we plan to explore further in the future.
CHAPTER 7: CONCLUSIONS AND OUTLOOK

In this thesis, I have investigated the use of volume holographic elements recorded in PTR glass for power scaling of narrow-linewidth fiber lasers. The research made during the course of this thesis is organized in three main directions – enhancing the performance of individual large mode area fiber lasers, power scaling by passive coherent combining of an array of fiber laser sources, and development of compact monolithic single-frequency solid-state lasers.

7.1 Large Mode Area Fiber Lasers

Summary
Single fiber lasers enable kW level output powers limited by optical damage, thermal effects and non-linear effects. Output powers can be further scaled using large mode area fibers, however, at the cost of beam quality and instabilities due to the presence of higher order modes. A spectrally stable, narrow-linewidth, and tunable large mode area fiber laser is built using an intra-cavity reflecting volume Bragg grating. An efficient technique for injection-locking several fiber lasers to a common narrowband spectrum is proposed and demonstrated for two lasers.

Self-pulsations in fiber lasers employing high gain LMA fibers (thus requiring a short length of active fiber) are investigated. It is shown that spatial hole burning is the primary cause of self-pulsations in narrow-linewidth laser operation. A completely self-pulsations free, continuous-wave operation of a VBG-stabilized unidirectional fiber ring laser is demonstrated with quasi
single-frequency (< 7.5 MHz) output. A compact unidirectional fiber ring laser system with wavelength tunability of over 5 nm is built and demonstrated.

A method for transverse mode selection in multimode fiber lasers to suppress higher order mode content and stabilize the output beam profile is invented using angular selectivity of reflecting VBGs. By placing the VBG output coupler in a convergent beam, stabilization of the far-field beam profile of a 20 μm core large mode area fiber laser is demonstrated.

**Outlook**

The method of transverse mode selection using the cylindrically symmetric angular selectivity of reflecting volume Bragg gratings demonstrated in this thesis holds a lot of promise and demands further investigation. Although initial proof-of-concept experiment is demonstrated for stabilizing the output beam profile of a large mode area fiber, an in-depth study of the modal content of the stabilized beam is yet to be made. To better understand the mechanism of transverse mode selection and aid the design of VBGs for this purpose, a theoretical model describing the interaction of VBG with broadband multimode finite incident beams and the amplification of the reflected modes in the gain fiber is needed.

The proposed technique of transverse mode selection can be integrated with any large mode area fiber design and such possibilities should be explored. For example, it is critical for passive coherent beam combining of large mode area fibers (as discussed in section 5.4) that all lasers
in the array have stable and diffraction-limited beam profiles to achieve good overlap. Integration of the transverse mode selection technique with the passive CBC setup should be investigated.

Another exciting development will be the integration of the transverse mode selection technique with the proposed unidirectional ring laser of section 3.2.3. A compact high power, CW, single-frequency fiber laser source with diffraction-limited beam quality is highly desired and should be realizable using this technique. Furthermore, this technique can be extended for increasing the brightness of larger core fibers and solid-state laser rods.

### 7.2 Passive Coherent Beam Combining

**Summary**

Beam combining techniques are essential to power scale beyond the limitations of single laser sources. Several beam combining techniques relevant to fiber lasers were compared in this study and found to be lacking in one or more of the following aspects: the coherence of the individual sources is compromised, the far-field beam quality is highly degraded with significant power in side lobes, spectrally broad and unstable, and uncertainty over scaling to larger arrays and higher power. Keeping in mind the key requirements of coherence, good far-field beam quality, narrow and stable spectra, and scalability in both array size and power, a new passive coherent beam combining technique using multiplexed volume Bragg gratings (M-VBGs) was proposed.
In order to understand the interaction of multiple beams for coherent combining, the spectral properties and beam combining efficiency of M-VBGs recorded in PTR glass were theoretically and experimentally investigated. Two single-mode fiber lasers were coherently combined using a 2nd order reflecting M-VBG in both linear and unidirectional-ring resonators with >90% combining efficiency and diffraction-limited beam quality. It was demonstrated that the combining bandwidth can be controlled in the range of 100s of pm to a few pm by angular detuning of the M-VBG. Very narrow-linewidth (< 210 MHz) operation in a linear cavity and possibility of single-frequency operation in a unidirectional ring cavity of the coherently combined system was demonstrated using this technique. It was theoretically derived and experimentally demonstrated that high combining efficiency can be achieved even by multiplexing low-efficiency VBGs, with the required diffraction efficiency of individual VBGs decreasing as array size increases.

Scaling of passive coherent beam combining to four fiber lasers was demonstrated using a 4th order transmitting M-VBG. Power scaling of this technique to 10 W level combined powers with 88% combining efficiency was demonstrated by passively combining two large mode area fiber lasers using a 2nd order reflecting M-VBG in a unidirectional ring resonator.

**Outlook**

A very promising technique for passive coherent beam combining is proposed and demonstrated that satisfies all the key requirements of – combined beam in free-space, good far-field beam
quality, narrow and stable output spectrum, high combining efficiency, and scalability to larger arrays. Though the results presented in this thesis prove the validity of this technique, further investigation is required to scale this technique to kW level output powers and larger arrays.

In terms of power scaling, the performance of M-VBGs must be studied at high temperature and techniques for proper thermal management of the M-VBG must be investigated. Furthermore, the impact of multimode beams from large mode area fibers on the combining efficiency of the system must be investigated and alignment techniques for achieving good overlap inside the M-VBG developed. An idea suggested during this thesis, but not yet implemented, is the integration of the transverse mode selection technique with the passive coherent beam combining setup. A focusing lens can be used to align the beams with the M-VBG fulfilling two key purposes – ensuring overlap of all beams inside the volume of the grating, and possibility of transverse mode selection.

In terms of array size scaling, the fabrication of higher order M-VBGs is critical. All M-VBGs used in the current study were provided by OptiGrate Corporation, and further efforts from them in this direction will be crucial. Of particular importance is the comparison between transmitting and reflecting M-VBGs for coherent combining applications in terms of scalability, combining efficiency, combined spectrum, and fabrication complexity.
7.3 Monolithic Solid-State Lasers

Summary

The photosensitive PTR glass is doped with luminescent rare-earth ions with the goal of making monolithic single-frequency lasers. In this thesis, a three-level laser model is used to design the parameters of Nd:PTR glass for efficient lasing. Lasing is demonstrated in a 2 mm thick Nd:PTR sample in an external cavity with a slope efficiency of 22%. With the use of a reflecting VBG the laser emission was narrowed to ~23 pm FWHM linewidth.

Outlook

Demonstration of lasing in rare-earth doped PTR glass and spectral narrowing using a reflecting VBG are very exciting first steps towards the development of high energy monolithic single-frequency lasers. Following this work, OptiGrate Corporation has already demonstrated recording of volume Bragg gratings in the doped-PTR glasses and initial demonstration of single-frequency operation from these distributed feedback PTR lasers. Further efforts for demonstrating high power CW operation and high energy pulsed operation are currently underway.
REFERENCES


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