Power Scaling Concepts in Fiber Lasers and Amplifiers

by

Jaclyn Su Phin Chan

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Fiber lasers and amplifiers have undergone rapid development in the past two decades, evidenced by the almost exponential rise in their output powers. This project investigates various concepts relating to high-power operation of fiber sources, focusing particularly on mode-area scaling, with the goal of developing a strategy for further power-scaling of fiber sources.

The first concept examined is the phenomena of multimode interference (MMI), which occurs when fiber core areas are scaled to the extent that they support the propagation of more than one mode. MMI gives rise to self-imaging, whereby the initial phase relationship and spatial profile of an input beam is recovered at the output. This was investigated using a multimode ytterbium doped fiber amplifier, seeded with a wavelength tunable single mode ytterbium fiber laser. Tuning of the seed source showed that the amplifier underwent periodic self imaging of the fundamental mode beam incident from the seed, with a measured self-imaging wavelength period of $\sim 0.7$ nm, consistent with predicted values. Despite significant higher order mode presence, self imaging yielded an excellent $M^2$ value of 1.16. The laser beam $M^2$ value in a non-self-imaging state reached a maximum value of 1.6. To illustrate the repercussions of these cyclical changes, the output of this amplifier was coupled into a single mode fiber. As the seed source was tuned the coupling efficiency underwent drastic changes from a maximum of 0.7 to a minimum of 0.04 due to changes in the amplifier’s beam pointing and quality as a result of MMI.

A novel concept for mode selection was introduced which would preclude the negative effects of MMI by virtue of operating only on a single selected mode. The concept involves exploiting the mode-dependent spectral response of the reflectivity of fiber Bragg gratings. Experimental work with a multimode thulium fiber laser undertaken in collaboration with colleague Jae Daniel. Selected fundamental mode operation was successfully
achieved, with an excellent $M^2$ value of 1.1 compared to 3.3 for the same laser free-running without mode selection. Other higher-order modes could be selected by tuning the fiber laser. Analytical and numerical modelling showed that the reduced spatial overlap between the fundamental mode and the gain profile of the fiber would have minimal effect on the laser slope efficiency if operated at least 8 times above threshold. We speculate scalability of this novel technique to core diameters of up to 70 $\mu m$.

To lay the groundwork for the transfer of the mode-selection technique to Q-switched multimode thulium fiber lasers, benchmarking experiments were conducted to probe the maximum achievable pulse energies and peak power from a thulium fiber. The highest pulse energy recorded was 618 $\mu J$, with a corresponding peak power of 23 kW. However, the output pulse shape contained multiple peaks separated by one round-trip time (~50 ns).

This multipeak phenomena was investigated numerically. It was found that the multipeak behaviour is initiated by the transient ASE wave injected into the cavity by the Q-switch as it is switched. A novel and elegant method for obtaining singly-pulsed, potentially high peak power output from a highly pumped Q-switch fiber source via regenerative amplification was proposed. This was proven experimentally in a Q-switched thulium fiber. We observed single-peaked pulses with a pulse width of $\lesssim$ 14 ns. However, measured pulse energies and peak powers were low (20 $\mu J$ and 1.5 kW) due to high cavity losses and deleterious parasitic lasing. Inspection of the output spectrum confirmed that the Q-switched system was in fact a Q-switched ASE source. It is hoped that a more optimal experimental setup will yield better results in terms of the pulse energies and peak powers obtained.
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Academic Thesis: Declaration Of Authorship

I, Jaclyn Chan Su Phin declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

Power Scaling Concepts in Fiber Lasers and Amplifiers

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;

2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;

3. Where I have consulted the published work of others, this is always clearly attributed;

4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;

5. I have acknowledged all main sources of help;

6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

7. Either none of this work has been published before submission, or parts of this work have been published as: [please see List of publications]:

Signed: ................................. Date: ......................................................
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List of Symbols and Abbreviations

AOM Acousto-Optic Modulator
PM Polarisation-maintaining
Tm Thulium
VBG Volume Bragg Grating
Yb Ytterbium
CBC Coherent Beam Combining
CW Continuous Wave
Er Erbium
ESA Excited State Absorption
FBG Fiber Bragg Gratings
LMA Large Mode Area
MFD Mode Field Diameter
MMI Multimode Interference
MOPA Master Oscillator Power Amplifier
PCF Photonic Crystal Fibers
RTP Rubidium Titanyl Phosphate
SBS Stimulated Brillouin Scattering
SRS Stimulated Raman Scattering
WBC Wavelength Beam Combining
\(\beta_0\) or \(\beta_v\)  Propagation constant of fundamental mode and mode number \(v\) respectively (Chapter 3)

\(\Delta N^o\)  Unpumped population inversion density

\(\delta\)  Cavity loss, including output coupling

\(\eta_2(t)\)  The time-varying feedback coupling efficiency for the Q-switched end of the fiber. (Chapter 6)

\(\gamma\)  Inversion reduction factor

\(\Gamma_p, \Gamma_k\)  Overlap factor between pump and signal respectively with the doped area of the core (Chapter 6)

\(\Lambda\)  Reimaging length (Chapter 3)

\(\lambda\)  Wavelength

\(\lambda_{FBG}, \lambda_{VBG}\)  Bragg wavelength for a fiber Bragg grating and volume Bragg grating respectively (Chapter 4)

\(\Lambda_{FBG}, \Lambda_{VBG}\)  Grating period for a fiber Bragg grating and volume Bragg grating respectively (Chapter 4)

\(\Psi(y)\)  1-dimensional field profile of a beam incident on a waveguide (Chapter 3)

\(\psi(y)\)  1-dimensional modal field distribution (Chapter 3)

\(\sigma_{as}, \sigma_{es}\)  Absorption and emission cross section for laser signal (Chapter 4)

\(c_v\)  Field excitation coefficient (Chapter 3)

\(E_{sat}\)  Saturation energy of the gain medium

\(f_a, f_b\)  Fractional population of the level \(a\) and \(b\) respectively (Chapter 4)

\(g_a, g_i\)  Degeneracies of states \(a\) and \(i\) (Chapter 4)

\(L_c\)  Total cavity length (Chapter 4)

\(n(x, y, z)\)  Population inversion density (Chapter 4, 5)

\(N_0\)  Total dopant population density (Chapter 4)

\(N_1\)  Population density of upper manifold (Chapter 4)

\(N_a, N_b\)  Population density for the lower and upper laser levels \(a\) and \(b\) respectively (Chapter 4)

\(n_{core}\)  Refractive index of the fiber core (Chapter 3)
List of Symbols and Abbreviations

$n_{eff}$  Effective refractive index of the core (for a particular mode) (Chapter 4)

$P_p(z, t)$  Pump power in the forward direction (Chapter 6)

$P_{k}^{\pm}$  Forward (or backward) propagating signal power in the $k$th channel (Chapter 6)

$R$  Pump rate (number of ions excited into the upper laser level by the pump light per second) (Chapter 4)

$s(x, y, z)$  Photon density (Chapter 4)

$t_{rise}$  Rise time of Q Switch (Chapter 6)

$W_e$  Effective width of the core (Chapter 3)

$S$  Cavity photon number (Total number of photons in the cavity) (Chapter 4)
Chapter 1

Introduction

1.1 Overview

Fiber-based laser and amplifiers have come a long way since the first fiber laser was demonstrated by Elias Snitzer in the early 1960’s [1]. In its early days, the growth of fiber technology was hindered by the lack of suitable pump sources. The advent of single mode pump diodes sparked a renaissance in fiber laser research, and in 1986, researchers managed to demonstrate the first practical erbium-doped fiber lasers [2]. These, however, were single mode devices which required pump sources to be similarly single mode, thereby raising the system’s cost and complexity.

In 1988, the introduction of cladding pumping [3], whereby the pump light could be coupled into the much larger inner cladding of a double-clad fiber, removed this restriction, leading to a gradual rise in laser power. This increase has been spurred on by recently devised techniques like the fabrication of large-mode area fibers and the use of photonic crystal fibers. These developments in fiber technology have enabled the power scaling of continuous wave (cw) fiber lasers by almost 2 orders of magnitude over the past ten years, well into kilowatt levels (Figure 1.1), empowering fiber lasers with the potential to not only replace most of today’s conventional solid-state lasers as the laser source of choice, but also significantly broaden the field of laser applications.
Chapter 1 Introduction

Power scaling in Ytterbium and Thulium fiber lasers

![Graph showing output powers for single Ytterbium and Thulium fiber oscillators over the years.](image)

**Figure 1.1:** Output powers for single Ytterbium and Thulium fiber oscillators over the years

[4–14]

Fiber systems possess many attractive properties; they are superbly efficient, possessing a high electric to optical as well as optical to optical efficiency. Since both the waveguiding and gain is provided by the active doped core, the output beam quality of fiber lasers is usually very good. Single mode fibers in particular excel in this respect, not only in enforcing single transverse mode operation but also possessing some freedom from thermally induced mode distortions that regularly plague solid state systems.

The flexibility, strength, and durability of optical fibers mean that the component fibers in laser and amplifier systems can be coiled to relatively small diameters for compact packaging. In addition, improvements in fiber splicing techniques and fiberised optical components have enabled the production of monolithic, all-fiberised systems, with in-fiber pump and signal beam delivery, increasing its portability and robustness against external perturbations like vibrations, shock or large variations in temperature. Together, these two properties make fiber sources straightforward to manufacture and easy to maintain, and increases its appeal to customers who do not wish to be encumbered with overly fragile and bulky devices, allowing for competitive pricing in the marketplace.

Unlike conventional bulk solid state lasers that usually use crystalline hosts, fiber lasers and amplifiers use glass hosts, which means that they have broad emission linewidths and consequently a larger range of operating wavelengths. This, and the fact that fibers have very high gain, means that fiber sources can be operated over a wide spectral range with high efficiency. The myriad of possible combinations of fiber hosts and dopants, each with their characteristic emission wavelengths and wide bandwidths, further serve
to extend the overall spectral coverage of fiber sources, particularly in the 1 μm to the 2μm wavelength regime (Figure 1.1).

Their large surface-to-active volume ratio gives fibers excellent heat dissipation and their long lengths mean that the thermal load due to heating effects is distributed over a considerably long distance. Additionally, exploitation of a fiber’s spectral characteristics e.g. via the usage of in-band pumping can reduce quantum defect heating and lower the thermal load further. This greatly reduces the demand on cooling mechanisms for applications.

Likewise the small core dimensions and long lengths enable very high gain values to be achieved in pumped active fibers, making them ideal for master-oscillator-power amplifier (MOPA) configurations. MOPA schemes, whereby the output of a low power seed laser is boosted by a high power fiber amplifier, is utilised by most commercial high-power fiber laser systems.

The uses of fiber devices are wide and varied. In general, its applications include welding, ablation, cutting, annealing, sintering, drilling, marking and patterning; fiber sources are versatile, effective, and increasingly important tools in industries ranging from manufacturing to medicine, food and packing to electronics and semiconductor processing.

There is a burgeoning commercial demand for high power and high brightness laser sources. As a matter of fact, the global laser market, currently valued at ∼ $1.5 billion, has experienced a healthy growth of 27% in the previous year - a positive trend that is forecasted to continue well into 2012 [16]. Further power scaling of the output power of fiber devices whilst maintaining excellent beam quality is thus crucial to keep up with the increasing demands of industry as well as to stimulate its expansion into new applications which would solidify its position among other types of lasers.
1.2 Outline of Thesis

In line with current trends in fiber laser research, this project is entitled “Power scaling concepts in fiber lasers and amplifiers”. The term power scaling refers to any systematic and well-defined procedure that can substantially and repeatedly increase the output power of lasers without increasing the severity of problems like excessive peak temperatures, optical damage or nonlinear effects [17].

The main goal of this project is to develop novel strategies for power scaling, specifically in the aspect of beam quality preservation with mode area scaling. The scene was set in this chapter, which began with a brief overview of the history of fiber lasers, charting its meteoric rise in performance, followed by a brief discussion on the favourable aspects of fiber lasers and amplifier that have led to its success and appeal. We mentioned in passing the wide range of applications for fiber lasers and amplifiers, and emphasise that further power scaling is essential for fiber lasers to increase its share in what already is a highly lucrative global laser market.

The experimental work for this project mainly involved ytterbium and thulium doped fibers. A discussion on the spectroscopic properties of these fibers is thus appropriately presented in Chapter 2, which should be useful for providing insight into the behaviour of ytterbium and thulium fibers and how their unique characteristics lend themselves advantageously to power scaling. This is then followed by some basic definitions of key performance benchmarks for fiber lasers which are central to power scaling, such as the slope efficiency, threshold and beam quality.

Before any strategies for power scaling can be developed, a knowledge of the main limitations such as nonlinear processes and optical damage is necessary. These are subsequently defined and expressed mathematically, enabling the rough estimation of these limit values for a given fiber specification if needed. Having identified the issues which hamper power scaling, we then surveyed the literature, highlighting the different routes taken to address them. This includes scaling of the mode area, the use of microstructured photonic crystal fibers, beam combination, and novel pumping architectures.

As will be detailed in the following chapter, mode area scaling is one of the main routes to ameliorating the threat of detrimental nonlinear effects. However, there is a limit to how large the fiber diameter can be before the fiber ceases to be single mode and supports the generation of multiple modes. In Chapter 3 we discuss Multimode Interference (MMI), a phenomena present when a fiber laser or amplifier is operating in such a multi mode regime. Its origins and behaviour are examined mathematically, followed by the results of experimentation with a ytterbium doped fiber amplifier seeded by a wavelength tunable laser, which sheds some light on the impact of MMI on the performance of multimode fibers with changes in operating wavelength.
Having gained an understanding on MMI in a multimode fiber amplifier, we attempted to apply it to a multimode fiber oscillator in order to achieve self-organising mode selection within the fiber cavity. The outcome of this endeavour is elaborated on in the latter half of the chapter.

The work done in Chapter 3 highlighted the need for a robust, simple, and scalable method for fundamental mode operation in fiber oscillators. Pursuant to that, in Chapter 4 we introduce a novel technique for achieving this by exploiting the mode-dependent spectral response of fiber bragg gratings. With the aid of rate equations, analytical and numerical, the potential impact of this mode-selection technique on the slope efficiency is probed. The experimental proof of the principle, carried out in a collaborative work with colleague Jae Daniel using a CW thulium doped fiber laser is subsequently documented. Some consideration is also given to the scalability of this technique with increasing core dimensions.

We sought to extend the mode selection technique of Chapter 4 to pulsed operation, specifically for Q switched operation in a multimode fiber laser. Accordingly, an explanation about Q switching processes was presented with the aid of the “point model” traditionally used to describe solid state Q-switched pulse lasers. We then conducted preparatory characterisation measurements on a thulium fiber identical to the one in Chapter 4 as a reference for comparison with future results obtained when the mode-selection technique is implemented. This preliminary data, which includes information about peak powers, pulse energies, and wavelength spectra, is recorded at length in Chapter 5.

In the course of running these benchmark experiments, we observed multiple-peaked Q switched output pulses, which could not be accounted for using the point model. Considerable effort was thus channeled into simulating the dynamics of Q switched fiber lasers in order to gain a better understanding of the cause and initiation of such multiple-peak pulses. The insight obtained from this modelling sparked the idea for a novel concept for obtaining single-pulse nanosecond operation in thulium lasers via regenerative amplification, and we expounded on the numerically modelled as well as experimental results of this endeavour in Chapter 6.

Overall, in this body of work we have researched various concepts, such as MMI and its effects, and introduced novel methods for mode selection in large mode area fibers and single-pulse generation in Q-switched fibers, under the overarching theme of power scaling in fiber lasers and amplifiers. The main findings and observations from the undertakings of these chapters are summed up in the Conclusions, and we take some time to consider the possibility of building upon the foundational work laid down in Chapters 3, 4 and 6, as well as ponder the future prospects for power scaling of fiber laser and amplifiers.


Chapter 2

Power scaling of thulium and ytterbium doped fiber sources

2.1 Spectroscopic properties of Ytterbium and Thulium

The core components of fiber gain media are rare-earth ions, which provide the optical gain necessary for lasing action. There are two main groups of rare-earths, namely actinides and lanthanides. Many actinides do not have stable isotopes, and will not be discussed here. All the rare earth ions commonly used as dopants in optical gain media (e.g. neodymium, erbium, holmium, thulium) are lanthanides, distinguished by their filling of the 4f shell and for their stable form in the trivalent (3+) level of ionisation.

In this section we examine two rare earth elements which were used in the experimental work for this project, namely ytterbium and thulium, particularly with regard to their respective emission and absorption cross sections, energy levels, and how those properties are relevant to power scaling laser output power.

2.1.1 Ytterbium (Yb$^{3+}$)

Despite the fact that historically, the first fiber lasers were doped with neodymium, and the telecommunications boom in the 1980’s mostly involved erbium doped fibers, it is ytterbium doped fibers which are the frontrunners in terms of setting high output power and pulse energy records. This is also reflected in the marketplace, where the majority of high-power laser products are invariably ytterbium-based. The reasons for this will become clear as we continue our overview of rare earth ion spectroscopy.

The energy level structure for ytterbium is shown in Figure 2.1; compared to most other rare-earth ions, the energy level diagram is very simple - the main manifolds of interest consist of the ground state $^2F_{7/2}$ and the metastable state $^2F_{5/2}$ for which lifetimes
range from 700-1400 $\mu$s depending on the host. The remaining manifolds are located in the UV, with the nearest excited state manifold separated from the metastable $^{2}\text{F}_{5/2}$ state by $\sim 10000 \text{ cm}^{-1}$, which is many times greater than the maximum phonon energy of silica $\sim 1100 \text{ cm}^{-1}$. As a result of this large separation, excited state absorption (ESA) of both the pump and laser wavelengths in ytterbium fibers are inhibited. This simple and widely spaced structure also helps quell concentration quenching via ion-ion transfers as well as non-radiative decay via multiphonon emission from the $^{2}\text{F}_{5/2}$ level. The suppression of these unfavourable processes make for efficient lasing action in ytterbium doped fibers.

Figure 2.1: a) The energy level structure of ytterbium, consisting of two manifolds $^{2}\text{F}_{7/2}$ and $^{2}\text{F}_{5/2}$ with their respective Stark levels b) Absorption and emission cross section of ytterbium doped germanosilicate fiber.

Both figures taken from [1]

Figure 2.1 also shows the ground state absorption and emission spectra of ytterbium in silica. Ytterbium fibers have a wide absorption band, stretching from $\sim 850 \text{ nm}$ to more than 1070 nm. As such, there is much flexibility in choice of pumping sources - ytterbium fiber lasers can be pumped with readily available high power laser diodes which operate at 800-850 nm and 915-980 nm, or in-band pumped with other lasers operating in the 1 $\mu$m regime such as Nd:YAG (1064 nm). The quantum defect (defined as the difference in the photon energies of the pump and laser) in Yb tends to be very small, leading to high efficiencies and reduced thermal loads.

The emission spectra of ytterbium ranges from $\sim 970 \text{ nm}$ to $\sim 1200 \text{ nm}$, which provides a wide wavelength range for laser operation, excellent for use in spectroscopic measurements (as a probe beam) or as a pumping source for tandem pumping or hybrid pumping schemes. Watt-level laser output has been demonstrated for a wide tuning range of 110 nm [2], although a wider ranges have been demonstrated for lower output powers [3]. The behaviour of ytterbium is 3-level at wavelengths below 990 and quasi 4 level at longer wavelengths ($\sim 1000 \text{ nm} - 1200 \text{ nm}$).
The high cross sections in ytterbium fibers allow strong pump absorption and consequently shorter device lengths. Compared to their crystalline counterparts, however, the cross sections are lower; ironically enough, that also works in favor of fibers as it decreases the generation of amplified spontaneous emission (ASE), paving the way for low noise and high-efficiency fiber amplifiers. Reduced ASE is also advantageous for pulsed fiber lasers as it increases the energy storage. For the same reasons, the relatively long lifetime of the metastable level is also conducive for pulsed laser operation. Together, the sum of these properties have made ytterbium fibers the record setter for output power from fiber lasers.

### 2.1.2 Thulium ($\text{Tm}^{3+}$)

The chief attraction of thulium is its emission band, which lies in the 2 $\mu$m regime (figure 2.2). As we shall see in the later part of this chapter, the V parameter of a fiber, which determines the number of modes it supports, is inversely proportional to the wavelength of operation. As such, thulium fiber cores can be scaled to larger sizes (while maintaining single modedness) than the equivalent ytterbium fiber, simply by virtue of this higher operating wavelength. Even when core sizes are scaled to the extent that the fiber becomes multimode, thulium fibers would support the propagation of fewer modes.

![Figure 2.2: The spectrum of thulium’s main emission band, with its corresponding absorption cross-section spectrum.](image)

This wavelength region is also frequently touted as being eye-safe, because these wavelengths are strongly absorbed by the cornea and lens of an eye, resulting in low transmission to the more sensitive retinal area. Thulium doped-lasers are thus useful for defense or military applications due to the lower risk of collateral damage. Likewise commercial applications would benefit from the reduced challenge of ensuring eye safety.
with thulium doped fiber sources. (The caveat, however, is obviously that regardless of wavelength, a very high-intensity beam is still likely to be harmful if it is incident on any part of the human body).

Emission at this wavelength enables very efficient in-band-pumping of holmium lasers. Moreover, this emission band boasts a broad bandwidth, ranging from 1700-~2100 nm [5]. As such thulium offers a wide wavelength tuning range and facilitates non-linear frequency conversion to the mid-infrared.

Figure 2.3 shows the full absorption spectrum for thulium doped silica [6]. Two of its absorption bands are conveniently located within range of readily available power pump sources - the first, which spans from ~1550 to 1750\(\mu\text{m}\), coincides with the emission wavelengths of erbium (Er)-doped fiber lasers. Thus, Er lasers can be used for in-band core pumping, leading to very high efficiencies as well as the ability to access a significant portion of thulium’s emission band (1723-1973 nm [7]). The second, which covers the range of~780-800nm, is readily accessible by commercial high power multimode diode pumps, which greatly simplifies the laser construction process. The theoretical Stokes efficiency for pumping here is estimated to be low value (~0.4). However, this efficiency can be boosted by modifying the dopant level and core composition to exploit the “two-for-one” \[^3H_4 +^3H_6 \rightarrow ^3F_4 +^3F_4\] cross-relaxation process (Figure 2.3). The highest reported slope efficiency for thulium doped lasers pumped at this absorption band is a very respectable 74%, almost on par with the slopes attainable from ytterbium fibers, but in general most commercially-drawn thulium fibers have slope efficiencies in the region of 60%. As far as we know, excited state absorption does not occur for either one of these pumping wavelengths.

The lifetime of the upper laser energy level \(^3F_4\) is sensitive to variations in the host material properties and concentration as well as fabrication methods and conditions. As such, published values can range from anywhere between 200\(\mu\text{s}\) to ~650\(\mu\text{s}\) [5, 4]. The transitions originating from this energy level are quasi-three level at shorter wavelengths (\(\lesssim 1.9\mu\text{m}\)), and approximate to 4 level behaviour at longer ones.

![Figure 2.3: a) The absorption spectrum for Tm-doped silica fibers b) A simplified energy level diagram for Tm-doped silica, showing the cross-relaxation transition. Both figures from [6]](image-url)
At the time of writing, the highest recorded output power from a single cw thulium fiber laser was 885 W [5], while for a MOPA system the record currently stands at 1 kW [8]. These results are compelling testaments to the advantageous properties of thulium doped fibers as well as their further untapped potential for power scaling.

### 2.2 Laser performance metrics

Often, the phrase “power scaling” implies the single-minded pursuit of raw output power alone. That is not strictly true, as there are various other laser performance indicators that need to be considered carefully when evaluating high power fiber lasers. It serves no purpose, for example, to achieve record power levels at the expense of the overall efficiency of the system, or having a massively degraded beam quality, such that the resultant fiber device is virtually useless for applications. In this section we look at the main criteria involved in the evaluation of lasers, fiber or otherwise.

#### 2.2.1 Slope efficiency and threshold

The basic expression governing the relationship between the pump power and the laser output is \( P_{\text{out}} \approx \eta_{\text{slope}}(P_{\text{pump}} - P_{\text{th}}) \). In other words, pump light of power \( P_{\text{pump}} \), having surpassed a threshold value of \( P_{\text{th}} \), is converted with a slope efficiency \( \eta_{\text{slope}} \) into laser signal with output power \( P_{\text{out}} \). The threshold pump power \( P_{\text{th}} \) is defined as the power at which the round trip gain in the cavity is exactly equal to the overall (round trip) losses; the attainment of this threshold value thus signifies the onset of lasing. For a quasi-three level fiber laser of length \( l \) with core area \( A_{\text{core}} \), output coupling of \( T \), a loss \( L \) due to imperfect feedback, and some round trip propagation loss \( 2\alpha Ll \), we can write the following equation for the threshold pump power (the derivation for this can be found in section 4.3.2 of Chapter 4):

\[
P_{\text{th}} = \frac{A_{\text{core}} h \nu_p}{2 \sigma_{\text{es}} \tau_f \eta_{\text{abs}} \eta_q} \cdot ((-\ln(1 - T) - \ln(1 - L)) - 2\alpha Ll - 2\sigma_{\text{as}} N_0 l)
\]

where

- \( \sigma_{\text{as}}, \sigma_{\text{es}} \) = absorption, emission cross section
- \( \tau_f \) = fluorescence lifetime
- \( \eta_{\text{abs}}, \eta_q \) = pump absorption efficiency and pumping quantum efficiency
- \( N_0 \) = ground level population
- \( \nu_p, \nu_s \) = pump and laser signal frequencies
Chapter 2 Power scaling of thulium and ytterbium doped fiber sources

Here we have defined the pumping quantum efficiency as the number of ions excited to the upper laser level for each absorbed pump photon. We note the dependence of the threshold on the core area - this means that for a given parameter set, the threshold value would increase quadratically with core radius. Likewise, the round trip gain would be negatively impacted. Previously this would have been a major consideration for core-area scaling, but in these days with the availability of high-brightness pump sources, increased requirements on pump power have become slightly less of a worry.

A laser is said to be operating many times above threshold when its intensity is much greater than the saturation intensity of the fiber, given by

\[ I_{\text{sat}} = \frac{h\nu_s}{(\sigma_e + \sigma_a)\tau_f} \]

The slope efficiency for a laser operating in such a regime can be written as follows:

\[ \eta_s = \frac{T\sqrt{(1-L)}}{L\sqrt{(1-T)} + T\sqrt{(1-L)}} \frac{\nu_s}{\nu_p} (\eta_{abs}\cdot\eta_q) \quad (2.1) \]

The appeal of using in-band pumping becomes clear as we examine equation 2.1, in which the slope efficiency is directly proportional to the ratio of its lasing frequency to the pump. Unlike the threshold, the slope efficiency shows no strong dependence on the core dimensions, being mostly a function of cavity and spectral parameters. However, should the core size be increased, the threshold would likewise increase, leaving less available pump power to be converted into laser light, even though the conversion efficiency may be high. Cavity design is thus of great importance to ensure a good balance of laser performance.

2.2.2 Beam quality

The quality of a beam is frequently quoted in terms of the \( M^2 \) parameter, also known as the beam propagation factor. The ISO Standard 11146 [9] defines this as the ratio between the beam parameter product with the beam parameter product of a diffraction-limited Gaussian beam, that is,

\[ M^2 = \frac{\theta \pi \omega_0}{\lambda} \]

where

\[ \theta = \text{(far field) beam divergence} \]
\[ \omega_0 = \text{beam radius at waist} \]
Conversely, according to the definition above, one can describe a diffraction-limited beam as one that has an $M^2$ of 1. The output of the fundamental LP(0,1) mode from a fiber has a theoretical $M^2$ value of 1, while higher order modes produce beams with significantly higher $M^2$ values. As such it has become standard practice to use $M^2$ values as a measure of how close the laser is operating to the single-mode regime. In Chapter 3, however, we show that this is not the case as it is possible to obtain low $M^2$ values despite the obvious presence of higher-order mode content in the laser output.

Good beam quality is essential, because it determines the minimum waist diameter that a beam can be focussed down to and consequently its maximum intensity. Not only that, but it also affects the beam’s depth of focus, more commonly referred to as the Rayleigh range. By definition, the Rayleigh range is the distance from the waist to the position at which the beam radius is $\sqrt{2}$ of its value at the waist. Mathematically, this can be evaluated via: $Z_R = \frac{\pi \omega_0^2}{M^2 \lambda}$. In practice, a good beam quality would increase the working distance between the beam and its target, allowing greater tolerance and flexibility. For example, in an industrial scenario this would allow a larger distance between objects being cut/processed and the focussing objective.

While the strong-focussing and long working distances may be useful for some applications, it is not always necessary - industrial applications exist that have relaxed requirements on precision and more emphasis on output power, such as welding or directed-energy schemes. In fact there are many research interests in intentionally exciting higher order modes instead of the fundamental because of the higher mode areas attainable and the unique propagation characteristics of some of these higher order modes. Nonetheless, for the majority of applications including interferometry and microscopy, a good beam quality is crucial, and remains one of the major selling points for commercial fiber lasers.

### 2.2.3 Pulsed Regime

Most of our descriptions so far (barring beam quality) have mainly been relevant to lasers operating in CW. In the pulsed regime, laser performance is often evaluated in terms of the pulse energy, width/duration, and its peak power. The pulse energy of a laser is simply the amount of energy contained within a laser pulse. It is often determined by taking the quotient of the measured average power with the repetition rate of the laser, which is accurate provided that there is negligible energy emitted in-between the pulses. However, in most cases, particularly in fiber lasers which have high enough gains for ASE or spurious lasing to significantly contribute to the measured average power, this condition does not hold. Failure to account for this would result in erroneous and misleading values of pulse energy. In Chapter 5 we used a measurement system which isolates the pulse from any inter-pulse signal, allowing more accurate measurement of its value.
Once the pulse energies have been determined, it is straightforward to determine the peak power. The peak power is often estimated by simply dividing the output pulse energy $E_{\text{out}}$ by the pulse width (defined as the full-width half-maximum time period of the pulse), $t_p$, whereby $P_{\text{peak}} \propto \frac{E_{\text{out}}}{t_p}$. The constant of proportionality differs depending on pulse shapes, with some authors leaving it out altogether. A more accurate value however can be obtained from the evaluation of the integral of the pulse shape and scaling it with the pulse energy.

### 2.3 Challenges of Power Scaling

In this section we examine the various factors that hinder power scaling, such as optical damage due to the high intensities involved, the onset of deleterious nonlinear processes like stimulated Raman scattering and stimulated Brillouin scattering, and the repercussions of overly high thermal loads such as coating damage and thermal guiding.

#### 2.3.1 Nonlinear processes

As the intensity increases, the response of light propagating in dielectric materials becomes increasingly non-linear. This is particularly true of high-power optical fiber media, where the high optical confinement of the beam over a long interaction length is conducive for the generation of a whole host of nonlinear effects. While nonlinear optics is the subject of intense study in many fields and is useful for various applications, some nonlinear processes are a nuisance for the purpose of power scaling, as their possible detrimental effects include reduced output power and disruption of the spectrum and beam quality (and pulse shape, for pulsed lasers). The two more dominant nonlinear effects relevant to this work are Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS).

#### 2.3.1.1 Stimulated Brillouin Scattering

Stimulated Brillouin Scattering is a nonlinear process originating from the interaction of the high-intensity electric field of the propagating light wave with acoustic phonons within the material (electrostriction), resulting in a periodic variation in the refractive index akin to a grating. These periodic variations act as a scattering mechanism, which retroreflects the incident light. As the optical intensity of the signal light increases beyond the threshold level of SBS, the amount of backscattered light increases as well, causing a rollover of the output power. Self-pulsing in CW lasers, which causes drastic temporal instability and increases the risk of damage due to random high-intensity pulses, have also been attributed to SBS \cite{10}.
The threshold power for the onset of SBS is approximated by [11]:

\[ P_{SBS}^{th} \approx 17A_{eff}K \frac{\Delta \nu_P + \Delta \nu_B}{\Delta \nu_B} \]  

(2.2)

Here, \( A_{eff} \) and \( l_{eff} \) are the effective core area and effective fiber length respectively. \( l_{eff} \) is defined for a fiber of length \( l \) with a loss coefficient for the 'pump' signal \( \alpha_P \) as \( \frac{1}{\alpha_P}(1 - exp(-\alpha_P l)) \). \( g_B \) is the Brillouin gain coefficient, which in silica is roughly \( g_B \sim 5 \times 10^{-11} \text{m/W} \) [12]. \( K \) is related to the polarisation state of the pump; \( K=1 \) for polarised light and \( 2 \) for unpolarised [13]. \( \Delta \nu_P \) represents the linewidth of the laser signal which acts as the 'pump' for SBS processes. \( \Delta \nu_B \) on the other hand is the linewidth of the Brillouin gain, which in silica is typically on the order of \( \sim 33 \text{MHz} \) at 1 \( \mu \text{m} \) [14], and \( \sim 10 \text{MHz} \) at 2 \( \mu \text{m} \).

In the limit of \( \Delta \nu_P \gg \Delta \nu_B \), i.e. for narrow-linewidth operation, equation 2.2 simplifies to the more familiar form

\[ P_{SBS}^{th} \approx \frac{17A_{eff}K}{g_B l_{eff}} \]  

(2.3)

Consider the general example of a 5m long ytterbium doped fiber operating at 1064 nm, with a core diameter of 6 \( \mu \text{m} \) and a corresponding mode field diameter of 7.5 \( \mu \text{m} \). Broadly speaking if the linewidth is 0.1 nm, the SBS threshold is \( \sim 4.8 \text{kW} \), but if the linewidth is halved to 0.05 nm, the SBS threshold decreases to \( \sim 2.4 \text{kW} \). The threat of SBS is thus more severe in sources that operate with narrow linewidths such as single frequency sources.

This expression is valid for CW and for pulsed operation if the pulse width \( t_p \) is greater than the phonon lifetime \( T_B \), which is typically \(<10 \text{ns}\).

### 2.3.1.2 Stimulated Raman Scattering

The origins of SRS are analogous to SBS, but arises from interactions with optical instead of acoustic phonons. These optical phonons scatter the incident 'pump' radiation (the laser signal) into a lower energy Stokes wave, with the energy difference lost as heat [15]. A portion of this wave is guided along the core in both the forward and backward direction, and in the case of long fibers, can accumulate substantial gain and amplification through stimulated emission.
The equations for the threshold is similar in form to that of SBS, that is [11]:

\[
P_{\text{th}}^{\text{SRS}} = \frac{16A_{\text{eff}} K}{g_{R}l_{\text{eff}}} \tag{2.4}
\]

where the Raman gain coefficient \( g_{R} \) has a maximum value of \( \sim 1.5 \times 10^{-13} \text{m/W} \) in silica [16]. Strictly speaking, the above equation was derived for narrow-linewidth operation, but as the Raman linewidth is very broad the equations are still reasonable approximations for broad-linewidth lasers.

If the first Stokes wave reaches a sufficiently high intensity, it could in turn serve as a ‘pump’ for further orders of Raman waves, further depleting the gain and clamping the main lasing signal further. We can imagine the impact of this in an amplifier scenario, where increasing SRS could couple power away from the signal into shifted wavelengths where laser amplification cannot occur. Furthermore, with the generation of each Stokes wave, more heat is dissipated within the core, increasing the thermal load on the fiber.

Considering again the hypothetical 5 m long ytterbium fiber mentioned above, we can see that the SRS threshold would be \( \sim 2 \text{kW} \). As such, if this fiber is operated in a relatively broadband regime \( \Delta \lambda > 0.1 \text{nm} \), SRS processes would be a bigger concern than SBS.

The equations are valid for CW operation as well as for pulses of widths \( > 1 \text{ ns} \) [17]. For pulses shorter than 1 ns, the effective length \( l_{\text{eff}} \) becomes

\[
l_{\text{eff}} = \sqrt{\pi} L_{W}
\]

where

\[
L_{W} = \text{Walk off length} = \frac{\tau_{\text{pulse}}}{|\nu_{\text{pump}} - \nu_{\text{Raman}}^{-1}|}
\]

Where \( \nu_{\text{pump}} \) and \( \nu_{\text{Raman}} \) are the velocities of the pump and Raman pulses in the fiber as determined by their respective dispersion relations.

### 2.3.2 Optical damage

Another constraint for power scaling is bulk or surface damage caused by electron avalanches driven by the laser beam electric field. These electrons transfer energy to the glass matrix, causing fracturing or melting, particularly towards the silica/air interface at the fiber end facets. Traditionally, the safe operating fluence limit in fused silica for a 1064 nm wavelength pulse was governed by:

\[
J_{\text{th}} = 22t_{p}^{0.5} J/\text{cm}^{2} \tag{2.5}
\]
However, later publications e.g. [18] assert that for pulses 50 ps or longer, bulk damage occurs at a fixed power level rather than a fixed fluence. This irradiance damage threshold is said to be

\[
4.75 \pm 0.25 \text{kW/\(\mu m^2\)}
\] (2.6)

In theory, the thresholds for surface damage can be equal to the bulk thresholds, but in practice, due to differences in surface preparation techniques as well as surface quality, dust, surface defects, or scratches, surface damage thresholds can be a factor of 2 to 5 times lower than the bulk one. Surface damage issues can be alleviated by various methods such as expanding the output beam and consequently decrease the fluence at the air/silica interface (either by the use of fiber end caps or by using a larger diameter core), or by ensuring good quality end-facet preparation.

The fact is that the exact values for surface value have not yet been explicitly determined. However, the high power amplifier used by Gapontsev et al [19], which had a MFD of 14 \(\mu m\), withstood output powers of up to 2 kW and consequently fluences of about 10 W/\(\mu m^2\), thus this value can be used as a reasonable operating limit provided all the other factors (end facet preparation, etc) have been taken into account [11].

2.3.3 Thermal effects

2.3.3.1 Coating damage

There are many physical mechanisms which contribute to heat generation within an optical fiber, such as quantum defect heating, absorption by impurities, excited state absorption and energy upconversion. Moreover, the increasing pump powers available from commercial diode sources mean increasing thermal loads imposed on a fiber. While, as mentioned in the Introduction, optical fibers generally possess excellent properties for thermal management, this is spoilt slightly by the low-index polymer commonly used as the protective outer jacket for the fiber. These fluorinated acrylate polymer coatings, chosen for their good optical properties and ease of application during the fiber drawing process, suffer from very poor thermal conductivities of \(k_\text{2} = 0.24 W K^{-1} m^{-1}\) [20] and begin to degrade at temperatures approaching \(T_d \sim 150 - 200^\circ C\) [6].

We can estimate the heat deposition per unit length required to cause damage to the outer polymer coating from [21]
Chapter 2 Power scaling of thulium and ytterbium doped fiber sources

\[ P_{h,max} = 4\pi(T_d - T_s) \left[ \frac{2}{k_2} \ln \left( \frac{r_{poly}}{r_{clad}} \right) + \frac{2}{r_{poly} H_2} \right]^{-1} \]  

(2.7)

where

\[ T_s = \text{ambient temperature} \]
\[ r_{clad}, r_{poly} = \text{inner cladding and polymer coating radius} \]
\[ H_2 = \text{heat transfer coefficient for polymer coating} \]

Applying this to a hypothetical situation with a fiber with a 400 \( \mu m \) cladding diameter and a 50 \( \mu m \) thick polymer layer, we can see that if a coating experiencing thermal load \( T_d = 200^\circ C \) is convection cooled \( (H_2 \sim 10 W K^{-1} m^{-2}) \) at room temperature \( T_s = 20^\circ C \), the maximum heat deposition per unit length the coating can withstand is \( \sim 46.9 W \).

From equation 2.7 we can see that increasing the fiber dimensions while reducing the thickness of the applied coating would have a positive effect on the longevity of the outer polymer coating. Increasing the fiber dimensions would also be helpful in terms of increasing the area over which the heat is distributed. However, in the long run the use of other coating materials or active cooling (which would increase the value of \( H_2 \)) would be more sensible.

2.3.3.2 Thermal guiding

Another adverse effect arising from a large thermal load is the problem of thermal guiding, which takes place when the thermal gradient within the core changes the refractive index profile of the fiber material. Eventually, the thermal guiding competes with the original refractive index waveguiding, resulting in stronger mode confinement. A stronger mode confinement, which results in a smaller mode area, would subsequently reduce the threshold values for nonlinear processes and damage as well as support the propagation of higher order modes which would degrade the beam quality.

The power limit for silica fibers imposed by this limitation is given by [11]:

\[ P_{lens\text{\ out}} = \frac{\eta_{laser}}{\eta_{heat}} \left( \frac{\pi k_{tc} \lambda^2}{2 \frac{dn}{dt} a^2} t \right) \cdot L \]

where

\[ \eta_{laser} = \text{optical – optical conversion} \]
\[ \eta_{heat} = \text{fraction of pump power turned to heat} \]
\[ k_{tc} = \text{thermal conductivity} \]
\[ \frac{dn}{dt} = \text{thermo – optic coefficient} \]
This researcher conjectured that if the fiber mode area could be increased arbitrarily, in a hypothetical situation with no limits on available pump brightness, the maximum obtainable output power for a laser would be 36.6 kW, limited by this thermal guidance phenomenon as well as the onset of SRS. However, we note that this requirement is for power scaling of single-mode fibers, with no clear mode selection technique in place. Hypothetically, then, this restriction can be lifted if a suitable method for enforcing single mode operation in a multimode fiber can be found.

2.4 Review of the prior art

Having identified these limiting factors to power scaling, the following section reviews the more prominent approaches to overcoming them that have enabled the power scaling of fiber lasers to its current level.

2.4.1 Large core and large mode area (LMA) fibers

One of the impediments to successful power-scaling of lasers has been the onset of non-linear effects, particularly SRS and SBS. These effects are generated mainly due to the tight confinement of the fundamental mode laser radiation in the fiber core. Increasing the fiber core diameter would increase the mode-field diameter (MFD) and consequently the mode area. Since the threshold power for nonlinear processes scales with the mode area (equations 2.3 and 2.4), using a large core diameter is an effective way to avoid these nonlinear processes. In a double clad fiber, for a given inner cladding size, any increase in core diameter would cause a corresponding increase in the overlap between the cladding and core area, leading to enhanced pump absorption. As such the fiber length required for optimal absorption is reduced. The threshold for nonlinear effects (as mentioned above) is also proportional to the fiber length, so a reduced fiber length would act as a further inhibitor.

There are also other motivations for scaling the core of a fiber; one would be to reduce the peak intensity of the beam within the core, thereby reducing the intensity-induced damage to the facet. More trivial advantages of a larger core would include improving the coupling efficiency for core-pumping schemes, and raising the threshold for detrimental ASE processes which could limit the energy storage of the fiber for pulsed operation.

However, a large core diameter would encourage the propagation of numerous higher-order transverse modes. As shall be discussed in Chapter 3, multi-mode operation could have adverse effects on the beam quality and the temporal/spatial stability of the system and is therefore a less than ideal operating regime.

The requirement for a large core fiber (with a step index profile) to remain single-moded is for its normalised frequency $V$ to be less than 2.4, where $V = d_{\text{core}} \cdot N.A \cdot (\frac{\xi}{\lambda})$, $d_{\text{core}}$ is
the core diameter, $\lambda$ is the wavelength and $NA$, the numerical aperture of the core, is $\sqrt{(n_{\text{core}}^2 - n_{\text{cladding}}^2)}$. To ensure single mode operation in a situation where $d_{\text{core}}$ is large, the numerical aperture and hence the refractive index difference between the core and the cladding must be reduced. This adds another limitation to power scaling as a small refractive index difference would lead to weak guiding in the core, eventually rendering the fiber mode too sensitive to bending loss to be of any practical use. Also, there are limits to how low the refractive index difference can be made. At present the minimum practical value of the NA is in the region of $\sim 0.05$. For an Ytterbium fiber operating at 1064 nm, this would mean a maximum beam diameter of only 16 $\mu$m, beyond which the fiber would support the propagation and generation of higher order modes which would degrade the beam quality. Despite that, a number of groups have demonstrated nearly diffraction limited and stable output from fibers with core diameters of up to 30$\mu$m [22, 23].

These stringent restrictions on $V$ (and NA) can be side-stepped altogether by using a multimode fiber (i.e. a fiber for which $V > 2.4$ and thus supports many higher order modes) whilst enforcing single-mode operation. This is usually achieved either selectively exciting the desired fundamental mode or attenuating the higher order modes. A popular technique in the latter category is to use bend loss in a coiled fiber as a form of mode filtering. This technique is based on the fact that while the bend loss attenuation coefficient for all modes changes exponentially with the radius of curvature [24], the fundamental mode is (relatively speaking) the least sensitive to bend loss. Therefore by choosing a suitable coiling diameter for the fiber, a higher loss is seen by the higher-order modes and thus, the propagation of higher order modes is suppressed. Researchers have successfully used this technique to achieve robust, high-power single mode operation, using fibers with cores up to 40$\mu$m in diameter [25–27]. However, as dimensions increase, bending the fiber may introduce severe distortions to the mode[28].

Other more novel concepts for higher order mode filtering include the use of specialised fiber designs, such as helical-core fibers which incorporate 'bend' loss into the fiber[29], as well as chirally-coupled-core (CCC) fibers (figure 2.4), in which the higher order modes are coupled into lossy helix side-modes [30, 31]. The latter technique has seen encouraging success, achieving up to 250 W cw output power from a 35$\mu$m core CCC fiber laser [32].
Much work has also been done with using tailored refractive index profiles for gain-guiding [33–35]. The gain seen by a mode in a multimode fiber depends greatly upon its mode field spatial overlap with the distribution of the active ions/dopants within the core. Thus, the refractive index profile can be shaped by optimising the doping levels and spatial distribution in order to give preferential gain to a selected mode, usually the fundamental. One group reported 2.1 kW from a Yb fiber laser with a core diameter of 50 µm and a good beam quality $M_2^2 < 1.2$ with no deliberate form of mode filtering other than ensuring “..that there was no central dip in the refractive-index profile (RIP) of the core” (Y. Jeong et al, 2009) [36].

### 2.4.2 Photonic Crystal Fibers (PCF)

Photonic crystal fibers (or holey/microstructured fibers) are fibers which have a built-in microstructure of periodic arrays of air holes through the length of the fiber. These air holes, depending on their size and position, give rise to different guiding properties in the fibers, such as strictly single mode propagation over a large wavelength range (‘endlessly single mode’ [37]) and the ability to create a ‘double clad’ structure within the fiber.

PCFs take an alternative route towards large mode-area core fibers. The air holes in a PCF act as a modal filter or sieve, thus the number of guided modes in the fiber is determined purely by the fiber geometry. Theoretically, by carefully choosing suitable air hole dimensions and arrangement one can ensure single-mode guidance regardless of the size of the core. (In practice the size of the core is still limited by increasing propagation losses due to weak confinement). Intrinsically single-mode ytterbium-doped cores with diameters up to 40µm have been demonstrated [38].
Additionally, PCFs can be given a double clad structure by surrounding the inner (microstructured) cladding with a web of silica bridges which are narrower than the wavelength of the guided radiation. This results in a large index difference between the inner and outer claddings of the fiber, and therefore a high numerical aperture (NA). NAs of up to 0.7 have been achieved thus far [39], limited only by practical handling and cleavability of the PCFs. The high NA is advantageous because, firstly, it allows the diameter of the inner cladding to be reduced, which increases the ratio of the active core area to the inner cladding area, leading to a higher pump absorption coefficient for pump light launched into the cladding for a given core size. The downside of this is that the pump beam needs to be more tightly focused, thus increasing the demands on the required pump coupling optics.

It is also possible, via more complex PCF designs, to structure the fiber such that it only supports the propagation of one polarization state. Single-polarization PCFs of up to 70\(\mu\text{m}\) diameters have been reported which were capable of generating more than 350 W of cw output [39].

![Figure 2.5: An example of a single polarization, double-clad PCF](image)

Figure 2.5: An example of a single polarization, double-clad PCF
Figure from [39]

This field of PCFs is a promising one, with one group reporting an impressive 1.53 kW emission with nearly diffraction-limited beam quality from a Yb-doped photonic crystal fiber [40]. The group speculates that powers up to 3-4 kW will be achievable in the near future.

### 2.4.3 Beam combination of multiple fiber lasers

Another route to high power from laser systems would be to combine arrays of lasers. Fibers are inherently well suited for use in beam-combined systems due to their high efficiencies, the ease at which they can be built into array formats and the ability to get good beam quality from individual fibers. Because many fibers contribute to the overall output power, each constituent fiber laser can be operated at lower powers, reducing the radiation intensity within each fiber and thus avoiding nonlinear issues. Likewise,
the thermal load of the system is spread over all the fiber elements, leading to better thermal management.

There are three general classes of beam combining techniques:

**Spatial beam combining** In this scheme, the array elements need not necessarily operate at the same wavelength, and the relative phase and spectra of the elements are left uncontrolled. The collective output is either focussed to a common point or integrated with the use of a fiber or free space combiner. An example of this would be conventional diode-laser arrays which consist of linear bars or two-dimensional arrays. The radiance of these types of sources cannot exceed the radiance of a single array element, and even in the best case scenario, high output power is achieved at the expense of beam quality. However, this would still be sufficient for many materials processing elements or short-range applications (such as short-range directed energy schemes [41]) in which good beam quality is not crucial.

**Coherent beam combining (CBC)** All the elements are made to operate at the same wavelength, and the relative phases are actively controlled to ensure constructive interference. CBC has been successfully demonstrated for small arrays of fiber amplifiers that were phase-controlled with active feedback techniques [42], with impressive powers of up to 470 W achieved for a 4-element array [43]. However, scaling to larger arrays of tens to hundreds of elements initially proved difficult due to the enormity of the task of finding a robust and simple method of controlling the phases of large arrays. In 2007 Shay et al successfully combined a 9-element fiber amplifier array with a total power of 100 W using a self-referencing and self-synchronous technique. [44]. They have projected the possibility of combining up to 100 elements with this technique. Using the same technique (referred to in their report as LOCSET), Flores et al subsequently achieved 1.4 kW power from CBC of 16 silica fiber lasers [45].

**Wavelength beam combining (WBC)** This method plays to one of the key strengths of fiber lasers, which is their wide operating wavelength range. In WBC, the array elements, which operate at different wavelengths, are overlapped in the near and far fields with a dispersive optical system e.g. gratings, prisms, and dichroic mirrors. Certain implementations of WBC have involved using gratings in external cavities such that the external cavity both determines the wavelength of each element and combines them spatially, such as [46]. One group very successfully combined three ytterbium fiber MOPA systems to achieve 522 W of combined output power with an excellent $M^2 < 1.2$, using a grating as a beam combiner but not as the wavelength selective element (wavelength selection occurred separately within each individual MOPA) [47]. More recently, a combined output of 2 kW was achieved from the beam combination of 4 PCF amplifier chains, but the beam
quality for this result is slightly poorer with $M^2$ of 2 and 1.8 in the x and y axis respectively [48]. Compared to tiled implementations of CBC, WBC is relatively easier to implement, but at the expense of an increased bandwidth.

Despite the significant complexity, cost, and instability associated with beam combination, beam combination remains an exciting route to power scaling, particularly as we approach the limits of obtainable power from single fibers.

### 2.4.4 Pump-coupling strategies

The main catalysts for the rebirth of fiber lasers in the 1990s were the introduction of cladding pumping and the ever-increasing brightness of available pump sources at the time. To this day improvements in pump sources continue to manifest as a rise in output power levels. Many of the high power results mentioned above claim to be limited only by pump power. It is thus a foregone conclusion that pumping architectures play an important role in the scaling of fiber lasers.

There have been many advances made over the years to improve the output delivery of pump sources, such as the use of tapered fiber bundles, air-clad pump combiners, various beam shaping techniques, not to mention actual augmentations in diode designs themselves, all of which have contributed to the meteoric rise in available pump power. But all this is will be of no avail if the corresponding technology to couple this pump power effectively into a fiber is poor.

Cladding pumped fibers, more commonly known as double-clad fibers, are typically composed of a doped signal waveguide (the fiber core) embedded within a lower refractive index secondary waveguide (the inner cladding, typically made of glass) which in turn is encased by a low index polymer jacket to provide waveguiding properties as well as lend strength to the fiber. Pump light is launched into this inner cladding, and as it propagates down the fiber it is absorbed by the core in proportion to the area ratio of the core and inner cladding.

![Figure 2.6: A typical D-shaped double-clad fiber](Image)

Figure courtesy of Jae Daniel
Cladding pumping has previously proved to be an invaluable architecture because it had enabled efficient coupling of pump light from low-brightness diode bars/stacks into the multimode, large inner cladding instead of into the smaller fiber core. However, it has its drawbacks - isolating the pump light from the signal light requires wavelength multiplexers or free space dichroic mirrors, which add to the laser’s cost and alignment. Also, in order to accommodate the highly divergent pump light, the cladding is typically an order of magnitude or more larger than the core dimensions, thus a long length of fiber is needed for efficient pump absorption. So, as the research into fiber lasers continue to push the boundaries of pump and output power, fiber laser manufacturers and scientists alike are in search of even more efficient pump coupling schemes.

As a result of this, many variations to cladding pumping architectures have emerged, two of which have been adopted by major players in the fiber laser manufacturing industry. The first of these is tandem pumping, which is the technology utilised by IPG Photonics’s now iconic 10 kW single mode ytterbium laser [49]. In tandem-pumping schemes, fiber lasers are pumped by other fiber lasers. This can be advantageous as one can pump in-band, close to the desired emission wavelength, reducing the quantum defect heating and thus the thermal load. Also the high brightness available from fiber lasers allows for the reduction of the inner cladding dimensions which increases pump absorption and reduces device lengths.

The second is SPI Lasers’ proprietary GT-wave technology [50][51]. A GT-wave fiber comprises a signal fiber placed in contact with two separate pumping fibers, all of which are bundled within a common low index cladding. This setup “enables multi-port, distributed pump injection, facilitates output power scalability and ensures system reliability, longevity and maintenance-free operation” (Horley et al 2007), and forms the basis of many of SPI’s laser products, notably their 1 kW redPOWER r4 laser [51].

One of the earliest fiber laser architectures to break the kilowatt barrier did not involve end pumping at all. Researchers coiled a multimode fiber tightly such that it resembled a thin disk, then side-pumped it. Three such discs were spliced to each other, giving a combined total output power of 1 kW [52].
Another novel concept for improving pump coupling, which has met modest success is the use of multi-core ribbon fibers\cite{53}, which exploits the elongated output beams from broad-area diodes and diode bars.

\section{Conclusion}

In this chapter we discussed the various factors that affect power scaling in fiber lasers and amplifiers. We probed the spectroscopic properties of ytterbium and thulium with the aid of emission and absorption spectra and energy level diagrams. Both ytterbium and thulium feature absorption bands which can easily be accessed by pre-existing, commercially available and increasingly bright pump sources, along with broad emission spectra, which facilitates wavelength tuning over more than 100 nm. Ytterbium, with its high cross sections, high efficiencies and inhibited excited state absorption properties, currently outshines other rare earth dopants in terms of high power laser operation. Thulium, however, by virtue of its emission in the $2\mu m$, is not without its own benefits - its emission falls within the “eye-safe” wavelength region giving it a niche in eye-safe applications. Thulium lasers can also be used for in-band pumping of Holmium lasers. More importantly, however, the dependence of a fiber’s $V$ parameter on operating wavelength mean that thulium lasers would support single-mode propagation for larger core dimensions than possible in ytterbium.

The output power of a laser is often coupled with other crucial criteria that define the laser’s performance as whole. In section 2.2, we reviewed the definitions and expressions for the primary performance metrics for CW and pulsed lasers, i.e. the slope efficiency, threshold, beam quality, pulse energy and peak power. The importance of these and their relevance to power scaling was discussed.

The limitations to power scaling, such as nonlinear effects, optical damage, and thermally-induced degradation of the polymer coatings, were briefly examined. We found that the threshold equations for SBS and SRS were proportional to the core area and inversely proportional to the fiber length. Likewise, the safe limit for operating fluence before the occurrence of damage can be extended by increasing the mode area of the beam.

Armed with some insight on these obstacles to power scaling, we carried out a literature survey of the various techniques employed in order to address these issues. Broadly, these involve either some form of enlargement of the core or mode area, or microstructured fibers, beam combination, pump-coupling schemes, or novel architectures for fiber designs. Each have their own merits, and it is our opinion that the future of high power lasers would involve combining one or more, if not all of them. This body of work, however, focuses mainly on the first, that is, mode area scaling.
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Chapter 3

Multimode Interference in Large Mode Area Fibers

3.1 Introduction

Multimode Interference (MMI) in a fiber or a waveguide is a well established phenomena - it arises because the velocity (or propagation constant) of each mode excited in a multimode waveguide is different for each mode. Thus, at each point along the waveguide the phase relationships of the modes differ, giving rise to certain effects and properties that can be harnessed and used in various devices. One such useful property of MMI is self-imaging. Self imaging describes the reproduction of the input field of the waveguide at periodic intervals along the guide’s longitudinal direction, either in single or multiple images.

In general, MMI effects have been applied in many optical devices and integrated optics such as Mach-Zehnder switches [1], modulators [2], 2X2 waveguide couplers [3], filters [4], and sensors [5]. While it is true that MMI may have some favourable properties, some of its effects may not be as beneficial, such as the induced coupling of power into the lossy higher order modes in short devices/waveguides or a deterioration of the output beam profile.

So far, little work has been done into studying the effects of MMI in actively pumped large mode area fibers used in high power lasers and amplifiers, especially in the 1µm wavelength regime. Given the number of published achievements in power scaling that have come as a result of such large mode area fibers it is essential that the effects of MMI in such fibers are studied in closer detail, in particular for issues such as power and beam quality. This work is thus directed, with the particular aim of using the self imaging effect to optimise the beam quality of the output beam of a multimode fiber.
3.2 Background Theory

3.2.1 Guided mode propagation analysis for a 2 dimensional waveguide

The following mathematical treatment is from the work by Soldano and Pennings, 1995 [6].

Consider a multimode fiber of length $l$ with an effective core width $W_e$ and core refractive index of $n_{core}$ operating at wavelength $\lambda$, which can support a certain number of modes $m$ with node numbers $\nu = 0, 1, \ldots (m - 1)$. By reducing the scope of the problem to fiber a step-index profile and considering the propagation of modes only along two dimensions, $y$, and $z$, along the fiber, as per Figure 3.1, we can use the planar waveguide approach expounded by [6].

\[ \Psi(y,0) = \sum_{\nu} c_{\nu} \psi_{\nu}(y,0) \]

where

\[ c_{\nu} = \text{Field excitation coefficient} \]
Assuming the “spatial spectrum” of this input field is sufficiently narrow that no un-guided modes are excited (which is usually the case) this sum is reduced to the guided modes alone

\[ \Psi(y, 0) = \sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y, 0) \]

The profile of the field at some distance \( z \) can thus be expressed as the superposition of the guided mode field distributions

\[ \Psi(y, z) = \sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y) \exp \left[ j(\beta_0 - \beta_\nu)z \right] \]  

where

\( \beta_0 \) = Propagation constant of fundamental mode

\( \beta_\nu \) = Propagation constant of mode number \( \nu \)

It can be shown [6] that the propagation constants spacing can be written as

\[ (\beta_0 - \beta_\nu) \simeq \frac{\nu(\nu + 2)\pi}{3l_\pi} \]  

where

\( l_\pi \) is defined as the beat length of the two lowest order modes

\[ l_\pi = \frac{\pi}{(\beta_0 - \beta_1)} \simeq \frac{4n_{core}W_e^2}{3\lambda} \]  

Substituting 3.2 into 3.1, for a field at a distance \( z = l \) we get

\[ \Psi(y, l) = \sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y) \exp \left[ j\left(\frac{\nu(\nu + 2)\pi}{3l_\pi}\right)l \right] \]
As a consequence of the structural symmetry of the fiber with respect to the plane \( y = 0 \), the following properties are true:

\[
\nu(\nu + 2) = \begin{cases} 
\text{Even for } \nu \text{ even} \\
\text{Odd for } \nu \text{ odd}
\end{cases}
\]

\[
\psi_{\nu}(-y) = \begin{cases} 
\psi_{\nu}(y) \text{ for } \nu \text{ even} \\
-\psi_{\nu}(y) \text{ for } \nu \text{ odd}
\end{cases}
\] (3.5)

Returning to equation 3.4, it can be seen that the profile of the resultant field at \( l \) will be dependent on the modal excitation \( c_{\nu} \) and the properties of the mode phase factor \( \exp \left[ j \left( \frac{\nu(\nu + 2)\pi}{3l_{\pi}} \right) l \right] \). Upon closer examination of equation 3.4, we can see that, under certain circumstances, the field \( \Psi(y, l) \) will be an image/self-image of \( \Psi(y, 0) \), the input field. The condition for \( \Psi(y, l) \) to be an image of \( \Psi(y, 0) \) is

\[
\exp \left[ j \left( \frac{\nu(\nu + 2)\pi}{3l_{\pi}} \right) l \right] = 1 \text{ or } (-1)^\nu
\] (3.6)

We can understand the first condition to mean that the change in phase of all the modes along \( l \) must be integer multiples of \( 2\pi \), in which case the guided modes would interfere with the same relative phases as in \( z = 0 \). The second condition, (which is only relevant if the input beam is not launched in the center of the fiber), means that the phase changes must be alternatively even and odd multiples of \( \pi \) (i.e. the even modes will be in phase and the odd modes in antiphase). Because of the odd symmetry of 3.5, the first condition will produce a direct replica of the input field, whereas the second would produce a mirrored image with respect to the \( y = 0 \) plane.

These two conditions as stated in 3.6 will be satisfied when the fiber length \( l \) is equal to a reimagining length \( \Lambda \) expressed as follows:

\[
l = m\Lambda = m(3l_{\pi})
\] (3.7)

with

\[
m = 0, 1, 2, ...
\] (3.8)

Thus, for fiber lengths \( l \) that are even and odd multiples of \( \Lambda \), direct and mirrored single images (respectively) of the input field will be formed.
Recalling the definition of $l_\pi$ (equation 3.3) it is sometimes more convenient to express the reimaging length 3.7 in the following form:

$$\Lambda = \left( \frac{4W^2_{e n_{\text{core}}}}{\lambda} \right)$$

(3.9)

### 3.2.2 Guided mode propagation analysis for a fiber

The following mathematical derivation is based on the work by W. S Mohammed, 2007 [7].

The derivation for the reimaging length for a circular waveguide such as a fiber is similar to the waveguide version, and with the same result. As above, we start by evaluating the propagation constant spacing for two modes, which are given by the asymptotic formulation provided in [8]:

$$(\beta_{\nu_1} - \beta_{\nu_2}) = \frac{u_{\nu_2}^2 - u_{\nu_1}^2}{4k_0n_{\text{core}}W^2_{e}}$$

where $u_{\nu_1}$ and $u_{\nu_2}$ are the roots of the zeroth-order Bessel function which can be written as [8]:

$$u_{\nu} = (2\nu - \frac{1}{2})\frac{\pi}{2}$$

Thus the mode spacing between a mode $\nu$ and the dominant radial mode $\nu_p$ is written as:

$$(\beta_{\nu} - \beta_{\nu_p}) = \frac{\pi\lambda_0}{2n_{\text{core}}W^2_{e}} \left[ 2(\nu^2 - \nu_p^2) + (\nu_p - \nu) \right]$$

where if $\nu_p$ is even

$$[2(\nu^2 - \nu_p^2) + (\nu_p - \nu)] = \begin{cases} 
\text{Even for } \nu \text{ even}, & \text{Odd for } \nu \text{ odd} \\
\text{Even for } \nu \text{ odd}, & \text{Odd for } \nu \text{ even}
\end{cases}$$

If $\nu_p$ is odd

As per equation 3.6,

$$\exp \left[ j\left( \frac{\pi\lambda_0}{2n_{\text{core}}W^2_{e}} \left[ 2(\nu^2 - \nu_p^2) + (\nu_p - \nu) \right] \right)l \right] = 1 \text{ or } (-1)^\nu$$

(3.10)
This will be satisfied when the fiber length $l$ is equal to a reimaging length $\Lambda$ expressed as follows:

$$ l = m\Lambda = m\left(\frac{4W_e^2n_{\text{core}}}{\lambda_0}\right) $$

with

$$ m = 0, 1, 2, ... $$

$$ \Lambda = \left(\frac{4W_e^2n_{\text{core}}}{\lambda_0}\right) $$

Which is identical to the expression for a 2-dimensional waveguide.

### 3.2.3 Discussion

Using the fiber parameters of $n_{\text{core}} \simeq 1.4614$, $\lambda \simeq 1053\text{nm}$, and $W_e = 28\mu\text{m}$ gives an estimated $\Lambda$ value of 4.35mm.

In a situation where the length is fixed and the wavelength is changing, it would be clearer to rearrange 3.9 such that

$$ \lambda_0 = \frac{m}{l}(4n_{\text{core}}W_e^2) $$

(3.11)

If we make the approximation that the refractive index and the effective widths are roughly constant with wavelength, then the spacing between two consecutive wavelengths $\lambda_0, \lambda_1$ that exhibit reimaging can be estimated by

$$ \Delta \lambda = \frac{(4n_{\text{core}}W_e^2)}{l}((m + 1) - (m)) $$

(3.12)

Substituting the fiber parameters above into 3.12 for a fiber length $l = 7m$ gives a wavelength spacing of $\Delta\lambda = 0.65\text{nm}$.

The consequence of this is that MMI effects and self imaging in a fiber of such specifications is only observable if the spectral bandwidth of the laser emission is <0.65 nm. For $\Delta\lambda \gg 0.65$ the effects of multimode interference and self imaging will be obscured due to the averaging effect of having varying relative modal phases across the wavelength spectrum.

Having perused the theory, consider a Gaussian beam launched into a fiber. It excites the various modes and propagates down the fiber, accumulating different phase shifts.
As the diagram in figure 3.2 illustrates, a beam launched symmetrically into a fiber would be reproduced at every imaging length. In more extreme conditions where the input beam is launched asymmetrically with respect to the fiber’s longitudinal axis, the position and direction of the field profile would switch between an inverted image or a non-inverted image of the input beam every imaging length. So, even though the general profile of the beam is retrieved, it may undergo a change in position and pointing direction. In short, the output beam direction, quality, and transverse profile depends on the phase relationship of the modes at the output, particularly with an asymmetric launch.

**Figure 3.2:** Three possible input configurations and their images at $1\Lambda$ and $2\Lambda$

Hypothetically, one could launch a single mode beam into a fiber, and if the initial phase relationship is perfectly retrieved at the output, the resultant output beam will be an image of that single mode beam [9]. In practice, of course, perfect imaging is not always possible, but the output would still possess excellent beam quality characteristics. However, unlike the case where a fiber is only operating in a single mode, this state is sensitive to changes in refractive index, which we illustrate experimentally in section 3.3.

### 3.2.4 Physical interpretation

To give a more qualitative and simplistic analysis for what is actually taking place in the fiber, consider a fiber amplifier being seeded with a diffraction limited source with a Gaussian electric field profile. This electric field profile will (as explained above) be decomposed into the modal field distributions of the modes in the fiber. Because this is
purely an exercise to show graphically what is taking place at the fiber end facet when
the beam exits the fiber, this discussion will be limited to a 2-mode scenario whereby
only two modes, namely the fundamental mode $LP_{01}$ and the $LP_{11}$ mode is excited
within the fiber.

The profile of the beam exiting the fiber will be a superposition of the 2 modes and its
amplitude at each point of the profile can be determined by the following relation [10]

$$ I = I_{01} + I_{11} + 2\sqrt{I_{01}I_{11}\cos(\alpha_{11} - \alpha_{01})} $$  \hspace{1cm} (3.13)

where

$I, I_{01}, I_{11}$ = Intensity of the
resultant, fundamental mode and
doughnut mode

$\alpha_{01}, \alpha_{11}$ = Phase of the fundamental mode and
the $LP_{11}$ mode

$(\alpha_{11} - \alpha_{01})$ = Phase difference

Likewise the resultant phase at each point on the exiting beam profile can be determined
by [10]:

$$ \tan(\alpha) = \frac{E_{01}\sin(\alpha_{01}) + E_{11}\sin(\alpha_{11})}{E_{01}\cos(\alpha_{01}) + E_{11}\cos(\alpha_{11})} $$

Where

$\alpha$ = resultant phase

$E_{01}, E_{11}$ = electric field amplitudes

Figure illustrates the concept outlined in the above paragraph. Figure (3.3a) shows
the radial distribution of two intensity profiles - a Gaussian profile, and the profile of
a ringed mode which has a 30% lower peak intensity than the Gaussian profile. Figure
3.3b) shows the resultant profile after the two original modes have interfered, for phase
differences of 0, $\frac{\pi}{4}$, $\frac{\pi}{2}$ and $\pi$. Similarly, Figure 3.3c) shows the phase profile of the
resultant interference pattern. When the two interfering modes have a phase difference
that is an integer multiple of $2\pi$, they interfere constructively, such that $E^2 = E^2_{01} +
E^2_{11} + 2E_{01}E_{11}$, resulting in a wider intensity profile, and the phase at each point on the
profile is the same (i.e. it has a flat wavefront). Similarly when the two interfering modes
have a phase difference of an odd integer multiple of $\pi$, They will interfere destructively
such that $E^2 = E^2_{01} + E^2_{11} - 2E_{01}E_{11}$, producing a narrow beam with two lower side
lobes, and a constant phase profile (i.e. it also has a flat wavefront). However, in the
situation where the phase difference is not an integer multiple of $\pi$ or $2\pi$, we find that the phase at each point on the profile will be different, which implies that there is a certain phase curvature and hence a wavefront curvature associated with that resultant profile. Practically speaking, this would mean that unlike the first two situations where the beam waist is located at the fiber end facet, the beam would seem to be converging or diverging as it exits the fiber, as if the beam waist was located either within the fiber or outside of it. This phenomena was exploited by Mohammed et. al. 2004 [7], to create a self-condensing fiber lens.
Figure 3.3: a) Intensity profile for a LP(0,1) and LP(1,1) beam. b) The resultant intensity profile after the two beams have interfered for varying phase differences. c) the local phase profile at each point on the intensity profile.
3.3 Experimental Work

3.3.1 Characterisation of MMI behaviour in fiber amplifiers

3.3.1.1 Background

The investigation into the effects of MMI in large mode area fibers was first instigated by an interesting observation - when a large mode area fiber amplifier was seeded with a (broadband) ASE source, the output wavelength spectra exhibited a combed effect whereby certain wavelengths had significantly lower intensities than others (see Figure 3.4). The magnitude and periodicity ($\approx 1\,\text{nm}$) of this effect suggested that there must be some form of destructive and constructive interference taking place as the beam exited the fiber, leading to the conclusion that it was a multimode interference effect. (This conclusion is in agreement with prior literature whereby MMI was intentionally excited to produce a similar multiwavelength comb [11]). This was further verified by the fact that when a sufficient bend radius was imposed on the fiber such that only the fundamental mode was propagating in the fiber, the comb spectra disappeared.

![ASE Spectrum](image)

**Figure 3.4:** Measured ASE spectrum from a multimode amplifier

Although MMI is a very well documented and exploited effect for waveguides and fibers, particularly in the low power telecommunications sector, there has not been much research on MMI in the context of high power and large mode area fibers. It was thus decided that this effect was worth investigating, especially if it had any influence on the beam quality of the amplified output. It was further proposed that the wavelengths which experienced constructive interference would have a significantly better beam quality than the wavelengths which experienced destructive interference.
3.3.1.2 Design and Setup

The experiment was planned as follows - a tunable laser would be used to seed an active fiber amplifier, and the beam quality would be measured as the wavelength was tuned, with particular attention to wavelengths corresponding to constructive and destructive interference respectively. A CCD camera would be used to monitor and record images of the beam profiles at the far field as an indicator of when the beam quality would be the best and when it would be the worst.

A seed laser was thus built using a 5 m length of single-mode Yb-doped fiber which had a core/cladding diameter of 9/125\(\mu m\) and a core numerical aperture of 0.07, pumped with a diode laser at 975 \(\mu m\). To achieve tuning, one end was angle polished and aligned in an external cavity with a diffraction grating. The advantage of this configuration is that the tunable source can be converted into a broadband amplified spontaneous emission (ASE) source simply by blocking the external cavity.

![Figure 3.5: Configuration of the seed source](image)

Because the linewidth of the seed laser needed to be reasonably narrow and certainly much smaller than the period of the “comb” of the spectrum, an achromatic doublet with a long focal length (200 mm) was used to collimate the beam onto a large-area diffraction grating, so as to decrease the beam divergence and hence decrease the linewidth of the beam that was fed back into the laser. The achieved linewidth of 0.05 nm was deemed sufficient to provide enough resolution in the measurements. The seed laser could, in principle, be tuned from 1040 to 1080 nm, but because the laser was prone to self-pulsing behaviour, the wavelength range over which it was the most stable was from 1040 to 1060 nm. The output of this seed laser was diffraction limited with an \(M^2\) parameter of \(\approx 1.1\).

The multimode fiber (MMF) used as the amplifier was a 7m long Yb doped fiber, with a core/cladding diameter of 28/380\(\mu m\) and a core numerical aperture of 0.1. Both ends of the fiber were angle polished to prevent parasitic lasing in the amplifier, and it was pumped with a high power diode source at 976 nm. The \(V\) parameter of this fiber
was calculated to be \( \simeq 8.3 \). Using the approximate formula \( \frac{4}{\pi} V^2 \), this fiber supports approximately 34 bound modes (although in practice not all these modes will be excited).

By placing a dichroic mirror with high reflectivity (>99.5%) over the wavelength range 1020-1200nm and high transmission at 976 nm in the collimated pump beam at an angle (\( \sim 10^\circ \)), the amplified output was collected and, after sufficient attenuation, the beam was focused down with a 300 mm achromatic lens and divided with a beam splitter to enable the simultaneous monitoring of the beam profile with the CCD camera and measurement of the beam quality. The beam quality measurements were made with a BeamScan while the CCD camera used was a Spiricon LBA-FW-SCOR20.

### 3.3.1.3 Results and analysis

The method used to measure the beam quality \( M^2 \) parameter of the output beam was to take measurements of the beam diameter at various points along a fixed scale (a ruler, in this case) and to fit a curve to the data. This would enable the calculation of the \( M^2 \) value, the (relative) position of the beam waist, and the beam waist size.

A preparatory measurement was firstly undertaken to show that there was an effect taking place that was worth measuring and investigating. This was done by placing the BeamScan at the far field of the beam and measuring the far field beam radius as the wavelength was tuned from 1050.8 to 1053.5 nm. The results, plotted in Figure 3.7 clearly showed a periodic change in the beam radius, which indicated that, at the very least, the divergence of the beam was changing, and, consequently, its \( M^2 \) parameter.
A preliminary experiment was then performed, firstly at low output power (200mW) whereby the seed laser was tuned from 1051.8 - 1054 nm in increments of 0.1 nm and beam quality measurements were taken to characterise the behaviour of the output with respect to seed wavelength. Based on these early results, measurements were repeated for higher output powers (11W) within a narrower tuning range of 1050-1055 nm.

**Beam profile and quality, and pointing behaviour.**

The images recorded by the CCD camera revealed that the beam profile at the far field would oscillate periodically between a “good” profile and a “poor” one corresponding to local minima and maxima of the beam quality $M^2$ values respectively. The highest and lowest recorded $M^2$ values were 1.2 and 1.6. Additionally, the dimensions of the beam waist also had a periodic behaviour, with the waist maxima occurring at $M^2$ local minima and the waist size minima at $M^2$ local maxima (in antiphase with the $M^2$ behaviour, so to speak).

Experimental data also showed that the position of the beam waist relative to the focussing lens was oscillating periodically. The two extreme positions of the beam waist were \( \simeq 3.22 \text{cm} \) apart. Unlike the beam waist, however, the extreme positions of the beam waist did not coincide with the peaks and troughs of the $M^2$ plot - rather, it lies somewhere in between.

The shifting of the beam waist position is consistent with the principle laid out in section 3.2.4. Due to its wavefront curvature, the beam would either be seen to be converging or diverging from the end facet and thus, after passing through the collimating and focussing lens would seem to have a beam waist position that was changing in position. That the focus positions of the beam waists with the peak and lowest $M^2$ lie in between two extreme values is testament that these are the wavelengths at which the phase
differences are multiples of $\pi$ and $2\pi$, and hence wavelengths at which the wavefronts of the beams are planar.

Figure 3.8 plots these three parameters with respect to wavelength.

Figure 3.8: The $M^2$ parameter, beam divergence, and position of the waist versus wavelength. Inset: The beam profile for one wavelength cycle $\sim 0.7$nm

Theory predicts that we would expect each occurrence of reimaging to produce an $M^2$ of 1.1, however we can see that this is not the case, as the $M^2$ values of the “good” beams fluctuate from 1.16 to 1.3. Even the two best $M^2$ values which correspond to 1.16 and 1.19 at 1054.5 and 1051.5 nm respectively are still slightly larger than the original input beam. While this could perhaps be accounted for by taking into account the possible abberations introduced by the lenses, it doesn’t explain the variations in local minima values. One cannot say for certain, from this data, whether or not there is some larger period for which the “good” $M^2$ values would be at a minimum.

However, it is important to recall that the conditions for self-imaging are that both the initial phase relationship and relative amplitudes of the fiber are retrieved at the fiber end facet. These theoretical predictions were made with the assumption of a step-index profile, whereas the MMF being used (and fibers in general) do not have such profile. Coupled with the fact that the amplifier is being strongly pumped, this could mean that certain modes experience preferential gain. Thus even if the phase relationship is correct, the change in the power distribution (compared to the start of the fiber) due to this preferential gain may distort the self-image.
Chapter 3 Multimode Interference in Large Mode Area Fibers

The graphs in figure 3.8 show wavelength periods of $0.6 \text{ nm} \leq \Delta \lambda \leq 0.8 \text{ nm}$, with an average separation of 0.74 nm between consecutive wavelengths for which the beam quality of the output is a local minimum. This is slightly larger than the predicted value of 0.65 nm, but considering the argument above that the fiber refractive index profile is not a step-index one, and that the reimaging phenomenon is sensitive to thermal effects, bending in the fiber and other parameters, this is a reasonable agreement.

Returning to a two-mode interference situation for simplicity, let us assume that for a particular wavelength $\lambda_1$, the phase difference between the two modes at the end of the fiber, $\Delta \phi_1$ can be written as:

$$\Delta \phi_1 = \frac{2\pi}{\lambda_1} (L \Delta n)$$

$$= 2\pi m \text{ for constructive interference}$$

where

$m = 0, 1, 2, 3...$

$\Delta n = \text{difference in refractive index}$

$L = \text{length of fiber}$

Likewise for the next wavelength on, $\lambda_2$, this is $\Delta \phi_2 = \frac{2\pi}{\lambda_2} (L \Delta n) = 2\pi (m - 1)$.

There will be a certain beat length, $\Delta L = L' - L$ which would fulfill the following condition

$$\Delta \phi_1' = \frac{2\pi}{\lambda_1} (L' \Delta n)$$

$$= 2\pi (m + 1)$$

Using the data from the graph, the beat length $\Delta L$ was estimated to be $\sim 4.4 \pm 0.7 \text{ mm}$. This is in good agreement to the result calculated from equation 3.9 on page 39 for the reimaging distance which was 4.35 mm.

3.3.2 Impact of Multimode Interference on Coupling Efficiency

The fact that the beam divergence, waist size and focal position, and consequently the net beam pointing, is changing has important repercussions for fiber sources which operate in this sort of narrow linewidth regime; a slight change in wavelength (which could easily happen due to misalignment, damage, thermal effects, etc) could drastically alter the beam properties, reducing the coupling efficiency (and thus the overall output power) into any devices downstream.
To illustrate the potential severity of this instability in applications, we launched the seed into the amplifier slightly offset relative to the core in order to induce a change in beam pointing as the fiber shifts from one self-imaging regime to the next (as per figure 3.2). We then coupled the output from the amplifier into a single-mode fiber, optimising for a chosen self-imaging wavelength. The coupling efficiency was then measured as a function of seed wavelength and plotted in Figure 3.9. As the wavelength is tuned, the beam pointing changes, causing the coupling efficiency to drop. This reaches a minimum of 4% when the beam is an inverse self image, then rises again, reaching a maximum when the beam reverts to its original position. It is worth noting that even though the $M^2$ parameter is minimised when the beam is an inverse self image (i.e. the beam quality is very good), the small translational change in the beam pointing is sufficient to significantly degrade the coupling efficiency.

![Coupling efficiency vs wavelength](image)

**Figure 3.9:** Impact of changes in beam pointing as a result of MMI to coupling efficiency into a single-mode fiber. Inset: Images (1)-(6) show the beam profile at the labelled points on the graph.

**Power**

Changes to the beam properties are not just induced by wavelength variations. Anything which could affect the relative propagation constants of the modes - like stress, strain, or changes in temperature – will alter the output phase relationship and alter the beam’s pointing. In the case of thermal fluctuations, for example, the general phase change $\Delta\phi$
induced by a temperature change $\Delta T$ due to the change in fiber length due to thermal expansion/contraction and the change in refractive index can be expressed as [12]:

\[
\frac{\Delta \phi}{\Delta TL} = \frac{2\pi}{\lambda} \left( n \frac{1}{L} \frac{dL}{dT} + \frac{dn}{dT} \right)
\]

where

- $L$ = fiber length
- $T$ = temperature
- $n$ = refractive index
- $\frac{1}{L} \frac{dL}{dT}$ = thermal expansion coefficient
- $\frac{dn}{dT}$ = thermo-optic coefficient

In a pure fused silica fiber, based on coefficient values from the above literature [12], $\frac{\Delta \phi}{\Delta TL}$ is predicted to be 63.4 radians/°C-m for 1053 nm wavelength operation. Thus the output beam will certainly be affected by thermal fluctuations.

A far more relevant parameter to fiber laser engineers, however, is the pump power. Without active temperature stabilisation, increasing the pump power inevitably causes a rise in the internal temperature of the fiber. We measured the wavelengths at which self imaging occured over a range of pump powers up to 36 W, with all other operating conditions held as constant as possible. We can see from Figure 3.10 that for a fixed operating wavelength, even a few W increase in power could shift a beam from a self-imaging regime to some intermediate state, altering the beam quality and pointing direction in the process. The self image is retrieved by further increasing the pump power. For example, for 1054.5 nm wavelength operation a beam at that was initially in a self-imaging state at 2.3W pumping power would return to a self imaging state at 25.7W (Figure 3.10, dotted line).

According to equation 3.14 above, this pump power increase of 24W corresponds to an estimated temperature increase of $\sim 55^\circ$C within the core. To check this, we referred to a different equation provided by Li et al who had harnessed modal interference for temperature sensing [13]. Their report gives the following relationship between the wavelength variation due to temperature change:

\[
\frac{\Delta \lambda}{\lambda} = \left( \frac{1}{L} \frac{dL}{dT} + \frac{dn}{dT} \right) \Delta T
\]

where $\Delta \lambda$ is the change in wavelength as a result of the increased temperature.
In our situation, a beam originally in a self-imaging state at 1054.5 nm would exhibit self imaging at $\sim 1053.97$ nm at a pumping power of 25.7 (figure 3.10, circles). Applying this wavelength shift to equation 3.17 gives a temperature rise of $\sim 52^\circ$C, which is in good agreement with the value computed using equation 3.14.

Figure 3.10: Wavelengths at which self-imaging takes place for a certain operating power. For constant wavelength operation at 1054.5 nm, self imaging occurs at 2.3W pumping power and 25.7W (dotted line). Conversely, maintaining self-imaging from pumping powers of 2.3 W to 25.7 W would require a wavelength shift from 1054.5 nm to 1053.9 nm (circles)

### 3.3.2.1 Amplification of an ASE source

As a comparison, we seeded the amplifier with ASE (using the same seed fiber, but with feedback highly supressed) and its beam quality was measured. This yielded an $M^2$ value of 2. We believe that this is due to the fact that in the ASE situation, there are many constituent wavelengths of nearly equal power (this is true especially for the central region of the ASE spectrum), experiencing modal interference, which will superpose at the output. Since each wavelength will have different divergences, focal positions, and output powers, the resultant beam will be the weighted integral of all the intensity profiles of these wavelengths, taking these factors into account.

By the same rationale, the wide wavelength spectrum has a positive effect on the beam pointing stability. When the amplifier was seeded with a narrow-linewidth source, the beam profile was extremely volatile - a slight touch or movement of the fiber would induce severe (and often irretrievable) degradation. Because of that, the measurements
made above had to be conducted with the fiber secured to the optical bench and with minimal disturbance to the fiber itself. Moreover, as seen in section 3.3.2, increasing the pump power would also cause the beam profile to change. However, when seeded with an ASE source, the effects of multimode interference on the output beam properties were obscured, and the beam pointing proved much more robust and stable against physical perturbation and temperature despite the increased $M^2$ value.

It is reasonable to say, then, that an ASE source would be preferable for applications requiring stable beam pointing without any requisite for narrow linewidths or low $M^2$ values.

### 3.3.2.2 Implications

What are the implications of this work for fiber amplifiers using large mode area fibers? Thus far this study has yielded some interesting results, particularly the fact that one can reimage the good beam quality incident on a multimoded amplifier (and possibly from even more multimode fibers with larger cores) that is seeded with a narrow-linewidth source without having to induce severe bending or use exotic fibers, simply by wavelength selection of the seed source. This implies the potential to obtain a good beam quality without the restriction of exciting only the fundamental mode. One could go as far as to speculate that one could potentially launch a Gaussian, diffraction-limited beam that is much larger than the fundamental mode into a step-index profile MMF and still be able to recover its Gaussian, diffraction-limited characteristics at the other end, plus the added benefits of having a beam that has a large mode area.

Equally, however, and on a more negative note, this also implies that a narrow-linewidth multimode fiber oscillator or amplifier would be hugely sensitive to perturbations to the refractive index of the fiber. Worse yet, despite the presence of multimode interference one can still measure excellent values of the $M^2$ parameter, giving misleading information about the higher order mode content of the beam [14]. This has severe repercussions for the field of fiber lasers, as the $M^2$ parameter has traditionally been used as an indicator of single-modedness.

It is worth mentioning here that we had originally attempted to launch the seed beam into the fundamental mode of the multimode fiber (MMF). The appropriate calculations were made to determine the radius of the fundamental mode and the necessary optical alignments were made to ensure the input beam size was a close match to the calculated size. The fact that MMI is observed means that we were unsuccessful in doing so, and that in practice, it is generally difficult to achieve a precise launch condition such that only the fundamental mode is excited, due to various factors such as misalignment, or an incorrect beam size.
The fact that the beam divergence, waist size and focal position is changing has important repercussions for devices which operate in this sort of narrow linewidth regime; a slight change in operating conditions (which could easily take place due to misalignment, damage, thermal effects, etc) could distort the beam, changing its transverse position, focussing position, quality, and dimensions. This would be particularly severe for situations such as free-space coupling from an amplifier into another fiber device, or for applications requiring high-stability, high-precision output.

Suppose an application had greater requirement on the spatial stability of the beam than on its beam quality. There would be several courses of action one could take to fulfill that requirement. One would be to use a broadband seed source instead of a narrow linewidth laser source since that would be robust against bending and wavelength shift. However as mentioned previously it would mean that one would have to put up with a degraded beam quality. Another option would be to stabilise the system by controlling the wavelength so that any drift can be either prevented or quickly corrected. The third option, of course, would be to strip out higher order modes altogether by mode filtering or bend loss, so that only the fundamental mode is allowed to propagate and no MMI effects manifest.

Incidentally, one could potentially use MMI effects as a diagnostic for ascertaining if a fiber is robustly single mode. One method could involve launching an ASE source to ensure that the output spectrum is a smooth one. Another method could be simply seeding with a narrow linewidth seed and tuning the wavelength to check that the beam divergence remains constant.

MMI and its effects in large mode area fibers is certainly something that merits study. In certain applications it may be a hindrance; in others it may be advantageous. Either way, a good understanding of it is necessary, so that one is aware of the pitfalls associated with MMI in LMA fibers and can take the necessary precautions to avoid it (e.g. by inducing a bend loss on the higher order modes), or to utilise its characteristics to the advantage of the application.

The above research work was began in early 2007. In November that year, however, S. Wielandy published a paper on this topic [14]. Like us, he arrived at the conclusion that despite being able to contribute to good $M^2$ values, the presence of higher order modes makes fibers prohibitively sensitive to the phase relationships of the modes, which in turn are affected by fluctuations in operating conditions. Nevertheless, having already obtained the experimental data, in December we submitted our results for CLEO (San Jose), which were accepted and duly presented the following year. Also presented during the conference were the results from OFS Laboratories. They too had recognised the pitfalls of using the beam $M^2$ parameter as a measure of the quality, and had developed a new technique, later named $S^2$ measurements, which would enable the individual identification of the higher order modes as well as the power contained within them.
This is a powerful and comprehensive diagnostic tool indeed, but for the purposes of power scaling, greater interest lay in harnessing the effects of MMI in a multimode fiber rather than identifying its modal content in great detail.

### 3.3.3 Preliminary work on self-mode selection using MMI in fiber oscillators

The self-imaging phenomena exhibited by fiber amplifiers prompts the question of whether MMI could be exploited within an oscillator configuration as well. With that aim, an early concept was conceived for self-mode selection within a unidirectional fiber ring cavity. Essentially, the output of one fiber end is spatially filtered such that only the fundamental mode sees high transmission while the higher order modes experience a high loss. This filtered light is then fed back into the other fiber end. Similar to the amplifier case, the profile of a beam injected into one end of a fiber will be reproduced at the other end, given the right conditions. In this case, the oscillator is constrained by the spatial filtering, and thus will self-select operating wavelengths which will actively reproduce an output beam profile that experiences the least loss through the spatial filter. This could potentially lead to fiber lasers and oscillators which would self-correct when perturbed, resulting in stable beam pointing.

A fiber ring cavity was duly constructed (as per figure 3.11) to test the validity of this concept. To minimise the possible polarisation losses, a polarisation-maintaining (PM) fiber was used which had a core and cladding diameter of 30\(\mu m\) and 400\(\mu m\) respectively. The numerical aperture of this fiber was 0.06, which meant that this fiber had a lower \(V\) number (4.7) than the previous one despite having a larger core size. 4.5 m of this fiber was used as the gain medium for the ring cavity. Unidirectional operation was enforced with an optical isolator, while a pinhole aperture (of variable dimensions) served as a spatial mode filter.

![Figure 3.11: Experimental setup for self-mode selection within a unidirectional fiber ring oscillator](image-url)
The outcome of this experimental endeavour proved less conclusive than hoped. We tested a range of aperture sizes and alignments, and while we were able to achieve a relatively stable circular beam profile, the best beam quality $M^2$ parameter obtained was 1.4. This is an improvement over the beam quality measured without the apertures in place, which yielded an $M^2$ value of 1.7.

A quick inspection of Figure 3.12 reveals that the insertion of the apertures had altered the optical spectrum of the laser output. A closer inspection of the spectra in the range of 1060-1080 nm shows a series of evenly-spaced peaks with a wavelength separation of 1.2 nm. In fact, almost all the peaks recorded in the spectrum for the laser with the apertures in place are separated by integer multiples of 1.2 nm. This uniformity is less apparent in the spectra for the setup without the apertures. Moreover, the insertion of the apertures has smoothened out the spectrum slightly (compared to without the apertures, which have rather noisy peaks, especially the one at 1085 nm). These results implied that there was indeed an effect taking place, however they were not compelling enough evidence of a viable technique.

A possible reason for the poor results could be due to the rather primitive and imperfect method of mode filtering used. Attempts to improve this by using different methods of spatial mode filtering such as using a smaller pinhole aperture at the focus of the beam (as opposed to the collimated section) mostly resulted in damage to the pinhole aperture due to the high intensity. Moreover, hard aperturing would cause diffraction rings and even cause degradation from clipping or misalignment, which could also contribute to our lacklustre results. As such more sophisticated methods such as graded apertures would be needed before better results can be obtained from this scheme.

6 lenses are used within the experimental setup (Figure 3.11), and it is likely that each introduced some further degradation to the beam quality. Also, like in the case of the amplifier, the differential modal gain arising from the non-ideal refractive index profile of the fiber could have contributed to the poor reimaging. This however raises the question of what exactly constitutes an ‘ideal’ refractive index profile for the purposes of self-imaging - preferably, the gain should be distributed evenly across all the modes such that, at the fiber output, both the initial phase relationships and the relative amplitudes are recovered. In a strongly pumped step index fiber this will not be the case, since the mode with the highest intensity would deplete the gain, leaving less available for the lower intensity modes. Calculating the optimum profile will thus involve accounting for both spatial overlaps and gain saturation, and is certainly worth further study.

Also, the effects of Transversal Hole Burning (THB) had not been accounted for at the time. Jauregui et al have recently reported the results of their modelling in which a 3-dimensional beam propagation method was used in conjunction with spatially resolved rate equations in order to account for THB [17, 18]. They had found that the changes in the relative phases of the modes resulted in periodic changes to the intensity along
the fiber, which induce local refractive index changes, ultimately mimicking a long period grating. This ‘grating’, referred to as the inversion grating in their report, can couple energy between the LP(0,1) and LP(1,1) modes, disrupting the relative powers contained within each mode and thus disrupting self-imaging.

Optical spectra with and without pinhole apertures

![Graph](image)

**Figure 3.12:** A comparison between the optical spectrum of the laser output a) with and b) without the apertures in place. c) The same comparison, but in zoomed in the range 1060-1080 nm.

In parallel with our efforts, Shalaby et al [19] published a paper which proposed and
proved a similar concept. However, the crucial differences between our work and theirs lie in the fact that the multimode fiber segment of their setup was an undoped and therefore imparted no gain whatsoever onto the propagating modes, and that their mode selection was achieved via the use of a single mode fiber. At the time this paper, although vital in confirming that the technique was indeed one worth researching, was deemed unhelpful to our conundrum since in our setup the multimode fiber was active and therefore gain considerations had to come into play. Also, using a single-mode fiber as a filter in our case would be self-defeating since the point was to use large mode areas, and it imposed the additional constraint of needing to avoid optical damage to the facet of the single mode fiber. Since then, the work done by Shalaby has been used successfully as the basis for self-mode selection in multicore fiber systems [20, 21]. However, to the best of our knowledge there have been no corresponding results for single-core laser systems.

Due to time constraints and the conception of an alternative novel method for mode selection in fiber lasers, research efforts on this particular topic were put on hold. At the very least, we have demonstrated, via changes in $M^2$ values and spectra, that the technique has *some* effect on the oscillator. The fact that this technique was shown years later to work well for multicore fibers is also encouraging. As such, there is still much scope for future work to be done in this area, particularly with regard to finding a robust method of spatial filtering as well as in solving the modal gain issues by numerical modelling of an ideal profile, and finally combining the two in order to achieve self-mode selection in a single-core multimode fiber.

### 3.4 Conclusions

#### 3.4.1 Concluding remarks

In the pursuit of power scaling through increasing the mode area, we have investigated the effects of multimode interference (MMI). Section 3.2 on page 36 covers a simple mathematical treatment describing MMI, and the experimental results to verify this were analysed and reviewed in section 3.3.2.1 on page 53. We observed that one can recover the good incident beam quality on a fiber amplifier by harnessing the self-imaging effect through careful selection of the operating parameters such as the seed wavelength. However, a more sinister implication of this is that an $M^2$ measurement is by no means a good indicator of whether the output from an amplifier (and by extension, a fiber oscillator) is truly single mode [14], since as clearly shown it is possible to obtain good $M^2$ values even when there are many modes present in the fiber. We exhibited experimentally the detrimental effects of MMI in coupling sensitive devices due to beam quality and pointing instability arising from changes in operating conditions, and in light of this, discussed the advantages (in terms of the pointing stability and divergence) of using a broadband seed source over a narrow linewidth one.
An attempt was made to exploit MMI in a fiber oscillator configuration, with lacklustre results. This was further exacerbated by the publication of another group of a similar concept, but with more convincing proof of the success of the technique. However, having examined the possible reasons for the poor performance, we surmised that an investigation into ideal refractive index profiles for the harnessing of MMI in strongly pump fibers, improved spatial filtering techniques as well a more optimised cavity design would lead more conclusive and publishable results in the future.

The various issues covered in this chapter have served to highlight the dire need in the field of fiber lasers for robust methods of mode selection in fiber lasers which would be relatively immune to MMI. We address this in the following chapter by proposing and demonstrating a simple, novel, and effective technique for selective modal excitation in multimode fibers.
Bibliography


Chapter 4

Selective mode excitation in multimode fibers

4.1 Introduction

Having studied the effects of multimode interference and its implications for large core area multimode fiber lasers in the previous chapter, the question then arises as to how one can operate a laser on a single transverse mode without encountering such issues. At present there are a diverse range of methods being used with varying degrees of success, including selective-ion doping which promotes only a certain mode [1], microstructured fibers [2], special large-mode-area core designs [3], distributed mode filtering such as bending the fiber [4], or careful and deliberate launching into a specific (in this case, the fundamental) mode of the multimode waveguide [5]. While all these techniques have their merits, they tend to increase the cost and complexity of the device designs and are not necessarily scalable to larger core sizes.

In this chapter we report the design and subsequent demonstration of a mode-selection technique applicable to fiber lasers based on the spectral responses of Fiber Bragg Gratings (FBGs) with different transverse modes. A brief description of the underlying principles of the concept is outlined, followed by analytical and numerical analysis on its possible impact on CW laser performance, as well as its potential scalability with larger mode area fibers.

4.2 Fundamental principles and conceptual design

An FBG is a distributed Bragg grating, created within the core of an optical fiber by inducing a periodic variation of the core’s refractive index. The spatial variation in refractive index act as grating planes, and light propagating along the core of an optical
fiber will be scattered off each of these planes. If the Bragg condition is satisfied, reflected light from each grating plane will constructively interfere in the backward direction; the net result is that the incident light sees high reflectivity and is back reflected. If the Bragg condition is not met, the reflections off the grating planes will cancel out and the light sees no net back-reflection.

The Bragg condition for a fiber Bragg grating with a period \( \Lambda_{FBG} \) is given by

\[
\lambda_{FBG} = 2n_{eff}\Lambda_{FBG}
\]  

(4.1)

Where \( \lambda_{FBG} \) is the incident wavelength which satisfies the Bragg condition and \( n_{eff} \) is the effective refractive index of the core. Because each transverse mode in a multimode fiber possesses its own characteristic effective propagation constant, each will have their own corresponding value of \( n_{eff} \), and consequently different values of \( \lambda_{FBG} \). Simply put, for a given FBG written in a fiber, each mode in the fiber would have a unique value of \( \lambda_{FBG} \) at which the reflectivity of the grating is maximum.

Volume Bragg Gratings (VBGs), like FBGs, are also a form of distributed Bragg gratings, but as the name implies, these Bragg gratings are written into bulk material such as photo-thermo-refractive (PTR) glass [6]. The Bragg condition for a grating with period \( \Lambda_{VBG} \) is then as follows:

\[
\lambda_{VBG} = 2n_{VBG}\Lambda_{VBG}\cos(\theta)
\]

Here, \( \theta \) refers to the incident angle, and \( n_{VBG} \) is the effective refractive index of the VBG material which, unlike its fiber counterpart, has no waveguiding geometry and consequently very little or no mode dependence.

If both these components are used as the main feedback mirrors for a fiber laser resonator, efficient lasing action would only take place when the following requirement is met:

\[
\begin{align*}
\lambda_{FBG} &= \lambda_{VBG} \\
\therefore n_{eff}\Lambda_{FBG} &= n_{VBG}\Lambda_{VBG}\cos(\theta)
\end{align*}
\]

(4.2)

Thus for a given value of \( \Lambda_1 \), by careful choice of \( \theta \) and \( \Lambda_2 \) (i.e. certain values of \( \lambda_{VBG} \)), a particular spatial mode can be selected for lasing action. A conceptual schematic of the proposed technique is illustrated in figure 4.1.
This technique is attractive because it is conceptually and inherently simple, obviating the need for complex fiber geometries, tailored refractive index profiles, or expensive electronic and optical components.

4.3 Theoretical analyses

It was necessary, prior to any experimentation, to conduct a thorough study of the fiber gain medium and its modal characteristics in order check the feasibility of the concept as well as to predict the behaviour of the system once implemented. Rate equation modelling, taking into account the spatial distribution of the laser mode was then undertaken to probe the possible impact mode selection would have on the laser performance in terms of the slope efficiency. The prospects for further scaling were then discussed with regards to efficiency, the wavelength spacing of modes with increasing core size, as well as mode coupling.

4.3.1 Fiber parameters and modal properties

The fiber chosen as a gain medium was a Tm, Ge co-doped double-clad fiber, fabricated in-house by standard modified chemical vapour deposition and solution doping. The fiber was then co-doped with germanium to photosensitise the fiber, enabling direct writing of the FBG in the core of the active fiber. This photosensitivity was later enhanced by hydrogen loading just prior to the grating writing process.

There are many reasons behind the move from working with ytterbium doped fibers to thulium doped ones, many of which are listed in Chapter 2, such as the eye safe emission wavelengths, thulium’s burgeoning prospects for use in applications as well as pumping sources, and so on. One particularly relevant consequence of the emission wavelengths of thulium is the fact that thulium doped fibers would have a lower V number than an
equivalent ytterbium fiber of similar numerical aperture and fiber dimensions. Crucially, as well, the effective wavelength spacing between modes (see table 4.1 below) would be greater in a thulium fiber, allowing better mode discrimination and selection.

The core diameter of the fiber was 22.5 microns, with a 300 micron diameter D-shaped silica cladding. The doping concentration was estimated to be 1 wt.% Tm, giving an effective core numerical aperture of 0.22 NA. Calculations of the V parameter yielded a value of 6.3.

<table>
<thead>
<tr>
<th>Mode</th>
<th>( n_{\text{eff}} )</th>
<th>Profile</th>
<th>( \lambda_{\text{FBG}} ) for ( \Lambda \sim 0.66\mu m ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP(0,1)</td>
<td>1.4516</td>
<td><img src="image1" alt="Profile" /></td>
<td>1923.0</td>
</tr>
<tr>
<td>LP(1,1)</td>
<td>1.4485</td>
<td><img src="image2" alt="Profile" /></td>
<td>1918.9</td>
</tr>
<tr>
<td>LP(2,1)</td>
<td>1.4452</td>
<td><img src="image3" alt="Profile" /></td>
<td>1914.5</td>
</tr>
<tr>
<td>LP(0,2)</td>
<td>1.4450</td>
<td><img src="image4" alt="Profile" /></td>
<td>1914.3</td>
</tr>
<tr>
<td>LP(1,2)</td>
<td>1.4396</td>
<td><img src="image5" alt="Profile" /></td>
<td>1910.96</td>
</tr>
<tr>
<td>LP(3,1)</td>
<td>1.4421</td>
<td><img src="image6" alt="Profile" /></td>
<td>1910.44</td>
</tr>
<tr>
<td>LP(2,2)</td>
<td>1.4395</td>
<td><img src="image7" alt="Profile" /></td>
<td>1907.07</td>
</tr>
</tbody>
</table>

Table 4.1: Supported modes and their properties for the 22.5 micron Tm-doped fiber

Cutback measurements estimated the cladding absorption coefficient of the pump light at 793 nm to be about \( \sim 3dB/m \). To ensure efficient pump absorption therefore a 4 m length of fiber was used.
The VBG selected for this particular experiment was designed to be highly reflective (>99.5%) in the wavelength range of 1900-2000 nm with a reflection bandwidth FWHM of about 0.5 nm. This overlaps well with the gain spectrum of the thulium fiber and thus dictated that the FBG should be written within that wavelength regime as well.

Based on available data on the refractive index profile of the fiber, a fiber mode propagation software (Optifibre) was used to predict the modes that would be supported by this fiber and their properties. Table 4.1 lists these modes, their effective refractive indices, profiles, and Bragg wavelength for a FBG with a period of 0.66 microns.

The wavelength separation between the two main modes of interest, LP(0,1) and LP(1,1), is ~ 4nm. In order to achieve good modal discrimination between the two, the linewidth of both the FBG and the VBG needs to be less than this value. This requirement is easily met with the current optical components and fiber - how this condition changes with increasing mode size will be studied later in section 4.5.

4.3.2 Potential Impact of Mode Selection on Slope Efficiency

In many commercial and industrial applications, the desired mode of operation for a fiber laser is the fundamental LP(0,1) mode. Figure 4.2 illustrates the spatial profile of this fundamental mode against the doped area of a fiber with dimensions as above, compared to a fiber with a core diameter of 8.25 microns. The spatial overlap between the mode and the doped core is poorer with increasing core size. This raises a few pertinent questions- what effect will this have on the slope efficiency of a laser which is constrained to operate only on the fundamental mode? Is the performance penalty severe enough to outweigh the benefits of fundamental mode operation? How would this compare with the selection of another mode instead, e.g. the LP(1,1) mode?
Figure 4.2: Spatial overlap of fundamental LP(0,1) mode with the inversion/doped core for fibers with 8.25 \( \mu m \) and 22.5 \( \mu m \) core diameter (For a uniform top-hat dopant distribution)
4.3.2.1 Quasi-3 level rate equations

We can gain a qualitative understanding of the effect of spatial overlap on the laser properties based on the laser rate equations for quasi-three level solid state lasers as per [7].

Consider a simple laser cavity like the schematic in figure 4.3, with a fiber gain medium that has upper and lower laser levels \( N_b, N_a \).

![Figure 4.3: Schematic of simple quasi-three level laser for modelling](image)

The relative populations of the levels in the lower manifold (at thermal equilibrium) are given by a Boltzmann distribution. The lower laser level population (at equilibrium) is then given by [7]:

\[
N_a = \frac{g_a N_0}{Z_a} \exp \left( -\frac{E_a}{kT} \right) = f_a N_0
\]

where

\[
Z_a = \sum_i g_i \exp \left( -\frac{E_i}{kT} \right)
\]

is the partition function, \( E_a \) is the energy of the lower laser level, \( k \) is the Boltzmann constant, \( T \) is the temperature, \( f_a \) is the fractional population in the level, \( g_a, g_i \) are the degeneracies of states \( a \) and \( i \), and \( N_0 \) is the total dopant concentration. The sum is over all states in the lower manifold.

In steady state pumping, if the relaxation between levels in the upper manifold is rapid, the relative populations of the levels in the upper manifold can also be described as a Boltzmann distribution. The upper laser population \( N_b \), is then given by \( f_b N_1 \) as in 4.3, where \( N_1 \) is the upper manifold population. We assume here that the population of the upper manifold is always small compared to the total doping level, \( N_1 \ll N_0 \).

We can thus write the following rate equations for levels in quasi-thermal equilibrium with steady state pumping [7]:
\[
\frac{dN_b(x,y,z)}{dt} = f_b r(x,y,z) - \frac{N_b - N_b^o}{\tau} f_b c_n \sigma [N_b - N_a] s(x,y,z) = 0 \tag{4.4}
\]
\[
\frac{dN_a(x,y,z)}{dt} = -f_a r(x,y,z) - \frac{N_a - N_a^o}{\tau} f_a c_n \sigma [N_b - N_a] s(x,y,z) = 0 \tag{4.5}
\]

where
\[
c = \text{speed of light}
\]
\[
N_a^o, N_b^o = \text{unpumped population of levels a and b at thermal equilibrium}\tag{4.6}
\]
\[
r(x,y,z) = \text{pump rate density}\tag{4.7}
\]
\[
s(x,y,z) = \text{photon density}\tag{4.8}
\]

We can combine 4.4 and 4.5 into one eq in terms of the population inversion density \(n(x,y,z) = N_b - N_a\), and the unpumped population inversion density at equilibrium \(\Delta N^o = N_b^o - N_a^o\). Likewise, let \(f = f_b + f_a\). To avoid unnecessary confusion, we shall treat \(\sigma_{es} = \sigma_{as} = \sigma\), that is, both the upper and lower levels have the same degeneracy. This simplifies into a rate equation for the population inversion:

\[
\frac{dn(x,y,z)}{dt} = f r(x,y,z) - \frac{n(x,y,z)}{\tau} - \Delta N^o \tau - f c_n \sigma n(x,y,z)s(x,y,z) = 0 \tag{4.9}
\]

We can also write an expression for the cavity photon number, \(S\)

\[
\frac{dS(x,y,z)}{dt} = \int_{\text{cavity}} c \sigma n(x,y,z)s(x,y,z) dV - \Gamma_{loss} S = 0 \tag{4.10}
\]

Where \(L_c\) is the total cavity length. The first term represents a rate of increase, whereas the second represents a rate of loss. In the absence of pumping, \(\frac{1}{\Gamma_{loss}}\) is the time taken for the photon number to decrease to \(\frac{1}{e}\) of its original value. We can approximate the loss rate in the cavity (assuming that the losses are incurred at the two mirror ends due to output coupling and feedback loss) by:

\[
\Gamma_{loss} = \frac{P_{loss} + P_{out}}{Sh\nu_s} = \frac{c}{2L_c} \left( \frac{T}{P_{out}} \right)(P_{loss} + P_{out}) \tag{4.11}
\]

which updates equation 4.10 as
\[
\frac{dS(x, y, z)}{dt} = \int_{\text{cavity}} c_n \sigma n(x, y, z) s(x, y, z) dV - \frac{c\delta}{2L_c} S = 0 \tag{4.12}
\]

Where \( \delta \) is defined above as the cavity loss including output coupling.

We define normalised distributions for the pump and signal:

\[
s_o(x, y, z) = \frac{s(x, y, z)}{S} \\
r_o(x, y, z) = \frac{r(x, y, z)}{R}
\]

where \( s(x, y, z) \) is the photon density and \( S = \int_{\text{cavity}} s(x, y, z) dV \) = total number of photons in the laser mode. Likewise the pump rate \( R = \int_{\text{cavity}} r(x, y, z) dV = \frac{P_{\text{pump}} \eta_{\text{abs}} \eta_q \nu_p}{h c} \)

where \( \eta_{\text{abs}} \) is the fraction of pump absorbed, \( \eta_q \) is the pumping quantum efficiency (the number of ions excited to the upper laser level for each absorbed pump photon) and \( \nu_p \) is the pump frequency.

Some manipulation and rearrangement of equation 4.12 yields the following expression

\[
\frac{\delta}{2\sigma L_c} = f R c_n \tau_f \int_{\text{cavity}} \frac{r_o s_o}{1 + f c_n \sigma \tau_f S s_o} dV + \Delta N^o c_n \int_{\text{cavity}} \frac{s_o}{1 + f c_n \sigma \tau_f S s_o} dV \tag{4.13}
\]

This is similar in form to the 4 level equation derived by \[8\] except for the additional term with \( \Delta N^o \) (as can easily be seen by setting \( \Delta N^o = 0 \) which is true for 4 level laser systems).

### 4.3.2.2 Threshold

At threshold, the gain is equal to the loss (\( \text{gain}, g = \delta \)), and there is NO signal light (i.e. \( S = 0 \)), and going by the usual definition we can write \( g \) as:

\[
g = \int_{\text{cavity}} 2L_c s_o \sigma (N_b - N_a) dV
\]

Substituting the definitions for \( N_b \) 4.4 and \( N_a \) 4.3
Chapter 4 Selective mode excitation in multimode fibers

\[ g = 2L_c \sigma (f_b R \tau_f \int_{\text{cavity}} r_o s_o dV + f_a N_0 \int_{\text{cavity}} s_o dV) \]

\[ = 2L_c \left( \sigma_{es} \left( \frac{P_{\text{pump}} \eta_{\text{abs}} \eta_q}{h \nu_p} \right) \tau_f \int_{\text{cavity}} r_o s_o dV + N_0 \sigma_{as} \right) \]

define small signal gain \( G \) as:

\[ G = \exp(g - \alpha L l) \]

where

\[ \alpha_L = \ \text{attenuation coefficient for signal light} \]

\[ l = \ \text{gain medium length} \]

In the above derivation we have referred to individual levels within a manifold, and we have quoted the absolute cross sections in relation the fractional populations as \( f_a \) and \( f_b \). In a glass host, these levels are not resolvable, and thus it is more common to refer to the effective cross sections such that \( \sigma_{es} = f_b \sigma \) and \( \sigma_{as} = f_a \sigma \) are the effective emission and absorption cross sections respectively.

Assuming no attenuation for signal light along the cavity (i.e. no propagation loss), the second term in the expression above drops out, and the round-trip gain at threshold is therefore:

\[ G = \exp \left( 2L_c \left( \sigma_{es} \left( \frac{P_{\text{pump}} \eta_{\text{abs}} \eta_q}{h \nu_p} \right) \tau_f \int_{\text{cavity}} r_o s_o dV + N_0 \sigma_{as} \right) \right) (1 - T) (1 - L) = 1 \]

\[ P_{th} = P_{\text{pump}} \text{ at threshold} \]

\[ = \frac{1}{2 \sigma_{es} L_c \tau_f \eta_{\text{abs}} \eta_q} \frac{1}{\int_{\text{cavity}} r_o s_o dV} \left( (-ln(1 - T) - ln(1 - L)) - N_0 2 \sigma_{as} L_c \right) \]

4.3.2.3 Slope Efficiency

While 4.13 cannot be evaluated analytically in its current form, we can make 2 approximations corresponding to 2 different regimes of operation. The first applies to the situation when the laser is operated very far above threshold, when the factor in the denominator \( c_n \sigma S s_o \tau_f = \frac{1}{I_{\text{sat}}} \) becomes very large such that \( \frac{1}{I_{\text{sat}}} \gg 1 \). The other possible regime of operation is when \( \frac{1}{I_{\text{sat}}} \ll 1 \) (very close to threshold).

For the first approximation \( \frac{1}{I_{\text{sat}}} \gg 1 \), we can write:
\[ \delta = \frac{2\sigma L_c}{c} R \tau_f \int_{\text{cavity}} \frac{\tau_L s_o}{\alpha \tau f S s_o} dV + \frac{2\sigma L_c}{c} \Delta N^o c \int_{\text{cavity}} \frac{s_o}{\alpha \tau f S s_o} dV \]

therefore

\[ S = \frac{2L_c}{\delta c} (R + \frac{\Delta N^o}{\tau_f} V) \]

If the photon density does not vary greatly with length, we can make the approximation

\[ S = \frac{2L_c}{\delta c h v_s} P_{\text{out}} \]

leaving

\[ P_{\text{out}} = \frac{T}{\delta} h v_s (R + \frac{\Delta N^o}{\tau_f} V) \]

recalling the definition of R, this gives

\[ P_{\text{out}} = \frac{T}{\delta} h v_s \left( \frac{P_{\text{pump}} \eta_{\text{abs}} \eta_q}{h v_p} + \frac{\Delta N^o}{\tau_f} V \right) \]

by definition, the slope efficiency is given by \( \frac{dP_{\text{out}}}{dP_{\text{pump}}} \), so the slope efficiency \( \eta_s \) is therefore :

\[ \eta_s = \frac{T}{\delta} h v_s \left( \eta_{\text{abs}} \eta_q \right) \]

substituting the expression for \( \delta \) (from equation 4.11), we end up with

\[ \eta_s = \frac{T}{(P_{\text{out}} / T)} (P_{\text{loss}} + P_{\text{out}}) h v_s \left( \frac{\eta_{\text{abs}} \eta_q}{h v_p} \right) \]

From Rigrod’s analysis on the two cavity ends, we have the following relationship [9]:

\[ \frac{P_{\text{loss}}}{P_{\text{out}}} = \frac{L}{T} \sqrt{\frac{(1 - T)}{(1 - L)}} \]

So the final resultant expression is
\[ \eta_s = \frac{T \sqrt{(1-L)}}{L \sqrt{(1-T)} + T \sqrt{(1-L)}} h \nu_s (\eta_{abs} \eta_q) \]

The other possible regime of operation is when \( I_{sat} \ll 1 \) (very close to threshold). Multiplying the top and bottom of the integral in 4.13 by \( 1 - c \sigma S_s \tau_f \) gives:

\[
\frac{\delta}{2 \sigma L_c} = f R c n \tau_f \int_{cavity} r_o s_o (1 - f c \sigma S_s \tau_f) \frac{dV}{1 - (f c \sigma S_s \tau_f)^2} + \Delta N^o c_n \int_{cavity} s_o (1 - f c \sigma S_s \tau_f) \frac{dV}{1 - (f c \sigma S_s \tau_f)^2} \]

\[
= f R \tau_f c \int_{cavity} r_o s_o - f c \sigma S \tau_f r_o s_o^2 dV + \Delta N^o c_n \int_{cavity} s_o - f c \sigma S \tau_f s_o^2 dV \quad (4.14) \]

Using the condition that \( I_{sat} \ll 1 \), and therefore \((f c \sigma S_s \tau_f)^2\) is negligible, and rearranging, we arrive at:

\[
P_{out} = (T c h \nu_s) \left( \frac{P_{pump} \eta_{abs} \eta_q}{h \nu_p} \right) f \tau_f \int_{cavity} r_o s_o dV - \frac{\delta}{2 \sigma L_c} + \Delta N^o \int s_o dV
\]

Performing the differentiation \( \eta_{slope} = \frac{dP_{out}}{dP_{pump}} \) and rearranging 4.14 so that:

\[
P_{pump} = \frac{\delta}{2 \sigma L_c} - \Delta N^o \int s_o dV + \Delta N^o f c_n \sigma \tau_f S \int s_o^2 dV
\]

\[
\Rightarrow \eta_{slope} = \left( \frac{T c h \nu_s}{\delta} \right) (\nu_s / \nu_p) (\eta_{abs} \eta_q) \left( \frac{(\int r_o s_o dV - f c_n \sigma \tau_f S \int r_o s_o^2 dV)^2}{\int r_o s_o^2 dV + \Delta N^o c_n (\frac{2 \sigma L_c}{\delta}) (\int r_o s_o dV \int s_o^2 dV - \int r_o s_o^2 dV \int s_o^2 dV)} \right)
\]

Again, due to the condition that \( I_{sat} \ll 1 \), we can simplify this to:

\[
\eta_{slope} = \left( \frac{T c h \nu_s}{\delta} \right) (\nu_s / \nu_p) (\eta_{abs} \eta_q) \left( \frac{(\int r_o s_o dV)^2}{\int r_o s_o^2 dV + \delta \Delta N_o} \right)
\]

where

\[
\delta \Delta N_o = \Delta N^o c_n (\frac{2 \sigma L_c}{\delta}) (\int r_o s_o dV \int s_o^2 dV - \int r_o s_o^2 dV)
\]
Going by the definition of $\delta$ as above, the expression for the slope efficiency in the low-intensity regime is thus:

$$\eta_{\text{slope}} = \frac{T \sqrt{(1 - L)}}{L \sqrt{(1 - T)} + T \sqrt{(1 - L)}} \frac{\nu_s}{\nu_p} \eta_{\text{abs}} \eta_q \left( \frac{[\int r_o s_o dV]^2}{\int r_o s_o^2 dV + \delta_{\Delta N_o}} \right)$$

The final generalised expression for the slope efficiency is then:

$$\eta_{\text{slope}} = \frac{T \sqrt{(1 - L)}}{L \sqrt{(1 - T)} + T \sqrt{(1 - L)}} \frac{\nu_s}{\nu_p} \eta_{\text{abs}} \eta_q \eta_{PL}$$

where

$$\eta_{PL} = \begin{cases} \frac{[\int r_o s_o dV]^2}{\int r_o s_o^2 dV + \delta_{\Delta N_o}} & \text{for } \frac{I}{I_{\text{sat}}} \ll 1 \\ \rightarrow 1 & \text{for } \frac{I}{I_{\text{sat}}} \gg 1 \end{cases}$$

and

$$\delta_{\Delta N_o} = \Delta N_o \left( \frac{2 \sigma L_c}{\delta} \right) \left( \int r_o s_o dV \int s_o^2 dV - \int r_o s_o^2 dV \right)$$

The effect of this is that the slope efficiency is reduced by a variable scale factor $\eta_{PL}$ which has a strong dependence on the spatial overlap of the doped/inverted area $r_o$ with the mode profile $s_o$. For a hypothetical cavity consisting of a HR mirror and 4% feedback off the fiber end facet, the lower limit of $\eta_{PL}$ for small values of $I$ was estimated to be $\sim 0.75$. As $I$ increases, this value of $\eta_{PL}$ increases as well, gradually approaching the value of 1.

Returning once again to figure 4.2 gives a clearer picture of why this is so - There are two main contributions to the rate equation 4.9 in the steady state, namely spontaneous and stimulated emission. At low intensity levels $\frac{I}{I_{\text{sat}}} \ll 1$, spontaneous emission will dominate over stimulated emission, particularly in the wings of the doped core where the fundamental mode is unable to extract sufficient gain. Only when $\frac{I}{I_{\text{sat}}} \gg 1$ over the entire doped region will stimulated emission dominate, leading to more efficient extraction of the inversion.

Numerical modelling of the above scenario (the explicit rate equations for this are available in the Appendix) for our fiber confirms this behaviour; Figure 4.4 plots the slope efficiency against the incident pump power (expressed here in terms of the number of times the incident pump power is above threshold) for operation on a Gaussian fundamental mode, and operation on a ‘top hat’ profile mode to approximate multimode operation. The top hat profile mode would naturally have a perfect overlap with the doped core, and as such its value of $\eta_{PL}$ is always 1, resulting in a constant slope efficiency of 39% for this particular fiber. The slope efficiency for the fundamental mode which is initially reduced by $\sim 0.75$, approaches this value at about 8 times above threshold. Considering that the threshold value for this fiber is $\sim 6W$, this would mean that
the laser does not achieve its optimum efficiency until it is pumped at a rather high value of $\sim 48\text{W}$.

Extrapolating further, we can speculate on the outcome of the same fiber laser with the first higher order LP(1,1) mode selected for operation. Since the overlap $\int r_0 s_0 dV$ of the LP(1,1) mode would be greater than the LP(0,1) case, the decrease in efficiency would be far less severe compared to the LP(0,1) case.
4.4 Experimental confirmation

The technique for mode selection in thulium doped fibers was successfully implemented and reported by group member Jae Daniel [10] using the fiber described in section 4.3.1, which had a core diameter of 22.5 microns, and a 300 micron diameter D-shaped silica cladding. This was diode-pumped at 790 nm. With this setup, he was able to produce a robust and stable, fundamental mode output beam with a good beam quality $M^2$ value of 1.05 at 1923, in contrast to an $M^2$ value of 3.3 for the same fiber laser without any mode selection. As further proof of the versatility of the technique, laser operation on higher order modes was also demonstrated by tuning the angle of the VBG (figure 4.5).

![Beam profiles and spectrum](image)

**Figure 4.5:** Lasing spectrum and beam profile for selected modes. Inset: The beam profile for a free-running, non-mode selected laser

Data courtesy of J. Daniel

Output power measurements made on the fiber for different operating conditions corroborate the simulated predictions that selecting a particular mode impairs the overall slope efficiency of the system; furthermore the selection of the LP(1,1) mode does, as speculated, show improved output power performance compared to the LP(0,1) mode (figure 4.6). These slope efficiencies are lower than predicted values due to a substantial core propagation loss introduced by the hydrogen loading process. This is highlighted in 4.6, which also features for comparison the slope efficiency for the same fiber without hydrogen loading.
Figure 4.6: Slope efficiencies for a free-running laser compared to an LP(0,1) selected, LP(1,1) selected laser, and a non-hydrogen loaded gain medium.

Data courtesy of J. Daniel

A hydrogen-loading rig is currently being developed that would enable selective loading of short sections of fiber. This would mean that any induced propagation loss would occur only in the sector of the fiber on which the grating is written, thus minimising the overall loss suffered by the fiber. Other plans and strategies have also been devised for further streamlining and optimisation of the experimental set-up with the aim of improving output power performance.

4.5 Prospects for further core scaling

In accordance to the current trends in fiber laser research, the next step forward would be to scale the core area to large mode sizes. In this section we examine the effects of having an increasingly larger core on a fiber laser utilising this technique, particularly with regards to the slope efficiency, the modal wavelength separation, and mode coupling.

4.5.1 Slope efficiency

In the section above it was shown that when a single mode is selected, the slope efficiency is reduced by a variable scaling factor related to the spatial overlap of the mode with the doped area, \( \eta_{PL} \). Enlarging the core area, with corresponding increases in cladding
area to maintain the core/cladding ratio and pump absorption properties, exacerbates this issue. The lower limit of $\eta_{PL}$ decreases with increasing core size, eventually rolling over for core sizes $>50$ microns. As a general rule for this fiber the optimum efficiency cannot be achieved until the laser is pumped to about 8-10 times the threshold value. For a 100 micron core diameter fiber, this represents a $\sim 50\%$ drop in slope efficiency when the laser is pumped close to threshold.

![Slope efficiency with pump power](image)

**Figure 4.7:** Calculated slope efficiencies with increasing core diameter

In the grand scheme of things, however, this effect is merely a deterioration of performance, and is not a major obstacle if good beam quality with robust pointing stability is valued above output power alone. This is especially true when we considering the meteoric rise in available pump powers as well as the relative ease of core-pumping with increasing core diameter.

### 4.5.2 Mode discrimination

For a given numerical aperture and doping profile, as the core size is increased, the spacing between the effective propagation constant for the modes supported by the fiber decreases. This corresponds to a reduction in the wavelength spacing between modes as given by Equation 4.1 for a constant grating period. Figure 4.8 depicts this spacing reduction for two lowest order modes. For our current specifications i.e. an operating linewidth of $<0.3$ nm for the VBG and $\sim 0.1$nm for the FBG, this limits our mode selection technique to a maximum core diameter of slightly more than 60 microns. This limit can be extended further to 70 microns simply by utilizing a VBG with a
Figure 4.8: The wavelength spacing between the LP(0,1) and LP(1,1) modes with increasing core diameter. The current resolution limit of our setup is shown in red dotted lines smaller linewidth, and beyond that with the usage of wavelength selective/narrowing optical components within the laser cavity such as etalons and birefringent filters, but eventually the mode spacing will be too small for robust mode selection.

4.5.3 Mode Coupling

Mode coupling describes the effect in which power in a mode is randomly coupled into some higher order mode due to various reasons such as irregularities in the fiber and micro (as well as macro) bending. It presents a serious potential setback for this technique in terms of power performance as well as degrading the purity (and beam quality) of the mode being selected.

Griebner et. al (1996) in their paper defined the upper limit for fiber lengths $l$ at which the effects of mode coupling were acceptable (from the criteria that the power content in higher order modes cannot exceed $1/e^2$), given by [11]

$$l < \frac{\lambda^2}{16D W_{core}^2}$$
where $W_{\text{core}}$ is the core diameter and the quantity $D$ is known as the mode-coupling coefficient. $D$ scales with core size as per the following [5]:

$$D \propto \frac{W_{\text{core}}^8}{W_{\text{cladding}}^6 \lambda^4} \quad (4.15)$$

where $W_{\text{cladding}}$ is the cladding diameter. For a fixed core-cladding ratio and wavelength, this implies that the maximum fiber length scales inversely to the fourth power of the core diameter

$$l \propto \frac{1}{16W_{\text{core}}^4}$$

Certainly, based on the experimental observations, the fiber exhibits little or no signs of mode coupling at its current dimensions. Without a measured value of $D$ it is difficult to comment or quantify the severity of mode coupling - what is known is that its probability increases with core size, and that it can be reduced by operating at a longer wavelengths (which highlights yet another advantage of using thulium as the rare-earth dopant) and shorter device lengths.

Using the parameters provided in [5] as a guideline, we calculated for a range of core diameters and a fixed core-to-cladding ratio, the maximum fiber lengths before mode-coupling effects become prohibitively large (Figure 4.9). For a 4 m length thulium fiber operating at 1930 nm such as ours, this limits core diameter scaling to about 70 $\mu$m.

**Figure 4.9:** The maximum fiber lengths for which mode coupling effects are acceptable for increasing core diameters up to 100 $\mu$m
4.6 Discussion and conclusion

An elegant and effective technique for mode selection in a thulium fiber laser was outlined and described analytically with laser rate equations. The impact of the technique on the laser performance was scrutinised, which revealed that the preferential operation of a single mode imposed a variable scaling factor $\eta_{PL}$ on the slope efficiency. The magnitude of this factor is highly dependent on the intracavity intensity relative to the saturation intensity $I_{sat}$ for a given transverse mode, $\eta_{PL}$ is lowest when the intensity is low (close to threshold), and approaches 1 as the intensity increases. $\eta_{PL}$ is also a function of the spatial overlap between the mode and the doped/inverted area, thus the slope efficiencies for modes with poorer overlap are more adversely affected than for modes with good overlap.

The technique was then implemented in a proof-of-principle experiment by J. Daniels. The key results from his work were quoted in section 4.4. While the feasibility of the technique was successfully proven, the system design was far from optimal, suffering from increased core propagation loss due to the hydrogen loading process as well as non-ideal reflectivity values from the FBG. Future work would involve minimising the core propagation loss by selective hydrogen loading and writing highly reflecting FBGs. The next stage for improvement would be to scale the core diameter with the aim of increasing the overall output power.

With that in mind, we discussed the possible obstacles which could hinder successful scaling of this technique to larger core diameters. While the effect of the $\eta_{PL}$ scaling factor becomes more pronounced with core area, the output power penalty it imposes is a small price to pay in the pursuit of good beam quality. A more crucial issue would be mode coupling. However, no evidence of mode coupling was observed in the proof of principle experiment, and without more information about the mode coupling coefficient of this particular fiber it is unwise to speculate about the severity of its effects with core area scaling. Ultimately, the decrease in mode spacing with core enlargement, coupled with the linewidth limits of our current optics set the limit of core diameter scaling to about 70 microns.

If the potential for this technique in CW lasers are exciting, its prospects for a pulsed laser system such as a Q-switched fiber laser is even more so. The implementation of this technique on thulium fibers with large mode areas and consequently high energy storage would lead to the generation of high energy, high brightness pulses in the eye-safe regime. With that end goal in mind, we begin an preliminary investigation into the dynamics of Q-switched thulium lasers in the following chapter.
Bibliography


Chapter 5

Q-switched Tm-Doped Fiber

5.1 Introduction

There are many applications in which pulsed laser output is preferred over CW, such as material processing (e.g., cutting, drilling, laser marking), pumping nonlinear frequency conversion devices, range finding, and remote sensing. A common method of achieving pulsed operation is by Q-switching, whereby the cavity Q is modulated to yield high energy, high peak power pulses.

Bulk laser technology is well established in this field; their large mode areas allow for high energy storage, while short resonator lengths are conducive for the generation of shorter pulses. The numbers are impressive, to say the least - for example 18 mJ pulses at 1 kHz repetition rates with a maximum average power of 64 W can be achieved by a single Q-switched thin disk laser oscillator [1]. Even more impressive results can be obtained if the solid state laser is cryogenically cooled. Researchers have demonstrated a Q-switched Yb:YAG laser which produces 114 W average power pulses with energies of 30 mJ for 5 kHz repetition rates. Moreover, there are a plethora of commercial pulsed laser products based on bulk solid state lasers emitting pulses with durations ranging from femtoseconds to nanoseconds and energies of up to hundreds of mJ.

Despite the dominance of bulk laser technology, high power Q-switched fibers have made significant headway in penetrating the pulsed laser market. This can be attributed to the fact that while most bulk Q-switched lasers are stable, robust and efficient, they suffer from the same failings as their CW counterparts, i.e. thermal effects (and the induced birefringence limit and stress damage limits associated with it), which hamper scaling average power. In many cases high powers and energy values are obtained at the expense of beam quality and stability.

Likewise the strengths of fiber architectures which are advantageous for CW operation still apply here- fibers offer compact solutions capable of emitting high brightness, good
beam quality output efficiently, with wavelength selection range, high wall-plug efficiency, excellent heat dissipation, and are well suited for operation at high repetition rates. Fiber based pulsed lasers (in general) are as flexible as bulk ones, offering options from low repetition rate nanosecond pulses to gigahertz repetition rate picoseconds with a range of pulse energies to suit the required application. Thus, despite the relatively modest power achievements to date, fiber lasers operating in the pulsed regime are still exciting and promising areas of research.

The initial concept of Q switching was first put forward by R. W. Hellwarth of the Hughes Aircraft Company in the early 1960’s [2]. Not long after, the idea was confirmed experimentally in collaboration with his colleagues with an optical ruby laser [3]. The renaissance of fiber lasers in the early 1980’s led naturally to the first demonstration of Q switching in fiber lasers [4]. Since then many notable advances were achieved, such as the demonstration of the first all-fiber Q-switched laser [5] and the first Q switched fiber ring laser [6].

At the time of writing, the highest recorded pulse energy was 27 mJ measured by Galvanauskas et. al [7]. In 2003, Y. Fan et.al. exploited stimulated Brillouin scattering in a pulsed pumped fiber laser to achieve 105 kW peak power (with 0.5 mJ pulse energies of 5 ns durations)[8]. While these outstanding high-power/energy results were obtained at the expense of beam quality, there were just as many reports which demonstrated that high energy operation of Q switched systems with good beam quality were feasible. An example of this would be the attainment of 1.21 mJ energy pulses with beam quality $M^2$ values of 1.1 [9]. More recent advancements in the arena include the demonstration of the first Tm-doped single frequency fiber laser [10], the first all-optical Q switched fiber laser [11], and a laser system boasting the shortest pulse durations for high repetition rates ranging from 100kHz to 1 MHz [12].

The technique outlined in the previous chapter could potentially be a viable route to power scaling of pulsed thulium lasers with good beam quality; before any experimental work is undertaken towards that goal, however, it is imperative that a greater understanding of Q-switched systems be gained through theoretical analysis and preliminary characterisation of a Q-switched thulium fiber laser.

## 5.2 General concepts of Q switching

Q-switching generally involves the use of a switching element to modulate the quality factor of a laser cavity. Initially, the cavity is pumped, with the switch set to induce high losses in the cavity and thus suppress lasing action. As such, the population inversion in the gain media increases and energy is stored therein. The cavity is then quickly switched to a low cavity loss state, and, beginning as noise from spontaneous emission, laser radiation within the cavity quickly builds up after numerous roundtrips, eventually
depleting the stored energy and resulting in the emission of a short, high peak power pulse. After that, the switch is reset to a high loss configuration and the process is repeated.

There are two main methods of Q switching, namely active Q switching and passive Q switching. In the former case, the operating parameters (frequency, opening time, etc) of the Q-switch are controlled externally; active Q switches can be mechanical devices such as choppers, shutters and turning mirrors, or electronic modulators such as Acousto-Optic or Electro-Optic modulators (abbreviated as AOM and EOM respectively). Passive Q switching (or self-Q switching), on the other hand, involves the use of a saturable absorber to automatically modulate the losses in the cavity. The pulse forms as soon as the stored energy is sufficiently high. All the Q-switched pulse work in this thesis has been done using active Q switching to allow greater flexibility and control over the behaviour of the laser system.

### 5.2.1 Point model for solid state lasers

#### Cavity rate equations

Traditionally, the point model has been utilised, with great success, to describe Q-switching behaviour in solid state laser systems. While the travelling-wave model (which will be discussed in Chapter 6) is more appropriate for numerical simulation of Q switched fibers, the point model still proves useful as a foundational analytical tool for understanding the physics behind Q switching processes. As such this *entire* subsection (5.2.1) is devoted to a recapitulation of the work done by J. Degnan and W. Koechner [13, 14].

The rate equations describing the evolution of the photon and population inversion density within the cavity can be written as follows:
\[
\frac{ds}{dt} = s(\sigma_e n \frac{l}{L} - \epsilon) \tag{5.1}
\]
\[
\frac{dn}{dt} = -\gamma n s \sigma_e c \tag{5.2}
\]

where

\begin{itemize}
  \item \( s \) = photon density
  \item \( n \) = population inversion density
  \item \( t_r \) = round trip time
  \item \( l \) = active material length
  \item \( L \) = resonator length
  \item \( \gamma \) = inversion reduction factor
  \item \( \sigma_e \) = emission cross section
\end{itemize}

The second term in the brackets of equation 5.1 is actually an expression for the photon lifetime or photon decay time, \( t_c = \frac{l}{2} \). \( \gamma \) is known as the inversion reduction factor, which shows the reduction in the population inversion from a single photon emitted via stimulated emission. A full treatment of this factor is given in the appendix of the paper by Degnan et. al [14], but in essence, it covers for relaxation within multiplet states or sub-levels and accounts for the Boltzmann equilibrium population densities of the upper and lower laser levels. In the case of Nd:YAG, for example, this inversion reduction factor takes the approximate value of \( \gamma \approx 2 \). In the case of thulium:YAG, this is ~1.04. [15] gives a simple definition of \( \gamma \) as \( \gamma = 1 + \frac{\sigma_{as}}{\sigma_{es}} \) where \( \sigma_{as} \) and \( \sigma_{es} \) are the absorption and emission cross sections of the upper laser level.

\( \epsilon \) here describes the total losses in the cavity, and can be written thus:

\[
\epsilon = -\ln(R) + \delta + \xi(t)
\]

The first term arises due to output coupling losses, determined by the reflectivity of the output coupling mirror, R. The second term includes all general cavity losses (absorption, diffraction, scattering). \( \xi(t) \) is the time dependent cavity loss introduced by the Q switch - occasionally, the Q-switching is done so rapidly that the population inversion does not change significantly during the switching process. When that is the case, \( \xi(t) \) can be approximated by a step function.

By numerically solving equations 5.1 and 5.2 we are able to simulate the behaviour of the inversion and the build-up behaviour of a typical single Q switch pulse in time (Figure 5.1). Because lasing action (which would ordinarily deplete the gain) is initially
suppressed by the low $Q$ of the cavity, the population inversion builds up to a steady-state peak value. Upon $Q$ switching the cavity to high $Q$, the photon flux in the cavity begins to build up from noise, eventually reaching a peak value $\phi_{\text{max}}$ when the population inversion reaches the threshold population inversion. The population inversion, having been depleted by the pulse, decays to the final value $n_f$ while the photon flux decays to noise level. If the system is repetitively $Q$ switched after a certain recovery time (which is dependent on pumping rate) the population inversion will once again accumulate and the cycle repeats.

**Energy storage and extraction efficiencies**

Based on the foundational rate equations (5.1 and 5.2), we can write an expression (the derivation of this can be found in the appendix of the paper by Degnan) for the predicted laser output energy:

$$E_{\text{out}} = \frac{h\nu A}{2\sigma_e \gamma} \ln\left(\frac{1}{R}\right) \ln\left(\frac{n_i}{n_f}\right)$$  \hspace{1cm} (5.4)

where $h\nu$ is the laser photon energy and $A$ is the effective beam cross-sectional area.

The final and initial population inversion densities just before and after $Q$ switching, $n_i$ and $n_f$, are related by the transcendental equation

$$n_i - n_f = n_t \ln\left(\frac{n_i}{n_f}\right)$$  \hspace{1cm} (5.5)

where $n_t$ is the threshold population inversion density given by

$$n_t = \frac{1}{2\sigma_e \gamma} (\ln\frac{1}{R} + \delta)$$  \hspace{1cm} (5.6)
The useful stored energy in the gain medium is

\[ E_{\text{stored}} = \frac{V \hbar n_i}{\gamma} \]  

(5.7)

where \( V \) is the active gain volume. The extraction efficiency, which by definition is \( E_{\text{out}}/E_{\text{stored}} \), then becomes

\[ \eta_E = \frac{1}{2 \ln i \sigma_e \ln \left( \frac{1}{R} \right) \ln \left( \frac{n_i}{n_f} \right)} \]  

(5.8)

**Output peak power and pulse duration**

The output peak power can be expressed as

\[ P_{\text{max}} = \frac{A \hbar \nu}{\gamma t_r} \ln \left( \frac{1}{R} \right) \left( n_i - n_t \left[ 1 + \ln \left( \frac{n_i}{n_f} \right) \right] \right) \]  

(5.9)

If we make the approximation that the output pulse shape is an asymmetric triangle (of baseline width \( t_b \), area \( E_{\text{out}} \) and height \( P_{\text{max}} \), then we can estimate the pulse width \( t_p \) as

\[ t_p \approx E_{\text{out}} P_{\text{max}} = t_c \frac{(n_i - n_f)}{n_i - n_t \left[ 1 + \ln \left( \frac{n_i}{n_f} \right) \right]} \]  

(5.10)

**Repetitive Operation under Continuous pumping**

For a repetition rate \( f \), the maximum time available for inversion to build up between pulses is \( \frac{1}{f} \) so the population inversion varies cyclically as per:

\[ n_i = n_\infty - (n_\infty - n_f) \exp \left( - \frac{1}{\tau_f f} \right) \]  

(5.11)

where \( n_\infty \) is the (asymptotic) population inversion at equilibrium. For low enough repetition rates \( \frac{1}{f} \geq \tau_f \), the cavity can be pumped to population inversions approaching \( n_\infty \), whereas for higher rep rates \( \frac{1}{f} \leq \tau_f \) the initial inversion will be reduced, resulting in less gain for the fiber and consequently smaller pulse energies and peak powers.

Using relations 5.1, 5.2 and 5.11 and spectroscopic data from [16], the pulse energy is modelled for a 4m length fiber pumped at 15 W for different repetition rates. This is then compared with measured experimental data in section 5.3.3, figure 6.8.
Assumptions

Many Q-switched solid state laser systems of interest have relatively short pulse durations; as such, spontaneous emission and optical pumping has been neglected in the rate equation 5.2. Also, all the above expressions were derived with spatially averaged photon density and population inversion densities, e.g. \( s(t) = \frac{1}{V} \int s(x, y, z, t) dV \), where \( V \) is the resonator volume occupied by the photons. This translates to the approximation that the laser field intensity along the resonator and in the transverse direction is uniform, which remains valid if the laser field is relatively invariant over a cavity round-trip time, and if the losses due to output coupling are not overly high [17].

5.2.2 Limitations of power scaling (non-linear effects, thermal effects, facet damage, etc)

The constraints to power scaling in fibers are more severe in Q-switched laser systems due to the high peak powers and intensities achieved. This is particularly the case for nonlinear effects such as SBS and SRS. For a Tm fiber with specifications as per Chapter 4, we calculated the thresholds for SBS and SRS using equations 2.3, 2.4 and ?? . The predicted critical thresholds are 340 kW and 26 kW for SBS and SRS respectively. The high threshold value for SBS is probably a result of the relatively broad spectral linewidth obtainable from the VBG. The point model predicts that even while operating at medium pump powers (e.g. 15 W), for low rep rates such as 4 kHz the pulse peak power is in excess of of several kilowatts (~2 kW), and as such SRS is the more imminent threat to high peak power operation.

In the previous subsection an expression was given for the useful stored energy within a gain medium. However, only a portion of this stored energy can be extracted, which is dependent on the saturation energy of the gain medium

\[
E_{\text{sat}} \approx \frac{Ah\nu}{(\sigma_e + \sigma_a)\Gamma_k}
\]

where

\[
\Gamma_k = \text{Overlap factor of signal with doped area}
\]

The maximum extractable energy is

\[
E_{\text{max}} = E_{\text{sat}} \cdot ln(G)
\]

where

\[
G = \text{small signal gain}
\]
It is a generally accepted rule of thumb, based on experimental observation, that the maximum extractable energy is approximately 10 times the saturation energy \[18\]. In our case, for 1930 nm wavelength operation, the extractable energy is capped at 1.3 mJ. Past this point, the stored energy is rapidly drained by the onset of ASE and parasitic lasing, and further pumping becomes increasingly inefficient.

The fourth constraint is bulk or surface damage, as described in Section 2.3.2 of Chapter 2. Applying the limits set by 2.5 and 2.6 to our thulium fiber which has a 22.5 \( \mu \)m diameter core, gives either a pulse energy limit of \( \sim 0.6 \) mJ or a peak power limit of 380 kW.

To avoid surface damage issues, the fiber is spliced with coreless silica end-caps (of appropriate diameter and length to avoid distortions to the output beam and to facilitate efficient pump coupling). This expands the output beam, decreasing the fluence at the air/silica interface. Depending on the level of feedback required these end-caps can then be flat or angle-cleaved.

5.3 Q switched Thulium-doped fiber

In this section we study and characterise a Q-switched thulium-doped fiber laser using a fiber identical to the one used in Chapter 4.

This experimental exercise not only provides insight into the behaviour of a slightly multimode Q-switched thulium switched laser, but also provides benchmark/reference performance indicators which will be used as a basis for comparison with predicted results for the Q-switched mode selected thulium doped fiber.

5.3.1 Performance benchmarks

The experimental setup

Figure shows the configuration of the Q-switched laser. 4.5 m of thulium doped fiber identical in specification to the one used in the preceding chapter (i.e. 22.5 and 300 micron core and cladding diameter) was diode-pumped at 790 nm. However, unlike the previous set-up, the fiber was end-capped using a coreless 380 micron diameter silica fiber which was then angle-cleaved as a preventative measure against facet damage as well as further suppressing feedback from the fiber end facets.
Feedback for oscillation was provided by a VBG on the non-pumped end of the cavity (which enforces lasing at 1930 nm wavelength) and retroreflection off a glass wedge on the pumped end of the cavity. The glass wedge is used to provide variable feedback via alignment.

Modulation of the cavity Q factor was achieved by using an electro-optic Q switch, i.e. a Pockels cell. The standard practice for half-wave operation of the Pockels cell is to place the Pockels cell in between two crossed polarisers, (see figure 5.2). When no voltage is applied to the Pockels cell, i.e. the cell is in an “off” state, incident linearly polarised light from the first polariser is transmitted through the inactive Pockels cell unaffected, then exits the cavity via the rejected port of the second polariser. This creates a large loss and thus a low Q value for the cavity. To create a high-Q state, the Pockels cell is switched on at a specific half-wave voltage such that it induces a $\lambda/2$ retardation on the beam, rotating its polarisation by $90^\circ$. In this state the light sees a high transmission through the second cavity, likewise the retroreflected beam will see very little loss. Thus the external cavity provides high feedback (and consequently a high Q value) to the fiber.

We chose a Quantum Technology RT-4 Pockels cell comprising two Rubidium Titanyl Phosphate (RTP) crystals, coated with anti-reflection coatings at 2 $\mu$m. RTP crystals have an operating optical bandwidth from 400 nm to 2500nm, which is more than adequate for our wavelength range of operation. RTP crystals also have high damage thresholds (an essential requirement given the peak powers we hope to achieve), high electrical resistivity, low electro-chromism, and has lower requirements for operating voltages, e.g. the half-wave voltage of an RTP crystal is almost half that of a BBO (Beta barium borate) crystal of similar dimensions. Unlike BBO and KD*P (Potassium Dihydrogen Phosphate), which are popular materials for Pockels cells, RTP is not hygroscopic, and thus does not require a sealed environment. In addition, this particular Pockels cell had a clear aperture of 4 mm, which was convenient for free-space optical alignment.

**Figure 5.2:** The experimental setup
However, RTP crystals are by nature biaxial, i.e. they possess some natural birefringence. To compensate for this (and to lower the operating voltage of the Pockels cell) they are often used in matched length pairs such that the “fast” ray in one crystal becomes the “slow” ray in the next one, and vice versa, thus cancelling out any static birefringence in the composite crystal pair. However, it is nontrivial for manufacturers to achieve perfect matching, and even in the best case scenario, optical absorption (however small) may induce localised heating within the crystals, which may affect the compensation of the two crystals. In general, some residual birefringence in RTP Q-switches is fairly common.

This residual birefringence is present in our Q switch. Preliminary optical measurements of the Mueller matrix of the Pockels cell (in an inactive state) at 1930 nm yielded the following:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 0.98 & 2.1 \times 10^{-8} & 0.16 \\
0 & 2.1 \times 10^{-8} & 1 & 2.5 \times 10^{-7} \\
0 & 0.162 & -2.5 \times 10^{-8} & 0.98
\end{pmatrix}
\]

these values approach those of an identity matrix (i.e. the matrix of an optical component which has no effect on the polarisation of the transmitted beam):

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\]

Further calculation yields an effective retardation of approximately 0.16 rads/9.3° or 0.02λ.

In practice, this slight birefringence reduces the isolation of the polariser-Pockels cell-polariser configuration during the “off” or low-Q phase. Measurements indicate a single-pass transmission of 1.62% and consequently an isolation of approximately 35.8 dB. This is a reasonable, albeit non-optimal value, since a higher isolation would result in a higher parasitic lasing threshold, better holdoff, and increased energy storage in the cavity.

Figure 5.3 shows the transmission of the crossed polarisers plus Pockels cell arrangement with increasing voltage being applied to the Pockels cell. As a result of this measurement we ascertained the half wave voltage (the voltage at which the transmission was maximum, i.e. 100%) to be ~2.8 kV.
5.3.2 Isolated measurement of pulse energies

In our set-up and indeed in any strongly pumped high gain system such as Q-switched fiber lasers in general, parasitic lasing in between the pulses is significant, particularly at low repetition rates, which could cast doubt on the reliability and accuracy of pulse energy measurements and data. In particular, the common simplification that the pulse energy is simply the quotient of the average power over the repetition rate is certainly no longer valid.

Thus, it was imperative to implement an improved measurement system that would distinguish between power in the actual Q-switched pulse and any power arising from parasitic lasing or ASE. Because of the extremely high peak powers involved, the output from the pulse laser requires heavy attenuation before being measured on a photodetector to avoid damaging the detector. The implication of this is that any pre- and post-pulse lasing/ASE is often buried in the noise level, making it nontrivial to extract any useful information from oscilloscope traces on its own.

Our measurement system involved using an acousto-optic modulator (AOM), model number M111-2J-AV1, as a gate that would transmit only either the main Q-switched pulse, or signal between the Q-switched pulses (figure 5.4). In the former case, the AOM driver is triggered by the same signal generator as the Q switch driver, and the AOM diffracts the (attenuated) beam to the first order onto a photodetector in sync with the opening of the Q switch. Once the Q-switched pulse is transmitted, the AOM is switched off again, and the beam reverts to the zeroth order and is dumped. This operating procedure is then inverted, with the attenuation removed to allow transmission of signals in-between pulses (referred to throughout this chapter as “noise”). The two
oscilloscope traces are then appropriately scaled relative to each other then integrated with respect to the average power (measured by a power meter) to give values of pulse energy and peak power.

Figure 5.4: Pulse energy measurement setup, illustrating how any portion of the laser signal in time can be measured in isolation depending on the shape of the signal driving the AOM.

5.3.3 Results and discussions

Pulse energy considerations

Figure 5.5 shows the measured values of pulse energy at 1930 nm wavelength for a given pump power over a range of repetition rates. The highest pulse energy recorded for this system was \(312 \mu J\), with a corresponding peak power of 12.3 kW.

Figure 5.5: Pulse energy repetition rates for pumping at 15, 23, 30 and 43 W.
It can be seen that for moderate pump powers greater than 23 W, as the repetition rate decreases to 10 kHz and below, first ASE then parasitic lasing/spiking begin to deplete the stored energy in the gain medium, causing a rollover in the pulse energy. At even higher pump levels of 30-40 W, the pre-pulse spiking for low repetition rates is intense enough to deplete a significant amount of the stored gain, cause a severe reduction in the output pulse energy. This ASE+parasitic lasing “noise” actually accounts for a significant percentage of the measured average power; the increasing of this “noise” energy to the pulse energy with decreasing repetition rate is plotted in figure 5.6 b).

![Signal-noise ratio vs Repetition Rate](image)

![Inter-pulse signal at 4kHz](image)

**Figure 5.6:** a) Signal-noise ratio vs repetition rate. b) A time-averaged oscilloscope trace of the inter-pulse signal for 4 kHz repetition rate at 43 W pump power. The onset of spiking/spurious lasing behaviour can be observed at ~47 microseconds.

A typical oscilloscope trace the inter-pulse behaviour for the fiber pumped at 43 W and operated at a 4 kHz repetition rate is shown in figure 5.5b. After a pulse depletes the gain in the system, the cavity is reverted to an “off” or low-Q state. The gain medium however, is being continuously pumped, so the population inversion gradually builds up again. This cavity recovery time is of the order of 10µs. Beyond that, the threshold for ASE is reached. Eventually the gain is comparable to the losses in the cavity and
spurious/parasitic lasing or spiking begins to occur. All these detrimental processes cap the energy being stored in the system, resulting in a reduced initial population inversion for the Q-switched pulse.

There are various loss mechanisms at play here which are also instrumental in reducing the output pulse energies. Aside from the inevitable feedback coupling losses on both ends of the cavity, the most significant loss arises from the fact that the gain fiber in this particular set up is not a polarisation-maintaining (PM) one. Consequently, even though light being fed back from the far external cavity is linearly polarised, by the time it has made a double pass through the fiber it would have been scrambled, resulting in randomly polarised output. As a result, approximately 50% of the light exiting the fiber on the far end is dumped/rejected/lost at the first polariser. Not only does this incur a loss of at least ~50% on the pulse per pass, but it also imposes a limit as to the amount of feedback achievable in that far external cavity. Comparative measurements of the CW slope efficiency of this set-up (with the addition of a half waveplate placed between the crossed polarisers) versus a setup with just a VBG in the external cavity yields a ballpark figure of ~15% net feedback efficiency in this crossed-polariser external cavity. Using a PM fiber would certainly improve this value, however none were available to us at the time.

To improve the pulse energies we intentionally misaligned the feedback wedge at the pumped end of the fiber to raise the threshold for spurious/parasitic lasing. According to slope efficiency measurements, the effective feedback at that pumped end of the fiber was reduced to ~0.01%.
Comparison of pulse energies for well aligned and misaligned feedback

![Graph showing comparison of pulse energies](image)

**Figure 5.7:** Comparison of the pulse energy vs repetition rate behaviour for well-aligned feedback and misaligned front feedback.

This dramatically improved the performance of the system, yielding a maximum pulse energy of $618 \mu J$ and a corresponding peak power of 23 kW. A comparison of the pulse energy versus repetition rate behaviour at 2 different pump powers for the well aligned and the misaligned feedback configuration is shown in figure 5.7. While the former configuration clearly exhibits a rollover at lower repetition rates, this rollover is less obvious for the latter case.

Figure 5.8 shows the inter-pulse oscilloscope trace for this configuration. In accordance to our expectation of a raised threshold for ASE, we can see that the ASE build-up time for the cavity in this setup has increased to $\sim 30 \mu s$. However, the noise level has also increased significantly - this is mostly related to Rigrod’s expression of inverse powers, whereby reducing the feedback of the pumped end of the system increases the proportion of output-coupled power from it. Conversely, though, this also means that a smaller portion of the pulse energy is lost at the first polariser. For example, when the fiber was pumped at 40 Amps and Q switched at a repetition rate of 6 kHz, only 0.64 W (average power) was lost at the first polariser for the reduced feedback configuration, compared to 2.43 W average power measured with the well aligned feedback configuration.
Pulse shape

In the traditional point model, and indeed in actual solid-state crystalline Q switched lasers, the expected output is usually a single, almost Gaussian pulse. This seems to be the case for repetition rates > 60 kHz. However, for lower repetition rates we observed instead multiple peaked output. These peaks were of different heights and were evenly spaced in time. Figure 5.9 illustrates the output pulse shapes for increasing repetition rate for the laser pumped at 15 W.

Closer examination of the figures allow us to glean few general insights into the multi-peak pulsing phenomena - one of the most striking features is the fact that the sub-pulses are separated by a cavity-round-trip time, which in this particular case is about 50 ns. This could imply either that there is some mode-locking occurring in the cavity, or that the effect arises from the pulse making multiple passes through the system. A second noticable characteristic is that the number of peaks (and therefore the width of the pulse envelope) is related to the repetition rate, suggesting that gain saturation/depletion effects play a key role in determining the shape of the pulse. This multipeak phenomena is actually not uncommon for fiber lasers and will be modelled and discussed in greater depth and detail in the proceeding chapter.

Temporal considerations

There are two main factors which affect the pulse-to-pulse stability : spurious lasing and non-linear effects. We observed that for medium to low-repetition rate operation
(20 kHz–4 kHz) in regimes where no spurious lasing is taking place, the pulse shapes are stable in time, with less than 5% peak power jitter and timing jitter < 5 ns.

Upon the onset of parasitic lasing, however, the pulses suffer some variations in terms of pulse shape, buildup time, and peak power. These instabilities can be accounted for by the fact that the spurious lasing, which manifests as sporadic and unstable pulses, significantly changes the initial population inversion and therefore the available gain for each pulse cycle by different amounts.
Figure 5.10 shows two measured pulse shapes corresponding to two different scenarios observed in the oscilloscope traces. Pulse shape 1 in red is the normal, semi-stable pulse shape. Sporadic and spurious lasing can affect the pulse behaviour, manifesting in changes in peak height or build-up time; despite this, the pulse still maintains its characteristic round-trip-time separation between sub-pulses. Occasionally, however, pulses such as pulse 2 occur, which breaks the regularity in terms of sub-pulse separation. A pronounced dip is observed (i) which looks as if a normal pulse like pulse 1 has had power coupled away from it. Another interesting feature is the uncharacteristically narrow and high-peak power pulse emitted just after the first one. The origin of these random peaks is unknown at present and would make an interesting subject for further study.

**Theoretical predictions**

We have already seen that the point model falls short when it comes to simulating the output pulse shape. It does not fare any better when it comes to predicting the pulse energies with respect to varying repetition rate, plotted in Figure 5.11. The point model consistently predicts a higher energy than is observed experimentally. This can be attributed to the various assumptions and simplifications involved in deriving the model, especially the assumption that the population inversion is uniform along the
Chapter 5 Q-switched Tm-Doped Fiber

Modelled and Experimental results for pulse energy vs repetition rate pumped at 15 W

![Graph showing pulse energy vs repetition rate](image)

**Figure 5.11:** Comparison between experimental and predicted data for the Q-switched laser operated at various repetition rates and pumped at 15 W

fiber, which, for a system with low output coupling and high loss such as ours, is clearly not going to hold.

It is clear that the dynamics of Q-switching in a fiber are far more complex than the framework of the point model allows for. Therefore an alternative numerical model is needed, both to explain the multipeak behaviour of the output pulses, and also to facilitate the simulation of the effects of the mode-selection technique on a Q switched system. In the following chapter we outline a kinetic model to simulate the dynamics of a Q switch laser and present preliminary proof-of-principle results of a method for ameliorating the multipeak behaviour.
Bibliography


Chapter 6

Single, short ASE pulse generation in Q-switched Tm-doped fiber lasers

6.1 Introduction

Since the first demonstration of Q-switched fiber lasers, many published results in the field report a structured, multiple-peak output pulse shape for a wide range of operating parameters [1–4]. The (solid state) point model had not predicted these features, so many theories were put forward to try to account for this behaviour. An early publication speculated that the multi-peak phenomenon arose due to “an interplay between the mode beats, present at a low light intensity at the beginning of pulse evolution”, stabilized by the Kerr lens effect or self-focussing [3]. Another group, which observed multi-peak properties as a result of a frequency shift in the cavity, attributed it to mode locking [5]. These hypotheses were contradicted by other papers in which multi-peaked output was recorded even for low intensity regimes, in which nonlinear effects are minimal [6], as well as in configurations where no frequency shift was applied to the cavity.

Numerical simulations by [4, 7, 8] eventually provided a greater understanding about the origin and the dynamics of this multi-peak phenomena. It was shown that the multiple peaks were the result of multi-pass amplification of the initial transient pulse generated from noise upon Q-switching.

Many industrial applications such as machining, range-finding, and OTDR require single-pulse output. These multi-peak pulse outputs are therefore far from ideal. While it is perfectly possible to use pulse-selective elements to isolate a single pulse out of the multiple peaks, this would be done at the expense of the energy contained in the other discarded peaks and would require complex synchronous controls.
Wang et al. [9], in another paper on the subject of the multi-peak phenomena, suggested several methods of mitigating this effect, including manipulating the switching and opening time of the Q switch, careful choice of pumping powers and dual switching, whereby ASE pulses are generated at both ends of the cavity to nullify each other. It turns out that the former strategy is only effective for certain operating regimes (further discussion of this will be made in section 6.2.2) and is, at best, a pulse-smoothening technique. The latter method, while considerably more successfully, requires not one but 2 Q switches with controlled triggering, which increases the complexity and the cavity loss in the system.

In the following section we will examine the travelling wave model, which provides the framework for numerical simulation of the Q switched thulium laser. The model is then used to simulate the initiation and generation of multi-peaked pulses, and its resultant output compared to experimental data from the previous chapter. We then propose a technique for obtaining single-pulse nanosecond operation in thulium lasers via regenerative amplification, supported with numerically simulated results. A proof-of-principle experiment was then conducted, in which we were successful in generating a single pulse with a pulse width of 13 ns for a range of repetition rates, with a maximum peak power of 1.2 kW for a corresponding pulse energy of $\sim 22\mu J$. Some discussion will then be made about the possible sources of loss in the current configuration and the best way forward to realise the full potential of this novel method.

6.2 Kinetic simulation of a Q-switched Tm-doped fiber laser

In this section we examine the travelling-wave model used by [4, 7, 9], appropriately adapted for quasi-three-level thulium doped lasers.

![Figure 6.1: A simplified reference laser cavity](image)

Figure 6.1 is a schematic of a simplified laser cavity, for which the rate equations (c.f. Chapter 4) are expressed as follows:
\[ N_b(z, t + \Delta t) = N_b(z, t) + \left( \frac{\Gamma_p \lambda_p}{hcA} \sigma_{ap} \lambda_p N_a(z, t) - \sigma_{ep} \lambda_p N_b(z, t) \right) P_p(z, t) \]
\[ + \sum_k \frac{\Gamma_k \lambda_k}{hcA} \left[ \sigma_{ak} \lambda_k N_a(z, t) - \sigma_{ek} \lambda_k N_b(z, t) \right] \cdot (P^+_{k}(z, t) + P^-_{k}(z, t)) \]
\[ - \frac{(N_b - N_b^0)}{\tau_2} \Delta t \]

\[ P_p(z + \Delta z, t + \Delta t) = P_p(z, t) - \alpha_p P_p(z, t) \]
\[ + \Gamma_p(\sigma_{ep} N_b(z, t) - \sigma_{ap} N_a(z, t)) P_p(z, t) \Delta z \]
\[ P^\pm_k(z + \Delta z, t + \Delta t) = P^\pm_k(z, t) - \alpha_k P^\pm_k(z, t) \Delta z \]
\[ + 2 \Gamma_k N_b(z, t) \sigma_{ek} hc^2 \frac{\Delta \lambda_k}{\lambda_k^3} \Delta z \]
\[ + \Gamma_k(\sigma_{ek} N_b(z, t) - \sigma_{ak} N_a(z, t)) P^\pm_k(z, t) \]
\[ for \; k = 1..K \]

where as per Chapter 4, \( N_b, N_a \) represents the population density of the upper laser and ground level respectively. \( \Delta z \) and \( \Delta t \) are finite steps along the length of the fiber and in time respectively. \( P_p \) denotes the single pass pump power in the forward direction - we assume that the end-caps provide little or no reflection of the pump power. \( P^\pm_k \) is the forward and backward propagating signal power in the \( k \)th channel, with a total number of \( K \) channels in the laser spectrum. We assign one of these channels \( k = s \) to be our main signal channel at 1932 nm. \( \Gamma_p(\Gamma_k) \) is the overlap factor between the pump (the signal) and the doped area of the core and \( \alpha_p, \alpha_k \) are the attenuation coefficients of the pump and signal. The \( N_b^0 \) term in the latter part of 6.1 is the correction for quasi three level behaviour as per the derivation from in Chapter 4 equation X. \( \sigma_{ek}, \sigma_{ak} \) are the emission and absorption cross sections at the wavelength of the channel \( k, \lambda_k \), and likewise \( \sigma_{ep}, \sigma_{ap} \) are the emission and absorption cross sections of the pump.

In order to evaluate the rate equations numerically, some initial boundary conditions consistent with the experimental setup in Chapter 5 need to be applied:

\[ P^+_{k}(0, t) = P^-_{k}(0, t) [R_1(\lambda_k) \cdot \eta_1 + R_{facet}] \]
\[ P^-_{k}(l, t) = P^+_{k}(l, t) [R_{vbg}(\lambda_k) \cdot \eta_2(t) + R_{facet}] \]

\( R_{facet} \), the residual reflectivity due to Fresnel reflection off the fiber end-caps is assumed to be less than \( 1 \times 10^{-5} \). \( R_1 \) in this case is the reflectivity at the pumped end of the fiber (or position \( z = 0 \)). In our experiment we used a 4% blank wedge, therefore \( R \) is fixed at this value. \( \eta_1 \), the feedback coupling efficiency, can then be varied between 0-1 to simulate how well aligned this blank wedge is for feedback. Similarly, \( R_{vbg}(\lambda_k) \) is the reflectivity of the VBG in the external cavity at the non-pumped end of the
fiber (or position $z = l$). According to the manufacturers’ specification, $R_{\text{vbg}} > 99\%$ at 1932nm operating wavelength and $R_{\text{vbg}} \simeq 0$ for any other wavelength when used as a retroreflector.

The feedback coupling efficiency for the VBG, $\eta_2(t)$, changes in time to simulate the behaviour of the Q-switch, i.e. $\eta_2(t)$ is low when the Q switch is inactive and high when the Q switch is turned on. In other words, when the Q switch is switched on, the feedback $\eta_2(t)$ is high, and the cavity is in a high-Q state. When the Q switch is off, the feedback $\eta_2(t)$ is low, and the the cavity is in a low-Q state. In general $\eta_2(t)$ encompasses not only the losses introduced by the Q switch, but also the cumulative transmission and alignment-related losses through the numerous optical elements in the external cavity.

Equations 6.1 to 6.3 were numerically integrated using Matlab.

### 6.2.1 Pulse Formation Dynamics

Because the aim of this modelling is to facilitate a greater understanding of the initiation and formation of pulses in a thulium Q-switched fiber lasers, nonlinear effects have been neglected. For similar reasons, we shall begin our study the cavity dynamics for a simple and basic setup, operated at 40 kHz repetition rate, with the fiber length $l = 2\, \text{m}$, $R_1 = 0.01$, $R_2 = 1$ and $\eta_2(t)$ varies from 0 to 1 over a rise time $t_{\text{rise}}$. Background (broadband) ASE is neglected and thus only the channel at the VBG’s peak reflectivity is considered.

Initially, the laser is in a steady state, with very low forward-propagating ASE output and most of the backward-propagating noise/ASE power being dumped out of the cavity. The opening of the Q switch changes the feedback coupling efficiency $\eta_2(t)$ of the external cavity, resulting in an increasing amount of noise power being injected into the cavity (Figure 6.2 b), injecting an ASE wave in the forward propagating direction.
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The evolution of this ASE wave is explained via figures (6.3-6.6). The left half of the figures shows the output coupled power (i.e. the shape of the output pulse), while the right hand side shows the small signal gain at each point along the fiber, superimposed with the spatial distribution of the signal light in the forward and backward directions.

Once injected into the fiber cavity, the ASE wave travels forwards, being amplified as it does so. A portion of this wave is output coupled while the rest of it is backreflected into the gain medium and propagates in the backward direction (Figure 6.3).

After several round trips we can see that the output pulse has a step shape. Thus far, each round trip only depletes the gain by small amounts (Figure 6.4).
Eventually, however, the leading edge of the travelling wave is of such high power that it significantly depletes the cavity gain as it propagates within the cavity, leading to reduced amplification of the trailing edge (Figure 6.5). At this point the output-coupled shape is no longer a step but a narrow peak which rises steeply then decays sharply.

Subsequent round trips result in more narrow peaks of diminishing height with a fast decay being output coupled. Meanwhile the internal travelling wave weakens with each
subsequent reflection and eventually becomes negligible. This is seen in Figure 6.6, and
the inset image shows the overall pulse shape plotted on a linear scale.

![Figure 6.6: Output pulse shape, small signal gain and spatial distribution after nu-
merous passes. Inset: The linear pulse shape.](image)

Reducing the repetition rate (or increasing the pump power) would have two-fold effect
- firstly, it could increase the initial background ASE in the steady-state when the Q
switch is off. Secondly, it would increase the amount of gain available within the fiber.
The sum of the two effects (higher intensity and higher gain) means that the gain will be
depleted more rapidly compared to the 40 kHz case. Figure 6.7 shows the logarithmic
output pulse shape for a repetition rate of 10 kHz. The difference is clear - the output
shape after the first pass is not a square step as per the 40 kHz pulse, but has already
undergone gain steepening. Due to this fast depletion, the output power rises and decays
quickly within 4-5 round trips.

![Figure 6.7: Output pulse shape for 4 kHz repetition rate](image)

### 6.2.2 Pulse shape considerations

We then appropriated the reflectivity parameters to reflect our actual Q-switched setup
and compared the simulated pulse shapes with measured data in figure 6.8. The sim-
ulated results show reasonable agreement with experimental data. There are of course
inevitable discrepancies such as differences in peak heights, number of peaks, pulse en-
ergy and build up time (differences in build up time however have been offset in these
graphs to improve clarity), which is possibly due to the usage of inaccurate spectroscopic parameters. The spectroscopic properties of thulium vary with dopant and co-dopant concentrations and the parameters we used for simulation were based on cross-section measurements taken from a different thulium fiber.

These modelled pulses confirm the observations made in the previous chapter and the preceding section: the number of peaks (and correspondingly the pulse width) is a function of repetition rate because the repetition rate determines the amount of time over which inversion can build up and consequently the amount of gain in the cavity. The lower the repetition rate, the greater the amount of single-pass gain seen by the travelling wave and the greater its amplification. Thus, after just several round trips the power in the travelling wave is sufficient to deplete the gain. This manifests as fast pulse build-up time (several round trips) and a small number of high power peaks.

Conversely, for a high repetition rate the inversion and thus the gain is reduced; the travelling wave has a smaller effect on the gain per pass, requiring more round trips before the gain is significantly depleted. Figure 6.9 contrasts the pulse shapes and single pass gain levels for two different repetition rates. Note the increase in build up time. The fact that a higher initial gain results in a lower final gain value is consistent with the equation laid out in the previous chapter.

By extension, for a given repetition rate, a pulse generated at a higher pump power will be narrower, and contain less peaks compared to a pulse generated at a low pump power due to the different gain levels for the two scenarios.
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The steepness of the leading edge is a product of the relatively quick rise time of our Q-switch (in our case, 15 ns). Increasing this value arbitrarily would smoothen the pulse, giving the illusion of a single pulse when operating at high repetition rates as we can see in figure 6.10. Thus the problem of multiple peaks is less apparent in Q-switched systems with slow rise time modulators such as AOMs. However, far from alleviating the problem, the slow rise time merely obscures its effects. If the system were operated at a lower repetition rates (i.e. in a higher gain regime) a slow rise time would have less impact on the pulse shape and the multiple peak structure would still remain. Thus not only is slowing the rise time ineffective as a means of generating a single pulse, but it incurs a penalty in terms of output pulse energies due to the losses associated with an extended switching time. In our example the pulse energy for 8 kHz has dropped by 15%.

One could argue that a trivial solution to this problem would simply be to use a shorter length of fiber such that the round trip time is less than or comparable to the opening time of the Q switch. This would have the additional benefit of a high threshold for non-linear effects. An extreme example of this would be solid state/bulk lasers, which generally have cavity lengths shorter than an average fiber laser and as such do not suffer from this multiple peak pulse train phenomena. However, using excessively short fiber
lengths would defeat the purpose of using a fiber in the first place. Additionally, it is generally true that unless core pumping is used, a shortened fiber length would result in poorer pump absorption and consequently lower available gain for a given pump power.

6.2.3 Wavelength considerations

An interesting implication of this numerical simulation is that the pulse is seeded from ASE/noise that is injected into the cavity during the initial opening of the Q-switch. In the high repetition rate regime where this transient noise wave makes tens or even hundreds of cavity round trips, the cavity has sufficient time over which to form self-consistent laser modes. However, in the low repetition rate regime, the pulse would have depleted the gain and have significant power output-coupled after only several round trips, which may not be sufficient for mode formation—this suggests that the pulsed output is not actually a laser pulse, but an ASE pulse.

We attempted to investigate this experimentally by replacing the VBG in our Q-switched set-up (Chapter 5 Figure 5.2, with the front mirror misaligned) with a HR mirror and examining the spectrum of the emitted pulse with increasing repetition rate as well as with increasing pump power. Figure 6.12 a) shows the logarithmic spectra at 16 W pumping power for increasing repetition rates. (This particular pumping level was chosen as it was below the threshold for spurious lasing in between pulses). It can be seen that as the repetition rate increases, the pulse spectrum evolves from broadband ASE, gradually steepening and narrowing until the onset of lasing (20 kHz and above).

The small peaks on the spectrum for 4 kHz originates from a very weak transmission etalon effect from a (currently unidentified) optical element in the external cavity, possibly within the RTP Pockels cell itself. We check this by comparing the spectrum of ASE light transmitted through the polariser-RTP-crossed polariser (figure 5.2) when the Pockels cell is switched on and off. When the Q switch is off, the low-level transmitted light was found to have a strongly modulated spectrum (Figure 6.11). However, as we increase the current to the Q switch, the transmission through the polariser-RTP-polariser component increases, and this low-level modulation becomes insignificant compared to the large ASE background being transmitted by the polariser-RTP-crossed polariser component. When the Pockels cell is fully switched on for a 50% duty cycle at 50 kHz repetition rate, the transmitted light (attenuated to avoid damaging the monochromator) has a relatively smooth broadband ASE spectrum (blue curve in Figure 6.11).
While the feedback from the external cavity during the low Q state is very low, it is non-negligible; thus the external cavity seeds the fiber with this low-level modulated ASE, which is amplified along the fiber and results in an output spectrum such as 6.12a). As the Q switch opens, the spectrum of the light being fed back would thus evolve from a modulated spectrum to a smooth broadband spectrum.

The effects of inter-pulse spurious lasing is examined in 6.12b), which shows the spectra of both the pulse and the forward-propagating noise (defined as per Chapter 5 as the inter-pulse signals) at increasing pumping powers for a constant repetition rate of 4 kHz. At 16 W, consistent with 6.12a), both the pulse and the noise consist of broadband ASE. However at 19 W we can see that one mode at 1948 nm seems to emerge (in contrast to a), where the peaks are almost uniformly amplified in a transient phase between ASE and lasing). As the pump power continues to increase different wavelengths compete for gain. Increasing the pump power also causes the signal-to-noise ratio to decrease as the growing amount of spurious lasing and ASE reduces the available inversion for pulsing. Eventually at 37 W, the amount of power contained in the spurious lasing is comparable, if not larger than the actual pulse itself, which is in good agreement with the observations in Chapter 5.

Note that the peaks for the pulse signal almost always correspond to that of the noise, confirming that it is indeed being seeded by the noise. However it is also worth noting that there is still a significant ASE background in the pulse spectra. This suggests that the pulse is seeded by and therefore consists of a combination of both parasitic lasing and ASE.

As a further contrast, we examine the spectra of the system operated at 37 W pumping power for 4 and 40 kHz repetition rate in figure 6.12 c). Despite the fact that there are strong lasing peaks in the 4 kHz (light blue) spectrum, there is still some background ASE
present, whereas in the 40 kHz (dark blue) regime there is virtually no ASE background. Moreover, if the peaks in the 40 kHz spectrum were simply the amplified peaks from the modulated ASE spectrum, they would occur at the same wavelengths as the 4 kHz situation. The fact that they do not imply that they are in fact lasing modes.

The chief implication of these spectral data is that at low enough repetition rates such that the pulse only makes several \( \leq 20 \) round-trips through the cavity, the set-up is in actual fact a Q-switched pulsed ASE source and not a pulsed laser source.

In an optimal Q-switched ASE setup without any spectral modulation due to internal etalons or spurious lasing, the output pulse at low repetition rates would have a smooth broadband wavelength spectrum. Additionally, this spectrum would be temporally stable due to the lack of mode competition normally present in lasers. These two features would make such Q switched sources highly attractive for applications which require low-coherence pulsed sources.
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a) b) c)

Figure 6.12: Pulse spectral evolution for a) Increasing repetition rate, for constant pumping at 16 W b) Increasing pump power at 4 kHz repetition rate. The blue curves show the output spectra while the red curves show the inter-pulse ‘noise’. c) A comparison of the pulse spectra for 4 and 40 kHz repetition rate at 37 W pumping power.
6.2.4 Beam Profile Considerations

That the Q switched source produces ASE output rather than lasing at low repetition rates has interesting effects on the output beam profile. Figure 6.13 exhibits the beam profile for the four different operation parameters, namely pumped at 16W and 39 W and switched at repetition rates of 4 and 60 kHz. While the there is not much difference in the beam quality for these two repetition rates, measured to be ~2.6 and ~2.2 respectively, their spatial profiles are distinct. The beam profiles at 60 kHz have a high-intensity region at the bottom right corner of the beam, whereas the intensity is more evenly spread for the 4kHz, particularly when pumped at 39 W. Their behaviour of the beams are dissimilar as well - The output beam at 60 kHz is unstable and sensitive to perturbation, while at 4 kHz the beam is stable, even when the fiber is perturbed. These are characteristics of multimode lasing and ASE respectively, and is consistent with behaviour observed in Chapter 3.

![Beam profile for 4 kHz and 60 kHz repetition rate for 16 W and 39 W pump powers respectively](image)

Figure 6.13: Beam profile for 4 kHz and 60 kHz repetition rate for 16 W and 39 W pump powers respectively
6.3 Novel technique for single pulse generation in Tm-doped fibers

6.3.1 Concept

As mentioned in the introduction, in many cases a single-pulsed output is preferred over one with multiple peaks. This is particularly the case if the source is used to seed amplifier chains, as the uneven amplification of the multi-peak pulse train may further distort the pulse shape. A few methods of rectifying this have been mentioned thus far, including careful choice of pump power and modulator rise time (which we have shown in the previous section to be ineffective for lower repetition rate and for further amplification), shortening the cavity length and dual switching. In this section we put forward a scheme for obtaining single-pulse output in Q-switched fiber sources based on the concept of regenerative amplification and cavity dumping.

Regenerative Amplification

Regenerative amplification, in essence, involves seeding a pulse into a high-gain optical resonator and releasing it after it has made a certain number of round trips. This technique, most commonly used in solid state amplifiers and typically seeded with mode-locked lasers, yields high gain and consequently high pulse energies and peak powers. However, fiber-based regenerative amplifiers have also been reported, such as the first all-fiber-based regenerative amplifier in a single-mode Er:silica fiber [10], as well as a PCF-based regenerative amplifier which attained a gain of 69dB, the highest gain achieved in such an amplifier at the time [11].

Cavity Dumping

Cavity dumping on the other hand is less relevant to optical amplification; rather, it is usually classified as a method of achieving Q-switch modulation. It was originally conceived as a means of achieving shorter pulse durations in Q switched bulk lasers operating at higher repetition rate as well as a preventative measure against pulse dropout. Crucially, the main difference between cavity dumping and conventional Q-switching is the use of highly reflecting mirrors instead of output coupling mirrors. Instead, output coupling is achieved either with the Q switch itself or with some external modulator.

The operating principles for cavity dumping are fairly similar to that of a normal Q switched laser - initially the cavity is kept in a low Q state, usually by introducing some form of output coupling or cavity loss. The cavity Q is then raised. However, since the cavity mirrors are highly reflective, the pulse is trapped within the cavity until coupled
out (by the Q switch or modulator). In most cases the output pulses are dependent on (and are of the order of) the cavity length and, unlike their conventional Q-switched counterparts, show little dependence on the repetition rate.

The chief requirements for efficient cavity dumping is that the rise time for the modulator is very short, i.e. $t_{\text{rise}} \ll t_r$ and for the intracavity loss to be low, lest the generated pulse become less energetic with each subsequent round trip.

One of the earlier experiments on cavity dumping in fiber lasers was, incidentally, published by the Optoelectronics Research Centre here in Southampton [12]. Since then most of the work in the field has been focused on novel methods of achieving cavity dumping (e.g. [13]), culminating in an all-fiber cavity dumping system in 2009 [14].

### 6.3.2 Numerical Modelling

Cavity dumping and regenerative amplification are fairly similar in that they both involve confining the pulse within the optical cavity for a number of round trips. As the work in the preceding section has shown, the multi-peak phenomena arises chiefly from the multipass output coupling of the pulse and is shaped by gain depletion effects within the fiber. It follows, then, that the prevention of output coupling until the gain has been sufficiently depleted would result in a single peak pulse. Further extrapolation of the findings from the earlier part of this chapter predicts that the pulse would also have a broad ASE spectrum as well as a stable beam profile.

This concept was tested numerically in the model derived in Section 6.2 by changing the reflectivity of the pumped end to $R_1 = 1$ and taking the output from the non-pumped end instead. A comparison of the simulated output pulse shape with experimental data is shown in Figure 6.15.

Another requirement for efficient cavity dumping mentioned was for the cavity loss to remain low. Unfortunately, due to rather large polarisation losses detailed in Chapter 5, our experimental set-up is far from ideal. Figure 6.14 shows the pulse energy and peak power versus opening time (in terms of number of round trips for simplicity) for a cavity with 50% cavity loss. We can see that the optimal opening time is 6 round trip times, below which the pulse is unable to extract sufficient gain and beyond which the pulse energy is greatly depleted per pass.
Peak power and pulse energy with number of round trips

Figure 6.14: Peak power and pulse energy vs number of round trips before the pulse exits the cavity

6.3.3 Proof-of-Principle experiment

Having ascertained that the concept is sound via numerical calculations, we endeavoured to verify this experimentally, using the same setup as before (Figure 5.2). It is testament to the simplicity of the concept that this was achieved merely by replacing the 4% feedback wedge at the pumped end of the fiber and the VBG with HR mirrors, and using the rejected port of the second polariser as the output coupler. The operating procedure would remain essentially the same - during the low Q phase, most of the noise power being generated by the fiber will be removed from the cavity via the output coupler. During the brief high Q phase, the Pockels cell is switched, rotating the polarisation state of the light thus increasing transmission through the second polariser and decreasing the amount rejected. The pulse is thus confined within the cavity until the Pockels cell is switched off again and it is able to exit the cavity.
We were successful in obtaining a single pulse shape with pulse widths $\lesssim 14$ ns for 4 to 100 kHz repetition rates, as shown in Figure 6.15a. The highest pulse energy measured was $\sim 20\mu$J, with a corresponding peak power of 1.2 kW for a Q-switch opening time of about 250 ns. The low pulse energies arose from the fact that quite a large proportion of the pulse energy was lost per round trip through the rejected port of Polariser 1. To highlight the severity of this loss, a plot of the pulse energies at the output and the rejected port for operation at 20 kHz repetition rate with increasing pump power was plotted in Figure 6.15b. In calculating the pulse energies we have assumed that the contribution from ASE or spurious lasing in-between pulses to the measured average power is insignificant, justifiable with signal-noise measurements shown in Chapter 5 which show high signal-to-noise ratios for that repetition rate.

The use of 2 HR mirrors reduced the threshold for parasitic lasing, which proved to be a hindrance, disrupting the stability of the pulse formation for pumping powers greater than 20 W. As such the results reported in this section are limited to pumping powers below 20 W. Another limitation was the opening time of this particular Q-switch - the shortest amount of time we could maintain the high-Q phase was 192 ns, which was more than 3 round trips.

The output beam profile, displayed in Figure 6.16a, is, as predicted, stable even when the fiber is perturbed. Another confirmation of our predicted pulse characteristics was with regard to the wavelength spectrum of the output pulse, which was a smooth, broadband ASE in the absence of spurious lasing. Examining the spectrum with increasing pump power, we can see that at very low pumping powers the spectrum contains large dips, indicating that it is still subject to the weak ‘etalon’ effect in the external cavity. As
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the pumping power increases, however, this effect becomes less significant, and at 19 W we eventually get an ideal, smooth spectrum. Beyond 19 W, however, spiking and spurious lasing begin to take effect and this is reflected in the peaks in the output spectrum. However we note that there is still significant power in the ASE component of the spectrum.

Unfortunately, experimental work was brought to an abrupt and premature end when the pumped facet of the fiber suffered catastrophic damage. This is surprising and unfortunate, given that at the time we were attempting to make measurements for 4 kHz operation at 19 W, which we speculate resulted in internal circulating peak powers in the range of 25 kW. This is comparable to values measured in Chapter 5 (which the fiber had previously withstood) and well below our estimated power damage threshold of 350 kW. Time and funding constraints rendered the option of preparing another facet unfeasible, and thus, having successfully proved the validity of our approach to achieving a single pulsed Q-switched ASE source, the exercise was brought to a close.

6.4 Discussion and future work

A proof of principle experiment was successfully carried out that showed the potential of this setup for generating single-pulsed Q switched ASE sources. However, the optical
configuration and cavity design is far from optimal. One of the crucial problems with our current configuration is the massive cavity loss induced per round trip due to polarisation losses. This can be rectified by the use of a PM fiber, or by using a Q switch or modulator which has no reliance on the polarisation state of the pulse. Another area which requires improvement is the holdoff of the cavity during the low Q stage. This too can be enhanced by using a Q switch which would provide superior isolation, and thus raise the threshold for spurious lasing. In the event that relatively small cavity losses are unavoidable, the choice of opening time would involve some trade-off between having sufficient round trips for efficient gain extraction and minimising the number of round trips to reduce the severity of the loss.

Future experimental exercises on single-ASE-pulse generation will be carried out by another member of the group, using a different fiber with a larger core diameter (which would not only increase energy storage, but also suppress parasitic lasing to a higher threshold value) and a superior performance Q switch with the aim to push the boundaries in terms of pulse energies and peak powers, demonstrating the potential of this technique and its potential for commercial and industrial applications.

In pursuing single-pulse output we had temporarily put aside our goal of achieving mode-selected Q-switched thulium-doped lasers. This work will hopefully be taken up in the near future by another colleague within the research group. We are confident that with a suitable Q switch, the combination of both techniques would result in an elegant and efficient method of achieving fundamental mode, single-pulse ASE output.
Bibliography


Chapter 7

Conclusions

The work done in this project has been in pursuit of power scaling fiber lasers and amplifiers through mode area scaling. Its findings and progress have been recorded here in this thesis. The context and motivations for the project were explained in the introductory chapter, expounding on the history and main advantages of fibers in general.

Chapter 2 contains a brief examination of the spectroscopic properties of ytterbium and thulium doped fibers, citing the unique characteristics which have contributed to the enterprise of power scaling. In the case of ytterbium, these are the wide wavelength range and high values of its absorption and emission cross sections, the long lifetime of its metastable energy level, and the large energy separation between the pump and laser wavelength with any other energy levels.

Like ytterbium, thulium also boasts a wide emission spectrum. One of its absorption bands conveniently fall in the 1550–1750 nm range, which overlaps with the emission range of Er-doped fiber lasers. This allows for in-band pumping and consequently high slope efficiencies. The chief attraction of thulium, however, is its long emission wavelength near the 2 micron regime - in addition to being eye-safe, this longer wavelength enables thulium doped fibers to be scaled to larger core areas than the equivalent ytterbium fiber while maintaining single-mode operation.

The attainment of high output power is usually achieved within the context of other criteria such as slope efficiency, beam quality and threshold for cw lasers, and pulse energy, duration and peak power for pulsed lasers. General and simplified expressions for these are presented for completeness. We then looked at the various critical limitations to power scaling, such as nonlinear effects, damage, and thermal effects. Having considered these issues we then reviewed the various techniques used in literature to address these obstacles, such as mode area scaling, photonic crystal fibers, and beam combinations.
In Chapter 3 we discussed the phenomena of multimode interference, something that fiber laser engineers certainly need to be wary of, pointing out the ineffectiveness of using $M^2$ values as an indicator of the modal content of the fiber. Since as clearly demonstrated in our experiments good values of $M^2$ (as low as 1.16) could be obtained even in the active presence of higher order modes through self-imaging. The severity of the beam pointing and quality instability arising from MMI was highlighted by measuring the coupling efficiency from our multimode fiber into a single-mode fiber. The drastic change in the coupling efficiency from 70% to 4% shows that MMI is not to be taken lightly. From this vantage point, it is perhaps more advantageous to use fiber ASE sources instead of laser sources as amplifier seeds, since ASE sources are immune to the ill effects of MMI.

The tantalising prospect of harnessing MMI for self mode selection in an oscillator, however, eluded us, as we failed to improve the beam quality from an $M^2$ of 1.8 to any value lower than 1.4. Another group eventually published the results of their endeavours on a similar concept, and the idea was put on hold in favour of pursuing other methods for transverse mode selection.

An alternative method for mode selection was consequently undertaken, researched and presented in Chapter 4, which exploited the mode-dependent spectral response of the reflectivity of FBGs. We considered the potential scalability of the technique, with particular emphasis on whether or not the poorer spatial overlap resulting from purely fundamental mode operation in a multimode fiber would strongly affect fiber performance, measured in terms of its slope efficiency. Hearteningly, it was found (for this fiber, at least) that as long as the mode selected laser was operated at greater than 8 times above threshold, its slope efficiency would be similar to the slope efficiency of the same laser without mode selection (modelled with a hypothetical top hat mode profile). We predict that this technique is scalable to core diameters of up to 60 $\mu$m before the modal separation of the fiber becomes too small to be resolved by our wavelength selection methods.

The technique was then realised experimentally in collaboration with colleague Jae Daniel, in which fundamental mode operation of a multimode thulium fiber was successfully attained, with an excellent $M^2$ value of 1.05 compared to 3.3 for a free-running laser. Operation on higher order modes by wavelength tuning of the laser were also demonstrated.

Encouraged by the evident success and potential of the mode selection technique, the next step was to translate this technique to enable mode-selection in Q-switched pulsed lasers. To lay the groundwork for this, the point model, obtained from literature, was used in Chapter 5 to describe the Q switching mechanism, and benchmarking and characterisation experiments of thulium doped Q switched fibers were subsequently undertaken. The maximum pulse energy measured from this thulium Q-switched laser was
∼ 618 µJ, with a corresponding peak power of 23 kW. A comparison between the obtained experimental data and predictions of the point model in terms of both the pulse energies and shape quickly revealed a discrepancy. Not only had the point model over-stated the expected output pulse energies with varying repetition rates, but it failed to account for the observed pulse shape, which featured multiple peaks separated by a round trip time.

Deeming this curious multipeak behaviour worthy of closer scrutiny, in Chapter 6 we used a kinetic numerical model to simulate the laser behaviour during Q-switching. We found that the multiple peaks in the output pulse originate from the initial transient ASE wave injected into the laser each time the Q-switch is switched. Having gained a better understanding of the multipeak formation mechanism, we put forward a novel technique for generating single, short ASE pulses in Q-switched Tm-doped fiber lasers through regenerative amplification. Simulations of this technique predict very high peak powers, easily reaching kilowatt levels, and short pulse widths in the range of 10-13 ns. This was proven experimentally with the attainment of single pulses for repetition rates of 4 to 100 kHz, albeit with poor output pulse energies (the maximum energy measured was 20 µJ, with a peak power of a mere 1.5 kW) due to non-optimal components. The measured pulse shapes and broadband spectra, however, served as sufficient proof of the validity, viability, and potential of this technique.

7.1 Future work and prospects

As mentioned above and in Chapter 3 itself, we were unsuccessful in attaining self mode selection from our fiber ring cavity. Nonetheless we remain convinced of the soundness of the concept and its potential for generating some novel and interesting results with modifications to the actual experimental execution of the concept.

At the time of writing, we had not, due to time constraints, been able to actually implement the mode selection technique of Chapter 4 on Q-switched thulium doped fibers. This task will probably be delegated to the successor of this project. Upon successful demonstration of the technique, it should follow naturally that the technique be implemented along with regenerative amplification such that the output pulses are not only single mode, but also singly peaked.

There are also plans for future experiments on the topic of single-ASE-pulse generation, using a fiber with a larger core diameter and an improved Q switch, leading to a more optimised cavity. Such enhancements to the experimental setup should vastly improve the resultant pulse energies and peak powers.

Over the past two decades, the output powers from fiber lasers and amplifiers have improved by leaps and bounds. While this trend is set to continue in the medium term,
there are those who predict that the limits of single-fiber output powers are in sight, and that eventually all high power systems will involve beam combination of multiple sources. While we have no doubt that the issues addressed in this body of work will be relevant even for beam combination schemes, it is hoped that the findings of this thesis would serve to inject some optimism into that outlook. Our results has shown that there is still plenty of potential and scope for novel and exciting techniques that can serve to advance the field. There are as yet many potentially groundbreaking concepts related to mode scaling that have not been thoroughly explored and optimised.

Considering how far fiber devices have come in the past two decades and the many advances made in the field in recent times, we are convinced that the future of power-scaled fiber lasers and amplifiers is very bright indeed.
Appendix A

The explicit rate equations for numerical modelling of the thulium-doped fiber are similar in essence to the ones presented above, but formed differently with different designations and radial coordinates, to facilitate programming into Maple and Matlab. Descriptions of the parameters used, if not in the text, are located in table 7.1.

For a quasi 3 level system such as thulium in a cavity set up as above (figure 4.3), the population densities of 3 levels are important, namely the population density of the ground level \(N_0(r, \phi, z)\), the upper pumping level \(N_3(r, \phi, z)\), and the upper laser level \(N_2(r, \phi, z)\), which are related to the total population density \(N_t\) as follows:

\[ N_0 = N_t - N_3 - N_2 \]

For simplicity we assume that the lifetime of the pump level is very short such that any excitation is immediately transferred to the upper laser level, i.e. \(N_3 = 0\) and omit the effects of ASE for the time being. We can then write

\[
\frac{d}{dt} N_2 = \psi_s(r, z)(N_0 \sigma_{as} - N_2 \sigma_{es}) - \frac{N_2 - N_0}{\tau_2} + N_0 \sigma_{ap} \psi_p(r, z)
\]

\[
\frac{d}{dz} P_p = \int_0^{d_{core}} (-N_0 \sigma_{ap}) \psi_p h \nu_p r dr d\phi
\]

\[
\frac{d}{dz} P_s^+ = \int_0^{d_{core}} (N_2 \sigma_{es} - N_0 \sigma_{as}) \psi_s^+ h \nu_s r dr d\phi
\]

\[
\frac{d}{dz} P_s^- = -\int_0^{d_{core}} (N_2 \sigma_{es} - N_0 \sigma_{as}) \psi_s^- h \nu_s r dr d\phi
\]
where $P_p(z)$ is the pump power, $P_s^+(z)$ is the forward propagating signal and $P_s^-(z)$ is the backward propagating signal at position $z$ along the fiber. The boundary conditions for this system is

$$P_s^+(0) = P_s^-(0)R_1$$
$$P_s^-(l) = P_s^+(l)R_2$$

where $R_1$ is the reflectivity of the mirror at position $z = 0$ and $R_2$ is the reflectivity of the mirror at position $z = l$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Definition or value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>Planck’s constant</td>
<td>6.63E-34</td>
</tr>
<tr>
<td>$\nu_p$</td>
<td>Pump frequency</td>
<td>3.797E+23</td>
</tr>
<tr>
<td>$\nu_s$</td>
<td>Signal frequency</td>
<td>1.559E+14</td>
</tr>
<tr>
<td>$\sigma_{es}, \sigma_{as}$</td>
<td>Signal emission and absorption cross section</td>
<td>3.5E-25, 3.221E-26</td>
</tr>
<tr>
<td>$\sigma_{ap}$</td>
<td>Pump absorption cross section</td>
<td>8e-25</td>
</tr>
<tr>
<td>$\psi_p$</td>
<td>Intensity distribution of pump</td>
<td>$\frac{P_p(z)\mu(r)}{h\nu_p}$</td>
</tr>
<tr>
<td>$\psi_\pm_s$</td>
<td>Intensity distribution of forward/backward propagating signal</td>
<td>$\frac{P_\pm_s(z)\mu(r)}{h\nu_p}$</td>
</tr>
<tr>
<td>$i_p(r)$</td>
<td>Normalised pump intensity distribution</td>
<td>$\frac{1}{\pi d_{clad}^2}$</td>
</tr>
<tr>
<td>$i_s(r)$</td>
<td>Normalised signal intensity distribution*</td>
<td>$\begin{cases} Top\ hat : &amp; \frac{1}{\pi d_{core}^2} \ LP(0,1) : &amp; \frac{V}{\omega} e^{\frac{-Vr^2}{\omega^2}} \end{cases}$</td>
</tr>
<tr>
<td>$d_{core}, d_{clad}$</td>
<td>Core, cladding radius</td>
<td>11.25$\mu$m, 300$\mu$m</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Fundamental mode radius</td>
<td>8.25$\mu$m</td>
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</table>

**Table 7.1:** List of parameters for numerical modelling of CW Tm-doped mode-selected fiber laser

*We have used gaussian approximations for the intensity distribution of the LP(0,1) mode as a simplification.
List of Publications

Journals


International Conferences


