UNIVERSITY OF SOUTHAMPTON

High-Power Diode-Pumped Solid-State 2 Micron Lasers

by

R.A. Hayward

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ABSTRACT
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Brightness scaling of diode-bar end-pumped solid-state lasers producing efficient output radiation in the 2 μm wavelength region is investigated. Problems and strategies for power scaling diode-bar end-pumped lasers in the 2μm region are also discussed.

Thermal lens measurements on Tm$^{3+}$:YAG and Tm$^{3+}$:(Lu,Y)AG were made. Thermal lens dependency on resonator loss is observed and attributed to heating from upconversion.

High-power room-temperature diode-bar end-pumped Tm$^{3+}$:YAG lasers were developed. Efficient high power operation of the Tm$^{3+}$:YAG laser producing 14.2W of output power at 2.013μm for 53.4W of incident pump power is demonstrated with $M^2$ values of 1.3 in orthogonal planes. The laser was then linearly polarised and compared with a similar laser using a scheme to compensate for the loss caused by thermally induced de-polarisation. Before the de-polarisation loss prevented lasing operation an output power of 8.4W was observed. Using the compensation scheme, the laser produced 11.5W of output power and was limited by pump power. The uncompensated de-polarisation loss was >5% reducing to <0.4% for the compensated laser.

A high power Tm$^{3+}$:(Lu,Y)AG laser producing 18W of output power at 2.022μm was demonstrated and compared with a Tm$^{3+}$:YAG laser.

High-power intracavity pumped Ho$^{3+}$:YAG lasers were developed. A collinearly intracavity pumped Ho$^{3+}$:YAG laser producing 8.4W of output power is demonstrated though application of the brightness scaling strategy was difficult to implement. A non-collinearly intracavity pumped laser showing 1.6W of output power is reported but showed alignment instability and was hard to replicate. Intracavity pumping schemes are discussed.

A Tm$^{3+}$:silica fibre laser produced 14.2W of output at 1.98μm for 38.3W of launched pump power with a slope efficiency of ~36%. This was the highest reported power from a Tm$^{3+}$:silica fibre laser to the authors knowledge. A tunable Tm$^{3+}$ fibre laser showed > 1.8W output power across a tuned wavelength range of 1870-2030 nm.
To Clare and my Parents
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Preface

The eventual aim of this work was to develop high power lasers suitable for use as lidar sources. The route investigated to this aim was to power scale a range of 2µm lasers that provide a path to a compact, efficient, long range, eye-safe 2µm lidar. This aim runs through all of the laser experiments presented here and is directed towards efficiently pumping Ho\(^{3+}:\text{YAG}\). Ho\(^{3+}:\text{YAG}\) has a suitable wavelength for atmospheric transmission and has a long upper laser level lifetime \(\sim 8\text{ms}\) which are favourable attributes for a high pulse energy \(Q\)-switched laser and subsequent lidar. These factors provide the potential for long range doppler lidar source as the range is dependent on the pulse energy. The difficulty with the Ho\(^{3+}:\text{YAG}\) material has been to efficiently pump the \(5I_7\) level. Current diode lasers operating at 1.9µm are low power devices and so poorly suited for developing a high power Ho\(^{3+}:\text{YAG}\) laser. The absorption in Ho\(^{3+}:\text{YAG}\) is weak for direct pumping from a Tm\(^{3+}:\text{YAG}\) laser therefore as an alternative co-doping Tm\(^{3+}\) with Ho\(^{3+}\) in hosts was researched. This has provided a route to high power cw lasers but unfortunately co-doping offers inter-ionic transitions out of the \(5I_7\) level reducing the energy storage.

In this work there are two main routes that have been investigated:-

One route starts with the development of an efficient high power, high brightness Tm\(^{3+}:\text{YAG}\) laser end-pumped by high power diode-bars. There are several strategies to power scaling diode-bar end-pumped lasers and this is discussed in this work. The problems faced in laser experiment design are discussed and primarily involve the handling of the thermal effects of high power pumping with diode-bars. Lasers emitting in the 2µm wavelength region open several more strategies and this is discussed. The high power Tm\(^{3+}:\text{YAG}\) laser is then taken as a platform to de-
velop an intracavity pumped Ho\textsuperscript{3+}:YAG laser where the Ho\textsuperscript{3+}:YAG laser rod is pumped within the Tm\textsuperscript{3+}:YAG laser cavity where the high intracavity powers offset the weak Ho\textsuperscript{3+}:YAG absorption at 2.013\textmu m. The intracavity pumping scheme offers the advantages of separating the Tm\textsuperscript{3+} and Ho\textsuperscript{3+} hosts to prevent the problems of co-doping and pumping Ho\textsuperscript{3+}:YAG on the weak absorption with the high intracavity powers. The obvious disadvantage is that to repetitively Q-switch the Ho\textsuperscript{3+}:YAG laser, then the Tm\textsuperscript{3+}:YAG laser must be separated or de-coupled in some way. The power scaling of simple intracavity pumped lasers is described in this work and then some of the de-coupling schemes are discussed.

The other route investigated is a hybrid fibre-bulk laser approach. A power scaled Tm\textsuperscript{3+}:silica fibre laser directly pumping the 1.9\textmu m absorption in Ho\textsuperscript{3+}:YAG firstly requires a high power fibre source. A high power cw double-clad Tm\textsuperscript{3+}:silica fibre laser is developed and experimented upon in this work and these experiments result in the highest power Tm\textsuperscript{3+} fibre laser yet reported. A tunable Tm\textsuperscript{3+}:silica fibre laser is also developed though not optimised. The tunability of the fibre laser is attractive as it allows selection of the optimum pumping wavelength for Ho\textsuperscript{3+}:YAG around 1.9\textmu m. Unfortunately, due to time constraints this laser was not used to pump Ho\textsuperscript{3+}:YAG which as has been discussed here was one of the aims. The geometry of the fibre laser sidesteps many of the thermal problems of pumping the bulk laser media. The distributed, small volume of the fibre core allows excellent heat dissipation whilst the beam quality and hence preservation of brightness is defined by the core laser mode. A high power Tm\textsuperscript{3+}:silica fibre laser is of interest as a source on its own and this is pointed to in the further work section of this thesis.

Another potential lidar source is investigated by the power scaling of a Tm\textsuperscript{3+}:(Lu,Y)AG laser. Some preliminary spectroscopy and thermal lensing measurements were conducted and a comparison with Tm\textsuperscript{3+}:YAG carried out. The materials attraction is the slightly longer emission wavelength at 2.022\textmu m which is the wavelength that Tm\textsuperscript{3+}:YAG lidars are tuned to for the advantageous atmospheric transmission. The experiments carried out in this work indicate a Tm\textsuperscript{3+}:(Lu,Y)AG lidar source would still be of interest.

One route which was not investigated in this work was a power scaled Tm\textsuperscript{3+}:YLF
laser pumping a Ho\textsuperscript{3+}:YAG laser. YLF was once seen as a poor candidate for power scaling as it is susceptible to fracture. However this route has since been shown to be an excellent means to a high power and high efficiency Ho\textsuperscript{3+}:YAG laser and uses the relatively large absorption in Ho\textsuperscript{3+}:YAG at 1.91 \textmu m. This will be discussed in later chapters.

It is to some extent unfortunate that all of the lasers demonstrated in this thesis are all cw lasers as the earlier stated aim has been to develop a source suitable for lidar. However constraints on time meant that none have been developed into pulsed lasers in this work. It is hoped that this preface has given the reader some background to the eventual aims of the work presented here and the context and direction with which these laser experiments were conducted. Many of the highest cw power laser yet reported to the authors knowledge have been demonstrated during the work in this thesis including the highest power intracavity pumped Ho\textsuperscript{3+}:YAG lasers, Tm\textsuperscript{3+}: (Lu,Y)AG laser and Tm\textsuperscript{3+}:silica fibre laser and the author was grateful for being in the privileged position to be able to power scale a range of laser systems and to compare them. It is hoped that the work in this thesis has built a good platform for further work in several areas.
Acknowledgements

During the course of this research project I have been helped by many people. I am very thankful for their help, tolerance and encouragement through the four years I spent at the Optoelectronics Research Centre (ORC).

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And finally but most importantly, Clare. Thank you for your help, support, vital encouragement, sacrificing x many years of weekends and just being there for me during the years of this work. I love you dearly.
The voyage of discovery is not in seeking new landscapes,

but in having new eyes.

Marcel Proust
Chapter 1

Introduction

The laser has been a solution to many problems unforeseen when it was first demonstrated by T.H. Maiman [Maiman60]. The role that the laser has played in scientific research cannot be underestimated and the consequences to technology affecting everyday lives are equally impressive. There has been a race between the lasers developed and the applications demanding them. So why are we still researching lasers today? Because there are so many more applications that we might envisage and equally more lasers that might bring new applications. This work investigates a variety of solid-state laser sources producing high-power output in the wavelength region 1.9 – 2.1μm.

1.1 Why High-Power Diode-Bar End-Pumped 2μm Lasers?

The motivations for research into high-power 2μm laser sources stem from a few particular qualities and the effect these properties have on different applications.

1. *Eye-safety*: wavelengths from ~1.4μm → 2.2μm are classed as eye-safe as radiation of these wavelengths incident on the human eye is absorbed in the front part of the eye instead of passing through to be focussed and damaging the retina. Common high power sources at 1μm (for example Nd³⁺:YAG laser
1.1 Why High-Power Diode-Bar End-Pumped 2μm Lasers?

<table>
<thead>
<tr>
<th>Material</th>
<th>Lifetime (ms)</th>
<th>Wavelength μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yb(^{3+}):YAG</td>
<td>0.95</td>
<td>1.030</td>
</tr>
<tr>
<td>Nd(^{3+}):YAG</td>
<td>0.23</td>
<td>1.064</td>
</tr>
<tr>
<td>Nd(^{3+}):YVO(_4)</td>
<td>0.1</td>
<td>1.064</td>
</tr>
<tr>
<td>Nd(^{3+}):YLF</td>
<td>0.46</td>
<td>1.047/1.053</td>
</tr>
<tr>
<td>Nd(^{3+}):Glass</td>
<td>0.33</td>
<td>1.062/1.054</td>
</tr>
<tr>
<td>Er(^{3+}):Glass</td>
<td>8.0</td>
<td>1.535</td>
</tr>
<tr>
<td>Er(^{3+}):YAG</td>
<td>0.10</td>
<td>2.937</td>
</tr>
<tr>
<td>Tm(^{3+}):YAG</td>
<td>10.9</td>
<td>2.013</td>
</tr>
<tr>
<td>Ho(^{3+}):YAG</td>
<td>7.2</td>
<td>2.091</td>
</tr>
</tbody>
</table>

Table 1.1: Intrinsic upper laser level lifetimes of laser materials.

Sources) for the same collected powers cause significant long-term damage to human eye-sight. The significance of this to the relevant applications will be discussed below.

2. Long upper laser level lifetimes: Many of the materials used for laser sources generating 2μm radiation (for example Tm\(^{3+}\):YAG and Ho\(^{3+}\):YAG) have intrinsically long upper laser level lifetimes. For applications requiring large pulse energies, energy must be stored in the upper laser level to be released by the laser pulse and so a long upper level lifetime is advantageous. To give a brief comparison, the upper laser level lifetime in the common Nd\(^{3+}\):YAG material operating at 1.064μm is ~230μs whereas the upper level lifetime of Ho\(^{3+}\):YAG operating at 2.091μm is 7.2ms and Tm\(^{3+}\):YAG is 10.9ms. See table 1.1 for further values for common materials.

3. Tm\(^{3+}\) Two-for-one cross-relaxation: Pumping Tm\(^{3+}\):YAG at 785nm (a wavelength available from high-power diode-bar pump sources) can yield a highly efficient process whereby for every pump photon absorbed at 785nm, the laser can produce two laser photons. This process, commonly called “two-for-one” cross-relaxation is an inter-ionic Tm\(^{3+}\) → Tm\(^{3+}\) process that has many advantages not only with pumping efficiencies but also with the thermal loading of the laser which we will see is an important factor in power-scaling lasers.
1.2 Applications of 2 µm Lasers

2µm lasers have many applications in the areas of medicine, communications and laser radar or lidar (Light Detection And Ranging). Lidar is an application where a laser source which can be either pulsed or continuous wave (cw), illuminates a target and either the time-of-flight or a change in frequency is measured from the reflection or 'back-scatter' from the target. Targets can be either 'hard-bodied', such as an aircraft, or 'soft-bodied' such as aerosols in the atmosphere. Medical applications like arthroscopy, lithroscopy, orthopaedics and angioplasty often require laser sources that are absorbed by water in medical tissue [Verdaasdonk99]. Eye-safety is not essential for most of these applications but is desirable for any applications that involve members of the public or untrained laser operators.

Most communications applications are excellently served by 1.55µm wavelength laser sources and components corresponding with the high transmission, low loss window in silica fibres at ~1.55µm. Free-space communications is an increasingly interesting application which requires high-power eye-safe sources as the radiation is not guided or enclosed within fibre or fibre coupled components. 1.55µm radiation also satisfies the eye-safe requirements, however power-scaling of Erbium (Er³⁺) lasers does not have the advantage of the efficiencies associated with the two-for-one cross-relaxation process available with Tm³⁺ lasers. Recently [Free-Space01] a gigabit bandwidth, 785nm/980nm wavelength based free-space communications system was installed for the South Africa Defence Industry. The system covered 19 buildings and transmitted data between 200m and 4km. This indicates the applicability of free-space optical networks in certain settings but the current systems are all based on non-eyesafe lasers. A high power, single frequency cw 2µm laser could act as a 'master' laser system that is then split and modulated and beamed to numerous collector sites. A 2µm fibre based laser would benefit from fibres inherent robustness and compatibility with other fibre communications components.

The main application of interest for this work is in 2µm lasers suitable for lidar. There are many applications for lidar and we will focus on two here that are well suited to 2µm based lidars due to their improved resolution over 10µm CO₂ systems. The shorter wavelength of 2µm radiation provides the improved resolution
1.2 Applications of 2 μm Lasers

Figure 1.1: Schematic of cloud microburst airflow skewed by cross-winds [Howell96].

Figure 1.2: Diagram of aircraft landing disturbed by microburst. 1) Landing approach appears normal. 2) Plane experiences increased downdraft. 3) Plane decreasing airspeed to land but suffers increasing downdrafts. 4) Plane crashes short of runway [Howell96].

necessary for many soft-bodied atmospheric targets.

Windshear and landing vortices/turbulence are large problems for the civil aviation authorities around the world [Storm91, Wagener95, Huffaker98, Henderson93]. Increasing air traffic may well see these problems becoming an even larger concern. Windshear has already been attributed as the main cause of several major air accidents, resulting in many fatalities, and a large number of incidents each year. As a result, the Civil Aviation authorities have commissioned a large amount of research into developing a solution. Windshear is a general term for a sudden change in airspeed direction. A particularly hazardous form of windshear is caused by cloud microbursts (see figure 1.1) where a rapid burst of air pressure and wind is pushed towards the ground from altitudes as high as 15,000ft. Figure 1.2 shows the effects of a microburst on an aircraft approaching to land.

Aircraft induced turbulence and vortices are an increasing problem as the requirements of air-traffic on airports increases worldwide [Huffaker98]. The disturbances
1.3 Requirements for LIDAR

Figure 1.3: Aircraft induced vortex turbulence. Aircraft behind experience variations in lift, pitch and airspeed due to turbulent airflow [Trier99].

to airflow caused by aircraft landing and taking-off is a hazard to following aircraft (figure 1.3). There are also studies underway to automatically fly aircraft in formations similar to flying geese to improve fuel efficiencies! [NASA01]. Studies into this type of turbulence are receiving increased attention.

1.3 Requirements for LIDAR

Researchers at the FAA and NASA/Langeley Research Center have defined the requirements for windshear avoidance as a forward looking, remote sensing technique capable of giving the pilot 15-45 seconds of advanced warning [Storm91].

It is generally believed that an aircraft mounted, windshear detection lidar system would require a pulse energy in the order of $5\text{–}10\text{mJ}$, a pulse-repetition frequency (PRF) of $100\text{–}300\text{Hz}$, the bandwidth of the laser output should be of the order of $1\text{MHz}$ in order to resolve wind speeds to $1\text{ms}^{-1}$ accuracy. The laser emission should be eye-safe (generally $\lambda_L > 1.4\ \mu\text{m}$ with telescoping) and the complete system should be reliable, compact, lightweight and maintenance free for > 2000 hours.

Subsequent research has shown that both $2\mu\text{m}$ and $10.6\mu\text{m}$ systems are capable of fulfilling these requirements (though the $2\mu\text{m}$ system outperforms the $10.6\ \mu\text{m}$ system in more adverse weather conditions and resolution). Lidars measuring soft
1.3 Requirements for LIDAR

<table>
<thead>
<tr>
<th>Laser Host</th>
<th>$\lambda$ nm</th>
<th>Extinction $dB km^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tm$^{3+}$:YAG</td>
<td>2013</td>
<td>-1.3</td>
</tr>
<tr>
<td>Tm$^{3+}$:YAG†</td>
<td>2022</td>
<td>-0.8</td>
</tr>
<tr>
<td>Tm$^{3+}$:(Lu,Y)AG</td>
<td>2022</td>
<td>-0.8</td>
</tr>
<tr>
<td>Ho$^{3+}$:YAG</td>
<td>2091</td>
<td>-0.5</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>10591</td>
<td>-2.7</td>
</tr>
</tbody>
</table>

† Output wavelength tuned away from peak emission

**Table 1.2:** Double-pass extinction in clear air for some potential LIDAR sources.

Targets such as aerosols for wind measurements and measurement of the global wind fields are also currently areas of heated research for 2 $\mu$m sources. The increased resolution of 2$\mu$m laser based lidars are favoured for these applications.

CO$_2$ and Nd:YAG laser sources have previously been used as the source for lidar systems. CO$_2$ lidar systems however, require cooled detection and replenishable gas supplies increasing their maintenance frequency. The Nd$^{3+}$:YAG systems used for lidars, emitting at 1064nm, are not eye-safe and can thus only be operated under highly supervised situations which prohibits them from a great many lidar applications.

2 $\mu$m laser systems hold the potential for relatively easy detection, $>2000$hrs maintenance period and assured eye-safety($\lambda_L > 1400 nm$ ). However, there are several problems facing the development of efficient, high-power 2 $\mu$m sources for the applications detailed above and it is these problems that are being addressed here. An informative review of the use of solid-state lasers in Coherent lidar at 2 $\mu$m, is given in [Henderson93].

Table 1.2 shows the double-pass extinction in clear air for some of the LIDAR wavelengths considered here. The double pass extinction is given as the returning backscattered signal for lidars must traverse twice the air path length.

The table shows that the Ho$^{3+}$:YAG laser output wavelength has a lower atmospheric extinction compared with Tm$^{3+}$:YAG and CO$_2$ emission. In addition to an advantageous atmospheric extinction, the Ho$^{3+}$:YAG emission also sits in a region of the atmospheric absorption spectrum that has fewer absorption features than Tm$^{3+}$:YAG emission. Subsequently, a Tm$^{3+}$:YAG based lidar system requires
more definition of the operating wavelength than a Ho\textsuperscript{3+}:YAG lidar system.

1.4 This Thesis

This chapter has discussed the reasons for this research into high-power solid-state 2\textmu m lasers. Chapter 2 will discuss some of the problems of the power scaling of these sources and outline some of the solutions that are available. Chapter 3 details experiments on the thermally induced lensing in two of the laser materials of interest in this work, Tm\textsuperscript{3+}:YAG and Tm\textsuperscript{3+}: (Lu,Y)AG. Chapter 4 then presents the high-power Tm\textsuperscript{3+}:YAG laser experiments. Chapter 5 compares high-power Tm\textsuperscript{3+}:YAG and Tm\textsuperscript{3+}: (Lu,Y)AG lasers. Chapter 6 reports work conducted on a range of intracavity pumped Ho\textsuperscript{3+}:YAG lasers. Chapter 7 presents work carried out on power-scaling a double-cladding pumped Tm\textsuperscript{3+}: alumino-silica fibre laser. This fibre laser work was aimed at being an alternative pump source for a range of high-power Ho\textsuperscript{3+}:YAG lasers. Conclusions and suggestions for future work are then given in chapter 8.

References


Chapter 2

Power-Scaling Diode-Bar End-Pumped 2μm Lasers

Chapter 1 discussed the motivations for the development of high power, high brightness 2μm lasers. In this chapter it is the intention to discuss the problems associated with power scaling these lasers and some of the solutions and strategies that are currently in use in the literature to overcome these problems. This is not intended to be an exhaustive review of the field but to pick some of the power scaling strategies and reflect on their suitability for the 2μm sources of interest to this work. It is also intended to highlight where possible strategies that give the 2μm field any potential advantages. Throughout this chapter and later in the thesis the terms power scaling and brightness scaling are used. Power scaling is generally intended to mean increasing the useful output power of a laser whereas brightness scaling is intended to mean increasing the output power of a laser whilst maintaining good beam quality (near diffraction limited output or $M^2$ close to ~1.1).

Note that throughout this work the main “levels” as denoted by $^{2S+1}L_J$ notation (e.g.$^5I_8$) shall be referred to as “manifolds”. Stark levels will be referred to as “Stark levels” and identified by a number indicating its relative position in increasing energy from the lowest energy Stark level in its manifold).
2.1 Quasi-Three-Level Lasers

All the lasers investigated in this work are referred to as "quasi-three-level" lasers. Quasi-three-level lasers are characterised by a finite lower laser level population under unexcited conditions above 0 K temperature. This population is commonly as a result of rapid thermal relaxation satisfying a Boltzmann distribution between levels. This assumes that the relaxation between levels is of a time scale much shorter than other radiative or non-radiative lifetimes in the system. This assumption is satisfied for the all the levels in the manifolds of interest in this work. Note that the term level here is generally the Stark level split by the crystal host field and the term manifold refers to the collection of Stark levels within a manifold. For Ho$^{3+}$:YAG and Tm$^{3+}$:YAG this thermal relaxation time is of the order $\sim$ picoseconds compared with a minimum lifetime of a few microseconds for some of the other levels. The terminal laser levels for both laser materials of interest in this work, Ho$^{3+}$:YAG and Tm$^{3+}$:YAG have a significant thermal population near room-temperature. In both the Tm$^{3+}$:YAG laser operating at 2.013$\mu$m and Ho$^{3+}$:YAG laser operating at 2.097$\mu$m, the lower laser Stark level resides in the ground state manifolds ($^3H_6$ manifold for Tm$^{3+}$:YAG and $^5I_8$ manifold for Ho$^{3+}$:YAG. The fraction of the total number of ions in a given manifolds energy state $f_{m,s}$ can be determined from equation 2.1.

\[
f_{m,s} = \frac{1}{Z_m} \exp \frac{E_{m,L} - E_{m,s}}{kT}
\]

where $Z_m$ is the partition function of the manifold and is given by equation 2.2, and $E_{m,L}$ is the energy of the lowest Stark level within the manifold $m$. $k$ is Boltzmann constant $\sim 1.38054 \times 10^{-23}$ J/K and $T$ is the temperature in Kelvin of the host material.

\[
Z_m = \sum_s \exp \frac{E_{m,L} - E_{m,s}}{kT}
\]

2.1.1 Laser Threshold

The laser threshold pump power for end-pumped quasi-three-level lasers is given below in equation 2.3 on page 11 from [Fan87] and [Risk88]. For contrast, the
2.1 Quasi-Three-Level Lasers

equivalent threshold equation for four level lasers is given by equation 2.5 on page 11.

\[ P_{th} = \frac{\pi \hbar \nu_P (w_L^2 + w_P^2)}{4\eta_{abs}\eta_{p-q}f_U\sigma \tau} (T + L + 2N_0f_L\sigma l), \]  

(2.3)

where \( \hbar \) is the Planck constant, \( \nu_P \) is the pump optical frequency, \( w_L \) is the laser beam waist, \( w_P \) is the pump beam waist, \( L \) is the internal losses not including the output coupling which is given by \( T \), \( \sigma \) is the laser transition cross-section, \( \tau \) is the upper laser level lifetime, \( N_0 \) is the total dopant concentration, \( l \) is the crystal length and \( f_L \) and \( f_U \) are the lower and upper fractional Boltzmann fractions for the lower and upper laser levels. \( \eta_{abs} \) is the absorption efficiency of the pump and is given by equation 2.4 for the case of no pump induced ground-state-depletion and \( \eta_q \) is the pumping quantum efficiency.

\[ \eta_{abs} = 1 - e^{-\alpha l} \]  

(2.4)

where \( \alpha \) is the absorption coefficient and \( l \) is the length of the laser rod.

The equivalent equation for the threshold pump power of an end-pumped four-level laser where there is no lower laser level population under unpumped conditions is given by equation 2.5.

\[ P_{th} = \frac{\pi \hbar \nu_P (w_L^2 + w_P^2)}{4\eta_{abs}\eta_{p-q}f_U\sigma \tau} (T + L), \]  

(2.5)

The effect of the finite lower laser level population on the quasi-three-level laser threshold can be seen by the additional term, \( 2N_0f_L\sigma l \), and an inversely proportional relationship with the fractional population of the upper laser level \( f_U \). The first term can be regarded as an additional loss for the laser to reach threshold and is often called “re-absorption loss”. We see that the additional loss is proportional to the rod length \( l \), and the fractional population of the ground manifold residing in the lower laser level \( N_0f_L \).

It can be seen that as the fractional populations of the upper and lower laser levels tend towards the four-level case (\( f_L \rightarrow 0 \) and \( f_U \rightarrow 1 \)) the quasi-three-level laser
threshold (equation 2.3) becomes equation 2.5.

2.1.2 Laser Slope Efficiency

Slope efficiency is the ratio of laser output power for incident pump power \( \eta_{\text{slope}} = \frac{dP_{\text{output}}}{dP_{\text{pump}}} \) above threshold. This becomes complicated for the quasi-three-level laser case due to the re-absorption loss near threshold. For pump powers above but near threshold, there are still many regions which have insufficient inversion to overcome the lower level population and so cause a re-absorption loss to the lasing wavelength. This results in a slope efficiency that is correspondingly lower than its four level equivalent (where in a four level laser there is no loss for insufficiently pump regions). This results in quite a complicated analysis for the exact laser output power behaviour near threshold. A spatial distribution for the pumped regions must be determined along with the mode matching \( w_P/w_L \) ratio throughout the gain media which will not be discussed here. However for high pump powers, \( P_P \) of 3 to 4 times above \( P_{th} \), then we can understand that a larger volume of the laser rod is sufficiently pumped to overcome the lower level population and thus no longer causes a loss to the lasing mode and the laser slope efficiency \( \eta_s \) tends towards the four-level-laser case. The four-level-laser slope efficiency is given by equation 2.6.

\[
\eta_s = \frac{T}{T+L} \eta_{\text{STOKES}} \eta_q \eta_{\text{abs}} \eta_{\text{PL}}
\]

where \( T \) is the laser output coupling fraction, \( L \) is other round-trip laser losses, \( \eta_q \) is the quantum pump efficiency, \( \eta_{\text{abs}} \) is the pump absorption efficiency, \( \eta_{\text{PL}} \) is an efficiency dependent on the overlap between the pump and laser modes which tends to 1 for high pump powers and \( \eta_{\text{STOKES}} \) is given by equation 2.7.

\[
\eta_{\text{STOKES}} = \frac{\nu_L}{\nu_P}
\]

where \( \nu_L \) is the laser radiation frequency and \( \nu_P \) is the pump radiation frequency.
2.2 Materials for 2μm lasers

Further information on these materials will be presented in the relevant chapter. Here it is intended to provide sufficient information for the reader to appreciate how the materials help or hinder power and brightness-scaling.

2.2.1 Tm$^{3+}$:YAG

Tm$^{3+}$:YAG is a well characterised material [Gruber89, Shaw94, Zayhowski97, Koechner95]. Rare-earth doped YAG Y$_3$Al$_5$O$_{12}$ (Yttrium Aluminium Garnet) is the most common combination for solid-state laser medium. Y$_3$Al$_5$O$_{12}$ has well defined thermo-mechanical properties with good thermal conductivity 13Wm$^{-1}$K$^{-1}$ compared with many glasses (∼1Wm$^{-1}$K$^{-1}$) and crystals YLF (Yttrium Lithium Fluoride) ∼6Wm$^{-1}$K$^{-1}$ and YVO$_4$ (Yttrium Vanadate ∼5Wm$^{-1}$K$^{-1}$) [Zayhowski97, Koechner95] and a good thermal shock parameter R. The peak of the emission is at 2.013μm. The absorption and emission spectra are shown in figure on page 54.

The four main manifolds of interest are shown in figure 2.1. The laser transition is between Stark levels in the $^3F_4 \rightarrow ^3H_6$ transition. The lower laser level is in the ground state manifold making the laser characteristic of a quasi-three-level laser. There is a highly favourable cross-relaxation process in Tm$^{3+}$:YAG when the $^3H_4$ manifold is pumped. There can be an inter-ionic energy transfer, or cross-relaxation, that takes place by de-exciting an ion from the $^3H_4$ manifold to the upper laser manifold $^3F_4$ whilst also simultaneously exciting a near-neighbour ion from the ground state manifold $^3H_6$ to the $^3F_4$ upper laser manifold. This process is shown in figure 2.1. These transitions ($^3H_4 \rightarrow ^3F_4 + ^3H_6 \rightarrow ^3F_4$) are commonly called the “two-for-one” cross-relaxation process and has many benefits. Without cross-relaxation the maximum slope efficiency achievable for pumping a 2μm laser with a pump wavelength near 1μm is the Stoke efficiency ∼0.5, which places a severe restriction on the power-scalability of 2μm lasers.

The efficiency of the cross-relaxation process can be affected by the doping concentration of the Tm$^{3+}$ ions (see chapter 4). The higher the concentration, the
Figure 2.1: Tm$^{3+}$ lower four energy manifolds showing the 785nm pump and 2μm laser transitions with the 'two-for-one' cross-relaxation process.

closer the nearest-neighbour Tm$^{3+}$ ion pairs, increasing the cross-relaxation efficiency. Unfortunately, there are also inter-ionic upconversion processes out of the upper laser manifold such as the $^3F_4 \rightarrow ^3H_5 + ^3F_4 \rightarrow ^3H_6$ upconversion transitions. Upconversion processes are also nearest-neighbour spacing dependent and hence concentration dependent. Therefore there is a doping concentration optimisation to be found. Further information regarding these factors is given in chapter 4.

Tm$^{3+}$:YAG has a low emission cross-section of $\sim 2.2 \times 10^{-25} \text{m}^2$ with the peak wavelength at 2.013μm ($^3F_4 \rightarrow ^3H_6$ transition). This is very small compared with the equivalent emission cross-section for Nd$^{3+}$:YAG at 1.064μm of $\sim 6.5 \times 10^{-23} \text{m}^2$. However this is offset by the long upper manifold lifetime of $\sim 10.9 \text{ms}$ giving a $\sigma\tau$ product only $\sim 16\%$ of the popular Nd$^{3+}$:YAG transition at 1.064μm.

The low-gain nature of this transition places stringent requirements on good pump beam quality for efficient power-scaling. It can be seen from equations 2.3 and 2.6 that small $w_p$ and $w_L$ are required for low-threshold and high slope efficiency operation, essential for efficient power-scaling.
2.2 Materials for 2μm lasers

![Energy Level Diagram](image)

**Figure 2.2:** Lowest four manifolds of Ho$^{3+}$:YAG showing the 2.097μm laser transition, near 2μm pump transition, upconversion processes and non-radiative decay.

### 2.2.2 Tm$^{3+}$:(Lu,Y)AG

Tm$^{3+}$:(Lu,Y)AG is a material whereby a given percentage of yttrium atoms in Y$_3$Al$_5$O$_{12}$ are replaced by lutetium in the lattice [Kmetec94]. The material closely resembles Tm$^{3+}$:YAG. This has an effect of shifting the peak emission wavelength from 2.013μm to ~2.022μm. This material has not been thoroughly investigated due to the many variations of percentage yttrium replacement and so it is difficult to give values for thermo-mechanical properties. The peak emission of Tm$^{3+}$:(Lu,Y)AG lasers appears to be lutetium doping dependent.

### 2.2.3 Ho$^{3+}$:YAG

The lowest 4 manifolds of Ho$^{3+}$:YAG are also the main levels of interest. A Ho$^{3+}$:YAG laser operating at 2μm has the laser transition from Stark levels between the upper laser manifold $^5I_7$ and the ground state manifold $^5I_8$ ($^5I_7 \rightarrow^5I_8$) again characterising a quasi-three-level laser transition. The lowest four manifolds are shown in figure 2.2.
Ho$^{3+}$:YAG has a larger effective emission cross-section than Tm$^{3+}$:YAG of $\sim 1 \times 10^{-24}$m$^2$ with an upper laser level lifetime of $\sim 7.2$ ms which is $\sim 62\%$ of the $\sigma \tau$ product of Nd$^{3+}$:YAG at 1.064$\mu$m. Ho$^{3+}$:YAG will be discussed further in chapter 6.

2.3 Problems Of Power Scaling

There are three main problems to understand and overcome in order to power scale 2$\mu$m lasers compared to 1$\mu$m lasers. These problems will be discussed in further detail later in the chapter.

1. Low gain transitions. Many of the common 2$\mu$m laser transitions have low $\sigma \tau$ products compared with 1$\mu$m lasers such as Nd$^{3+}$:YAG. The saturation intensity for a laser transition is inversely proportional to the $\sigma \tau$ product and inversely proportional to the laser threshold.

2. Quasi-three-level transitions. Many 2$\mu$m laser transitions are regarded as quasi-three-level lasers in which there is a finite population in the lower laser level similar to a three-level laser. These transitions require more pump power compared with a four-level laser to reach threshold due to the laser photon re-absorption by the lower laser level. The distinction between three and quasi-three level laser is that for a three-level laser, the lower laser level contains the total number of ions in the unpumped interaction region whereas the lower laser level in a quasi-three-level contains a fraction of the total number of unpumped ions.

3. Thermally induced effects. Non-radiative transitions and relaxations between levels commonly give up heat to the crystal host and this results in a range of effects. Thermal lensing, end-face bulging and thermally induced stress-birefringence de-polarisation loss are common effects.

The materials of interest in this work have been discussed earlier. Low gain transitions require intense pumping to keep thresholds low and to achieve slope efficiencies that produce the high power operation wanted. The main difficulties in power
or brightness scaling 2μm lasers are the thermal effects and these are discussed below.

2.4 Thermal Effects in Diode-Bar End-Pumped Lasers

Some of the processes of heat generation for Tm\(^{3+}\):YAG and Ho\(^{3+}\):YAG lasers have already been discussed and we now discuss some of the effects on this heat generation on efficient high power laser operation.

There are four main effects resulting from heat generation in the laser rod which are general to side-pumped and end-pumped high power solid-state lasers.

1. Thermal lensing caused by a change in refractive index due to a change in rod temperature \((dn/dT)\)

2. Stress-induced birefringence

3. Thermal lensing due to rod end-face bulging

4. Stress-induced fracture of the laser rod

2.4.1 Aberrated Thermally Induced Lensing

An important thermal effect in end-pumped lasers is the effect of change in rod temperature. Focusing of the pump radiation, which is required by end-pumping, results in an increased local heat loading in the rods. This increase in temperature can produce a strong lensing effect due to the change in refractive index due to change in temperature \((dn/dT)\). Much of the literature approximates this thermal lens as a parabolic thin lens as this is convenient for resonator design using ABCD matrices. However the refractive index profile of the lens is dependent on the pump laser beam profile. The actual lens refractive index profile can be highly aberrated from a parabolic lens profile. The aberrated thermal lens causes diffraction losses to the laser mode and hence reduces the brightness of the laser output. A relationship
between the beam profile and the increase in $M^2$ has been given by [Siegman93] and the aberrations measured for a Gaussian pump distribution with an end-pumped laser geometry [Clarkson98]. This thermally induced lensing can make resonator design difficult as the thermal lens focal lengths can be short (of the order of a few rod lengths) and the aberrated nature increases the laser loss.

An analytical expression for the aberrated thermal lens has been derived by Clarkson and Hanna [Clarkson98] and is an extension of [Innocenzi90] and [Siegman93] to arrive at a theory for the radially varying thermal lens focal length for a Gaussian pump intensity profile and its effect on the $M^2$ of a Gaussian beam passing through it. The theory assumes no axial heat flow and that the thermal lens is a thin lens. For the convenience of the reader the main results of the theory are repeated here with equation 2.8.

$$f_t(r) = \frac{2f_t(0)}{w_P^2} \left( \frac{r^2}{1 - e^{-2r^2/w_P^2}} \right)$$

(2.8)

where $f_t(0)$ is the thermal lens focal length on axis at $r=0$ and is given by equation 2.9.

$$f_t(0) = \frac{\pi K_c w_P^2}{P_P \gamma \eta_{abs} \frac{dn}{dT}}$$

(2.9)

and where $\gamma$ is the fraction of absorbed pump power converted to heat, $K_c$ is the thermal conductivity of the laser material, $\eta_{abs}$ is the absorption efficiency (fraction of pump power incident that is absorbed), $w_P$ is the pump waist radius, $dn/dT$ is the change in refractive index with respect to change temperature, $P_P$ is the incident pump power and $r$ is the radius from the pump beam axis.

For demonstration purposes it is useful to estimate the order of the focal length at the centre of a Tm$^{3+}$:YAG laser rod. Taking $K_c$ to be 13Wm$^{-1}$K$^{-1}$ and $dn/dT$ to be $9.86\times10^{-6}$ K$^{-1}$ for YAG. Assuming $\gamma \approx 0.3$, $\eta_{abs} =0.95$, $P_P =20$W and $w_P$ to be 275$\mu$m. Then a calculation of the thermal lens focal length at the rod centre would yield $f_0 =$55mm.
2.4.2 Stress-Induced Birefringence

Stress-induced birefringence is a problem for laser operation where a preferred polarisation for the output is required. Typically the polarising element, Brewster-plate for example, enforces a linear polarisation to the resonator but the stress-birefringence induces ellipticity in the polarisation state at different spatial positions in the oscillating modes. The polarisation component orthogonal to the polarising element is then lost to the mode and the output power of the laser is reduced. This is known as de-polarisation loss. Naturally birefringent laser media see a reduction in this effect as the natural birefringence is stronger than this induced effect. However YAG is a cubic and hence isotropic host and is prone to this problem.

The additional loss for a linearly polarised laser due to stress-induced birefringence arising from thermal loading is given by equation 2.10 [Koechner95, Clarkson99, Fluck00].

\[
L_{depol} = \frac{1}{A^2 + 4}
\]  

(2.10)

where

\[
A = \frac{K_c \lambda w_p^2}{P_{\text{abs}} \gamma n^3 \alpha C_B w_L^2}
\]  

(2.11)

where \(K_c, \lambda, w_p, P_{\text{abs}}, \gamma,\) and \(w_p\) are as defined before. \(\alpha\) is the thermal expansion coefficient \((\text{m}^{-1})\), \(n\) is the refractive index and \(C_B\) is a coefficient given by :

\[
C_B = \frac{1 + \nu}{48(1 - \nu)} (P_{11} - P_{12} + 4P_{44})
\]  

(2.12)

where \(\nu\) is Poisson’s ratio (the lateral contraction per unit breadth divided by the longitudinal extension per unit length) and \(P_{ij}\) are elements of the photoelastic tensor. For Nd\(^{3+}\):YAG the values are \(\nu = 0.25\), \(P_{11} = -0.029\), \(P_{12} = 0.0091\) and \(P_{44} = -0.0615\) giving a value for \(C_B = -0.0099\). It has been assumed that these values are valid for Tm\(^{3+}\):YAG.
2.4.3 Other Thermal Effects

The thermal expansion of the rod can cause bulging of the rod end-faces which generally add to lensing effect acting on the laser mode. It should be noted that some materials have a negative change in refractive index with change in temperature ($dn/dT$) (e.g. YLF) which means the thermal lens focal length can partially offset the lensing from end-face bulging. This bulging effect is relatively small compared to the thermal lens distortion in the rod for end-pumped YAG if the rod is radially cooled efficiently.

Thermally-induced fracture can be a problem for power scaling lasers. Thermal fracture can form an upper limit to the power that a laser medium can absorb and hence the maximum that the laser can be power scaled. Laser media can be characterised by a “Thermal-Shock” parameter R in Wcm$^{-1}$. For the crystal of interest in this work, YAG, the thermal shock parameter is $\sim 7.9$ which is high compared with YLF $\sim 1.6$, glass $\sim 1$ and GSGG $\sim 6.5$.

An additional thermal effect that is applicable to quasi-three-level lasers is the effect on the lower laser level population and the subsequent effect on laser threshold and slope efficiency. As the laser medium temperature increases with thermal load the lower laser level population increases as characterised by the Boltzmann distribution of populations, increasing the fractional population of the lower laser manifold in the lower Stark level $f_L$. It can be seen from equation 2.3 that the threshold pump power is proportional to the fraction $f_L$.

Upconversion and excited state absorption processes to higher manifolds can also contribute to thermal loading if there relaxation processes are not completely radiative. Similarly, pumped regions of the laser medium that are not extracted by the laser mode a can also contribute to spatially dependent thermal loading by non-radiative decay. It is extremely difficult to effectively model these effects analytically due to the cyclic dependencies of laser loss increasing the ion populations which subsequently undergo upconversion and increase the thermal lensing effects. These processes will be discussed throughout the later chapters.
2.5 Power Scaling Strategies

There have been several strategies to enable power scaling of diode-pumped solid-state lasers. These strategies commonly fall into one of the following categories:

1. Reduction of the thermal loading and heat generation
2. Specific laser resonator design
3. Improvements in pump arrangements
4. Side-stepping the thermal effects by using an alternative laser source
5. Compensation of the thermal effects

These strategies will be discussed below.

2.5.1 Heat Generation Reduction And Removal

The main sources of heat generation are pump quantum defect heating, non-radiative decay from ions that have undergone upconversion or excited-state-absorption to higher manifolds and non-radiative decay from the upper laser manifold under non-lasing conditions. One strategy for power-scaling is to attempt to address some or all of these heating processes although many of these processes are intrinsically related to the interaction between the material and the pump radiation. Heat generation under non-lasing conditions is of primary concern for Q-switched lasers and so won’t be discussed in detail here although lasers with high thresholds suffer some of these effects.

For a given laser transition in a material, the pump quantum defect heating process can generally only be affected by varying the pump wavelength and hence the manifolds or levels that are involved in the relaxation processes into the upper laser level and from the lower laser levels. Inband pumping can result in a very small fraction of pump power causing heat generation. Inband pumping is where the pump laser pumps from a level in the lower laser manifold to a level in the upper laser manifold. This strategy is restricted to laser transitions where the
pump and laser wavelengths are similar though it is theoretically possible for an upconversion pumped laser to have no heating due to pumping.

There are also heat generation routes that are related to upconversion or excited-state-absorption processes. Upconversion routes are related to the upper laser level population and hence are accentuated by non-lasing conditions and high thresholds. Reducing the doping concentration of a laser material can increase the nearest-neighbour ion spacing and reduce the efficiency of upconversion processes.

The effects of these heat generation processes can be reduced by efficient removal of the heat from the laser medium. This can be achieved by selection and design of high surface area to volume factor and efficient heat sinking of the laser material.

### 2.5.2 Resonator Designs

There are a range of resonators that provide strategies for power scaling solid-state lasers. A few designs are detailed here. Tightly-folded and multi-pass resonators [Baer92] allow the pump and laser modes and hence thermal loads to be distributed in different volumes of the gain medium. The tightly-folded geometry enables multiple pumping ports or positions but the alignment of these pumping positions with the laser mode reflection points (see figure 2.3) can be problematic. Also, for quasi-three-level lasers, part of the laser mode propagates through a volume of the rod/slab that is unpumped (on the opposite side of the slab from the diode-bar). [Shannon93] is an excellent example of this scheme used at 2µm with a Tm$^{3+}$:YAG laser.

An alternative resonator design is the "thin-disk" resonator (see figure 2.4). This design uses a thin-disk laser crystal which has a highly reflecting coating for the pump and laser wavelengths on one side of the disk which is also heat sunk. Generally the disk is not sufficiently thick to absorb a significant fraction of the pump power from a single-pass and so the pump is reflected to multi-pass the laser disk. This scheme has shown very high powers (>100W) with low $M^2 \sim 2$.

The thin-disk resonator design strategy utilises efficient heat removal by removing the heat axially to the laser propagation direction thus reducing the radial temperature profile and the thermal lens profile. This design also retains the advantages
Figure 2.3: Power scaling resonator scheme - tightly folded resonator.

Figure 2.4: Power scaling resonator scheme - thin-disk resonator.
of end-pumping. Berner et al [Berner99] compares the thin-disk setup with end-pumping and points out that the thin-disk setup suffers a relative reduction in performance due to the $^3F_4 \rightarrow ^3H_5$ upconversion transition. The short length of the gain media necessary to achieve the efficient cooling of the thin disk setup restricts the amplification length and hence increases the inversion density in the long-lifetime $^3F_4$ upper laser level due to reduced extraction. Subsequently the increased upconversion-induced thermal effects prevented high power operation in those experiments. However lowering the doping concentration and increasing the number of pump passes would reduce the thermal effects and the upconversion parameters and allow further power scaling.

2.5.3 Alternative Lasers

There are alternatives to pumping bulk lasers for efficient 2µm high power output. Fibre lasers [Dominic99] and planar waveguide lasers [Shepherd01] side-step many of the thermal problems encountered by end or side pumped bulk lasers. However, the advantages that these lasers bring such as distributing the thermal loading with a high surface area to volume ratio is offset by the problems of launching the pump light into the geometry. Double clad pump guide structures solve this problem in the main but there are still stringent restrictions on the pump beam quality. Planar waveguides can be coupled almost directly with diode-bars but improving the brightness to near diffraction limited waveguide output is problematic due to the lack of guiding in one of the dimensions of the plane. Double-clad fibre lasers make excellent high power cw lasers at many wavelengths.

2.5.4 Compensation Schemes

There are numerous schemes compensating for the different thermally-induced effects in lasers. A large body of work on phase-conjugate mirrors and compensating elements is available in the literature. Unfortunately these schemes require high gain, high power lasers as the phase-conjugate mirror reflectivities are often low. Resonator-specific diffractive elements introduced into a resonator may compensate for many of the aberrations and thermal effects but again at a cost
2.6 Power Scaling Strategies Used In This Work

There are several strategies that have been employed for different lasers in this work. The following sections discuss the resonator design considerations that have been incorporated and a particularly simple yet effective scheme for partially compensating for the stress-induced birefringence. To add to this are the strategies using the intrinsic material advantages that have been used to power-scale several 2μm lasers. This include the two-for-one cross-relaxation process detailed earlier, intracavity pumping of Ho\(^{3+}\):YAG by Tm\(^{3+}\):YAG (chapter 6) and using the advantages of fibre lasers by double-clad pumping a Tm\(^{3+}\):alumino-silica fibre laser (chapter 7).

2.6.1 Beam-Shaped Diode-Bar

Low gain laser transitions of Tm\(^{3+}\):YAG and Ho\(^{3+}\):YAG as described earlier require intense pumping for efficient operation. The threshold of end-pumped lasers is dependent on the pump and laser spot-sizes (see equation 2.3). The output from a diode-bar is typically highly elliptical with \(M^2\) values of \(\sim1000\) and 1 in planes orthogonal to the diode-junction plane. This not only restricts the shape of the pump profile but also the minimum spot size available. The minimum waist size for a gaussian beam when focussed by a thin lens is approximated by

\[
w_{\text{min}} = \frac{2 f M^2 \lambda_p}{\pi D}
\] (2.13)
where \( w_{\text{min}} \) is the minimum focussed waist size, \( f \) is the focal length of the lens, \( M^2 \) and \( \lambda \) are the \( M^2 \) value and wavelength for the incident beam and \( D \) is the diameter of the lens.

Taking the case for a diode-bar with \( M^2 \) values of 1000 and 1 in orthogonal planes operating at 785nm focussing a collimated beam by a 30mm focal length lens of diameter 20mm results in a minimum spot-size in the two planes of 750\( \mu \text{m} \) by \( \sim 1\mu \text{m} \). The resulting pump beam profile is restrictive and results in high laser thresholds.

A simple scheme to improve the usability of the diode-bar output is the 'two-mirror beam-shaper' developed by Clarkson [Clarkson96]. The beam-shaper (figure 2.5) is two parallel mirrors that cuts up the image of the diode-bar emitters and overlaps the output into a single output beam. This action thereby reduces the \( M^2 \) in one plane whilst increasing the \( M^2 \) value for the other plane with a small reduction in the total brightness. Typically the output \( M^2 \) values are equalised to \( \sim 70 \) in both orthogonal planes.

Given that threshold \( P_{\text{th}} \propto (w_L^2 + w_P^2) \) (equation 2.3) then the ratio of pump thresholds for a symmetric \( M^2 \) 'beam-shaped' incident pump to an asymmetrical pump beam can be \( \sim 10\% \). This can bring significant improvements in threshold and efficiency and is an integral strategy to power-scaling all the 2\( \mu \text{m} \) lasers in this work.

### 2.6.2 Resonator Design Considerations

The resonator designs discussed so far involve considerable alteration to the laser geometry. The strategy employed here is to use the response of the laser resonator to changes in mirror curvature and arm lengths to partially offset the aberrations and increasing strength of the thermal lens. This strategy was developed by Clarkson and Hanna [Clarkson01]. The resonator is designed such that the laser mode size at the lens position in the laser rod \( w_L \) increases as the focal length of the thermal lens \( f_{\text{thermal}} \) decreases. Figure 2.6 shows an example of the response of a simple 3 mirror resonator shown in figure 2.7. Figure 2.6 shows the change in the response to changes in the resonator arm length \( d \) where \( L_1 < L_2 < L_3 < L_4 \).
Figure 2.5: Simplified diagram of the two-mirror beam-shaper (a) shows a top view of the two mirrors whilst (b) shows a side view.

Figure 2.6: Resonator laser mode response to change in thermal lens focal length.
Figure 2.7: Simple 3 mirror resonator with $w_L$-$f_{thermal}$ response given by figure 2.6.

If we can consider that the central laser mode that sees the shortest focal length is at the centre of the lens then this mode is forced to be the largest laser mode. This central laser transverse mode should be the best approximation to TEM$_{00}$ with the smallest $M^2$. The laser resonator then forces the TEM$_{00}$ mode to compete with the higher order modes which intrinsically have larger mode sizes and propagate through the wings of the lens. The higher order modes pass though the "longer focal-length" lenses (the aberrations of the thermal lens) and the resonator forces the higher order modes to compete with the TEM$_{00}$ mode at the centre of the thermal lens axis.

This resonator strategy should improve the laser output beam quality as the higher order modes suffer reduced gain due to the competition with the TEM$_{00}$ mode. There are drawbacks to this strategy, the resonator response has a minimum thermal lens focal length for which the resonator remains stable and for the mode competition and discrimination to be effective the laser must operate near this limit.

2.6.3 Stress-Induced Birefringence Compensation

There have been several schemes to compensate for the stress-induced birefringence caused by the thermal loading. Resonators including two laser rods with a 90° quartz rotator between the rods have been used to partially compensate the birefringence but this scheme is complex due to the added laser rod and pumping
requirements and the scheme relies upon the two rods having near identical temperature distributions. Other schemes use phase-conjugation to compensate for aberrations.

A simple scheme is used here [Clarkson99] requiring the insertion of a standard quarter-wave plate between the laser rod and a resonator end mirror. The waveplate fast and slow axis are aligned parallel and perpendicular to the preferred plane of polarisation defined by the intracavity linear polariser. The linearly polarised radiation is separated into tangential and radial components by the rod birefringence. The radially and tangentially polarised radiation undergoes a 90° rotation and upon reflection from the cavity end mirror undergoes a further 90° rotation to provide a full 180° rotation. The radiation then passes through the laser rod to suffer the birefringence again. However, the effect of the 180° rotation is to swap the tangential with the radial birefringence encountered by the orthogonal polarisation states (tangential and radial). Thus on exit from the rod the birefringence is partially compensated for. The linearly polarised light that is wanted for output undergoes a 180° rotation and passes through the linear polariser without loss upon further resonator round-trips.

The formula for the additional loss to the laser due to depolarisation is given by [Fluck00]

\[
L_{\text{depol}} = \frac{1}{A^2 + 4} \tag{2.14}
\]

where

\[
A = \frac{K_c \lambda w_p^2}{P_{\text{abs}} \gamma n^3 \alpha C_B w_L^2} \tag{2.15}
\]

and the compensated laser including the quarter-wave plate is given by [Fluck00]

\[
L_{\text{depol}} = \frac{3}{4A^4 + 20A^2 + 16} \tag{2.16}
\]

For the lasers in this section we take the photo-elastic coefficient \(C_B \sim 0.0099\) for YAG [Koechner95] and \(K_c = 13 \text{Wm}^{-1} \text{K}^{-1}\) thermal conductivity, \(\gamma \approx 0.3\), \(P_{\text{abs}} \sim \)
$45 \lambda \lambda = 2.013.10^{-6} \text{m} \alpha = 7.5 \times 10^{-6} \text{K}^{-1}$ thermal coefficient of expansion and $w_P = 400 \mu m$ and $w_L \approx 300 \mu m$ and the refractive index $n = 1.82$ then we can calculate the expected depolarisation loss for two comparable compensated and uncompensated lasers at 2µm. $A = -7.699$ with $L_{uncompensated} = 0.016$ and $L_{compensated} = 1.967 \times 10^{-4}$.

2.6.4 Inband Pumping : Intracavity Pumping Ho$^{3+}$:YAG

Inband pumping is a strategy for power-scaling as it generally results in a very low percentage of pump power resulting in heating. Intracavity pumping Ho$^{3+}$:YAG within the cavity of a Tm$^{3+}$:YAG laser is an inband pumping scheme. The quantum defect heating of a Tm$^{3+}$:YAG laser operating at a wavelength of 2.013µm and pumping a Ho$^{3+}$:YAG laser operating at 2.091µm is only $\sim 3.7\%$ compared with 25% for a typical Nd$^{3+}$:YAG laser pumped at 0.808µm and operating at 1.064µm. If we combine this 3.7% fractional heating with the minimum quantum defect heating of 22% for a Tm$^{3+}$:YAG laser with 100% efficient two-for-one cross-relaxation, then the combined intracavity pumping scheme is comparable with heating efficiencies of the benchmark 1µm lasers.

2.7 Summary

A brief reiteration of quasi-three-level lasers theory and some 2µm laser materials has been presented. The problems of power-scaling diode-bar end-pumped solid-state 2µm lasers and several strategies from the literature for overcoming these problems have been discussed. Finally the strategies employed in this work are repeated here. Effort has been made to highlight the strategies that are suited to power-scaling 2µm lasers such as the specific physics of certain materials. For the most part the work in this thesis has involved using these strategies and their application to new laser systems.
References


2.7 Summary


1.4 This Thesis


Chapter 3

Thermal Lensing in Tm$^{3+}$:YAG and Tm$^{3+}$:(Lu,Y)AG

3.1 Introduction

The problems of thermal effects in end-pumped solid-state lasers have already been discussed in chapter 2. This chapter is devoted to the investigation of the thermal lensing in two materials of interest to this work; Tm$^{3+}$:YAG and Tm$^{3+}$:(Lu,Y)AG.

Thermally induced lensing can have many effects on the performance of end-pumped solid-state lasers. These effects will be discussed throughout this chapter. In order to design and optimise these lasers it is necessary to measure the extent of thermal lensing effects.

There are a various methods for determining the thermally induced lens in solid-state bulk lasers. The simplest is to take the output from the laser and use ray matrices to back-track the laser mode size to determine the intracavity laser mode size [Neuenschwander95].

Another simple method is to inject a known probe beam [Hardman99] through the laser rod at a small angle to the laser mode axis and measure the effect of the lens on the probe beam. The probe beam should be of a different wavelength to the laser so that it does not suffer gain or absorption which would distort the probe
beam in addition to the thermal lens.

There are also a range of interferometric methods [Clarkson98]. Interferometry is well known whereby a probe beam is split into two beams; one beam is passed through the rod and then re-combined with the other beam reference beam. Interferometric methods are more experimentally complex but can provide much more information regarding the transverse spatial variation of a thermal lens.

Information about a laser under non-lasing conditions (where a laser receives sufficient pump power to operate above normal threshold but the threshold is artificially increased to prevent lasing) can provide understanding of the thermal effects resulting from upconversion and excited pump absorption processes. Using a separate probe beam would give freedom to vary the threshold of a laser without changing the measurement process. However measurement of the output beam is experimentally simpler. Changing the output coupling of a laser allows variation of the threshold in a controlled manner and hence information about upconversion effects can be inferred but generally means changing the laser mirrors and hence requires laser re-optimisation. Use of an acousto-optic modulator as an output coupler would enable variation of the output coupling loss at the cost of added cavity complexity.

To gain the most from measurements of thermal lenses for the two materials some correlation with theory is most helpful. The analytical theory used was derived by Clarkson and Hanna [Clarkson98] and is an extension of [Innocenzi90] and [Siegman93] to arrive at a theory for the radially varying thermal lens focal length for a Gaussian pump intensity profile and its effect on the $M^2$ of a Gaussian beam passing through it. The theory assumes no axial heat flow and that the thermal lens is a thin lens. For the convenience of the reader the main results of the theory are repeated in chapter 2 with equation 2.8. The pump intensity profile resulting from a beam-shaped diode-bar is a Gaussian profile.

It is difficult to describe the aberrations of the thermal lens focal length given by equation 2.8 in a $4 \times 4$ matrix. The approximation throughout this work is that the thermal lens is a thin lens within the laser rod. This enables easy inclusion with other optical components (lenses, mirrors, rods) in ABCD round-trip resonator models.
In this work the thermally induced lens has been measured for the materials 3% at. doped Tm^{3+}:YAG and 3% at. doped Tm^{3+}:(50\%,50\%)at. doped (Lu,Y)AG. The simple method chosen was to measure the output beam characteristics from a range of plane-plane laser resonators under different pump conditions. The plane-plane mirrored resonator provides a waist at the output coupler which makes the ABCD resonator analysis easier and using a 4f-relay imaging lens setup outside the cavity to determine the imaged waist size and $M^2$ of the output of the laser. A 4f-relay-imaging system is a two lens telescope. Two identical lenses are used providing unit magnification with the distance between the lenses equal to their focal length. The system image and object planes are a focal length from the two lenses. See on page 153 for details of the 4f-relay-imaging system.

By using relay imaging, the error in the waist measurement is dependent on the transverse telescope ratio of the two lens arrangement. This is compared with measurement of the waist from single lens focusing where the error is dependent on measurement of both the object and image distance. The the 4f-arrangement, the measurement of a waist at a given position (the output coupler waist) reduces the error in the waist longitudinal position as this longitudinal position for the waist is implicitly the imaging systems principal planes distance from the output coupler. Any errors in the longitudinal position of the waist position translate into a very small error in waist spot-size and the subsequent calculation of intracavity spot-size measurements.

The waist spot-size at the output coupler was then determined using the ABCD matrix given in appendix B to back propagate from the measured waist size to the output coupler taking into account additional distances from components such as filters and mirror thicknesses. The additional length suffered by a divergent beam due to a components is given by equation 3.1.

$$L_{\text{with components}} = L_{\text{with no components}} + \frac{d}{n}$$  \hspace{1cm} (3.1)

where $d$ is the thickness of the inserted component and $n$ is the refractive index of the inserted component, $L$ (with components) is the distance between two points (i.e. two other optical components) with the inserted components present and $L$
3.2 Experimental Setup

(with no components) is the distance in between to points without the inserted components.

Once the spot-size of the waist at the output coupler mirror was known, the thermal lens (thin lens approximation without aberrations) was found using an ABCD round-trip matrix of the resonator similar to the that given in appendix A and the thermal lens focal length was then solved for the iterations of the ABCD matrix for the spot-size at the output coupler.

3.2 Experimental Setup

The aim of this experiment was to determine the focal length for a thermal lens in Tm$^{3+}$:YAG and Tm$^{3+}$:(Lu,Y)AG under intense end-pumping from a beam-shaped diode-bar. The thermal lens is approximated here as a simple thin lens. The lasers are pumped by a 40W beam-shaped diode-bar which is coupled through a multi-mode fibre 'jumper' or coupler before focussing into the laser rod. The pump source was used to pump a set of plane-plane mirror resonators and the output from the laser was collected by a 4f-relay imaging arrangement. The $M^2$ and waist-spot size was measured from the final focus and the thermal lens could then be inferred by calculations of the beam propagation back to the output coupling mirror of the laser. The 4f-relay imaging setup ensured that the measured waist was very close to the intracavity waist size at the output coupler mirror. The thermal lens was then inferred from a numerical iteration of a thermal lens input into an ABCD matrix round-trip model calculating the waist-spot-size at the output coupler.

The pump source was a 40W Coherent Inc [Coherent sales-brochure] (B1-785-40C-19-30-A) diode-bar which was mounted on a water-cooled copper heat-sink. The output wavelength was temperature tuned to the 785nm absorption peak in both Tm$^{3+}$:YAG and Tm$^{3+}$:(Lu,Y)AG. The diode-bar was beam-shaped [Clarkson96] and collimated and then re-focussed in to the fibre jumper with a $f =$100mm cylindrical lens followed by a $f =$30mm Gradium lens. The fibre coupler was a 250µm multi-mode fibre with an N.A. of 0.22 and was 1.5m long. The fibre jumper allowed easy access to the pump light and reduced spatial transverse drift of the pump beam. The Pump beam exiting the fibre jumper was then collimated with
an \( f = 50 \text{mm} \) Gradium lens and then finally focussed through the laser input coupler into the laser rod by a \( f = 80 \text{mm} \) Gradium lens.

The pump beam was focussed to 265\( \mu \text{m} \) and 272\( \mu \text{m} \) in the tangential and sagittal planes with corresponding \( M^2 \) of 78 and 79 at low powers (\( \sim 6.7 \text{W} \)) and 273\( \mu \text{m} \) and 281\( \mu \text{m} \) at higher powers (\( \sim 24.25 \text{W} \)).

The second moment beam radius spot-size at a given distance from a waist in a medium with refractive index \( n \) and known \( M^2 \) is given by equation 3.2.

\[
W(z) = W_0 \left[ 1 + \left( \frac{M^2 \lambda_0 z}{n \pi W_0^2} \right)^2 \right]^{1/2}
\]  

(3.2)

where \( z \) is the distance from the waist (position where the beam radius of curvature is \( = \infty \)), \( \lambda_0 \) is the wavelength of the radiation in vacuo and \( W_0 \) is the \( 1/e^2 \) beam radius at the waist position.

The confocal parameter for the beam (2 times the Rayleigh range) is the distance over which a Gaussian beam is said to be collimated and is defined as the distance over which the beam spot size \( W(z_{\text{Rayleigh}}) \geq \sqrt{2}W_0 \) and the intensity is half that at the waist. The Rayleigh range is given by equation 3.3

\[
z_{\text{Rayleigh}} = \frac{n \pi W_0^2}{M^2 \lambda_0}
\]  

(3.3)

The refractive index of YAG is 1.82 at 2\( \mu \text{m} \) and the pump beam has \( M^2 \) of \( \sim 79 \) with \( W_0= 275 \mu \text{m} \) and a wavelength in air \( \lambda_0 = 785 \text{nm} \) (\( \sim \) same as vacuo).

This gives a Rayleigh range of 7mm and a collimated distance in YAG of 14mm. As the rod length used in the experiments was 17mm then it is of interest to note what the pump beam spot-size is at the rod faces (assuming the pump waist is central to the rod length). Taking \( z = 8.5 \text{mm} \) and the waist size = 275\( \mu \text{m} \) the spot-size at the rod faces would be \( \sim 430 \mu \text{m} \) which is \( \sim 40\% \) of the intensity at the waist assuming no absorption.

The laser resonator and the 4f-relay imaging system accepting the output of the laser is shown in figure 3.1.
Figure 3.1: Experimental setup for measurements of relay imaged laser spot size at output coupler of Tm$^{3+}$:YAG (or Tm$^{3+}$:(Lu,Y)AG) laser.

The distance $l_1 = 1.5\text{mm}$ and length $l_2$ was 7mm. The laser rod length was 17mm for both the Tm$^{3+}$:YAG and Tm$^{3+}$:(Lu,Y)AG experiments. The plane - pump input coupling mirror was a high reflector, (HR) ($R > 99.9\%$) at the laser wavelength and highly transmitting (HT) at the pump wavelength ($T \approx 85\%$) on the intracavity side and anti-reflection (AR) coated ($T >99\%$) on the extracavity side. Three different mirrors were used for the plane output coupler. The available coating reflectivities were 3%, 6% and 10% transmitting across the 2.0 to 2.1$\mu$m wavelength region on the intracavity side of the mirror. In order to change the output coupling for the laser the end mirror had to be replaced and the laser re-aligned and optimised. To optimise the laser, the minimum threshold was found and this corresponded with the highest output power throughout this set of experiments. The incident pump power was then varied by altering the drive current on the diode-bar and the waist spot-sizes and $M^2$ values taken through the 4f-relay imaging system. A Merchantek Beamscope beam analyser was used to measure the spot-sizes at a range of points through the relayed imaged beam waist and the $M^2$ determined by fitting the Gaussian propagation equation 3.2 to the results.

Measurements of the 2$\mu$m laser output beam sizes were measured at a waist produced from a 4f (four focal lengths non-telescoping) relay imaging arrangement on exit from the laser resonator output coupler. The 4f arrangement is more robust than a single lens or non-unity telescoping arrangements [Neuenschwander95], with respect to changes and errors in the alignment and thickness of intervening optical components. Some calculation of errors is given below.
The 4f arrangement lenses were identical with a focal length of 100mm and were set \( \approx 215 \text{mm} \) apart (distance \( l_4 \) in figure 3.1) and \( \approx 97 \text{mm} \) from the extra-cavity output coupler mirror face to lens \( f_1 \) (distance \( l_3 \)) and 100mm from lens \( f_2 \) to the measurement plane of the Merchantek Beamscope (distance \( l_5 \)). These distances were altered from the 4f distances (100m - 100mm - 100m - 100mm) to account for the attenuating elements used to reduce the power from the laser to prevent damage of the beam analyser. These elements were, in order of distance away from cavity; the output coupler thickness (\( d =5 \text{mm}, n \approx 1.5 \); the partially reflecting mirror (\( d =5 \text{mm}, n \approx 1.5 \)) and two ND filters (\( d = 2.5 \text{mm}, n \approx 1.6 \)).

It is interesting to estimate the size of errors in the measurement of propagating beam waist-sizes from object plane (\( w_{\text{object}} \)) to image plane (\( w_{\text{image}} \)) and the sensitivity of the setup to mis-alignment. The difference in calculated spot size at the output coupling mirror of the test laser is \( < 1 \mu\text{m} \) for the case of the partially reflecting mirror and the ND filters inserted between the two lenses of the relay imaging system compared with no inserted components. For a 10% variation in the distances in the 4f relay arrangement the spot size \( \Delta w_{\text{image}} \approx 1 \% \) of \( w_{\text{object}} \) indicating that the relay imaging optical system is robust to relatively large errors in setup or measured distances. The arrangement should also be invariant to the \( M^2 \) of the laser (provided the 4f system doesn’t induce significant further aberrations).

The main errors for this method of measuring the thermal lens is the placement of the thin lens approximation position within the laser rod in the ABCD round-trip model and the resonator variations brought about by changing the output coupling mirrors. A position of 6mm from the input coupling face of the rod (distance \( l_{\text{rod}_1} \) in figure 3.1) was chosen and little difference was found (change in \( f_f(0) <5\% \)) for changes in the position of the thin lens \( l_{\text{rod}_1} \) up to 9mm. \( l_{\text{rod}_1} \) lengths of > 10mm had a greater effect on the calculation of \( f_f(0) \), the thermal lens focal length at the rod centre. It is reasonable to assume that the thermal lens is strongest nearest the pumped input face of the laser rod.

The measurements were taken for 17mm 3% at. doped Tm\(^{3+}\):YAG rods and 17mm 3% Tm\(^{3+}\) at. doped Tm\(^{3+}\):(Lu,Y)AG rod. The Tm\(^{3+}\):(Lu,Y)AG rod was grown by Scientific Materials to have 50% of the yttrium sites replaced with lutetium.
Figure 3.2: Tm$^{3+}$:YAG thermal lens power in m$^{-1}$ for given absorbed pump power in W with line plots of calculated thermal lens at rod centre ($f_t(0)$).

The pump power incident on the input coupler and transmitted through the rod for different diode-bar drive current was measured to determine the absorbed pump power.

Each data point required measurement of both the relay-imaged beam spot-size and the beam $M^2$ to correctly estimate the intracavity spot size at the thermal lens position.

3.3 Results

Figure 3.2 shows the thermal lens power in dioptres (m$^{-1}$) for the experiments conducted on Tm$^{3+}$:YAG lasers with 3 different output couplers (3%, 6% and 10%). The results show that as the pump power increases the thermal lens focal length shortens (thermal lens power increases). The thermal lens power in dioptres is inversely proportional to the thermal lens focal length. The lines (solid to dotted) show the calculated thermal lens at the thermal lens rod centre (equation 2.9) for different values of $\gamma$, the fraction of absorbed pump power the contributes to heat. Note that the plot is against absorbed power and this modifies the equation 2.9.
3.3 Results

to have $\eta_{abs} = 1$ and $P_F$ is replaced by $P_{abs}$. The solid line for implied $\gamma=0.22$ is of particular note as this is the minimum $\gamma$ given no upconversion contributing to heat and 100% efficient ‘two-for-one’ cross-relaxation. The results indicate that increasing output couplings give rise to an increased thermal lens power. This implies that there is additional heating to the laser rod (and hence increased thermal lensing) due to the increased loss to the laser (the increasing output coupling). Increasing loss for a laser increases the inversion density at and above threshold. Co-operative upconversion effects from the upper laser level reducing the available gain to the laser are dependent on the upper laser level population and are proportional to the population $N^2$. However there are other effects that may be responsible for the additional heating. The increase in output coupling may result in small additional heating sufficient for the thermal lens to be more aberrated, driving the laser to different modes and create increased loss to the laser from diffraction. Effectively this acts as an $M^2$ related loss to the laser that is exacerbated by the output coupling. There was no clear relationship between the $M^2$ for lasers and their thermal lens at given pump powers. This indicates that the laser self-heals its performance for different pump powers and output couplings by varying its beam quality. Any change in the laser mode size in the rod through the pumped region alters the inversion density and total inversion population which in turn would change the heat load from any upconversion effects. Because of this it is difficult to attribute the correlation between increased output coupling loss and increased thermal lens power to upconversion related heating. However there is some indication that this is the case and could be investigated further using interferometric measurements whereby the thermal lens profile can be monitored independently of the laser mode profile and position.

We can see by comparing figure 3.2 with figure 3.3 that the thermal lens power in Tm$^{3+}$:(Lu,Y)AG is stronger than for Tm$^{3+}$:YAG for the same absorbed pump power and pump spot size. It is difficult to determine an implied $\gamma$ from the Tm$^{3+}$:(Lu,Y)AG results though the results suggest that the fraction of pump power absorbed contributing to heat ($\gamma$) is larger in Tm$^{3+}$:(Lu,Y)AG.

Note that the approximation has been made that the thermal lens focal length at the centre of the rod is the thermal lens that has been measured. It is probable that the measured thermal lens is an effective focal length from the combination
3.3 Results

Figure 3.3: Tm$^{3+}$:(Lu,Y)AG thermal lens power in m$^{-1}$ for given absorbed pump power in W with line plots of calculated thermal lens at rod centre ($f_i(0)$).

of the thermal lens at rod centre and the longer focal lengths from the aberrated wings of the pumped region. It is difficult to determine the effective single thin lens focal length from a combination of thermal lens focal lengths. The effects of end-face bulging have also been ignored in this analysis.

If we assume that the thermal lens is approximated to a thin lens with a focal length equal to $f_0$, lens power equal to $D$ (equation 2.9) and fit the results to the equation 3.4 then we get the plots given in figures 3.4 and 3.5 and the corresponding data given in tables 3.2 and 3.3.

$$D = \frac{1}{f_0} = aP + Y_0 \quad (3.4)$$

where $Y_0$ and $a$ are arbitrary fitting values. $a$ is given by equation 3.5 but with an unconstrained $\gamma$ for fitting to the data and the values for the other constants given in table 3.1.

$$a = \frac{\gamma n_{laks}\frac{dn}{dT}}{\pi K_c w_P^2} \quad (3.5)$$

and where $\gamma$ is the fraction of absorbed pump power converted to heat, $K_c$ is the
3.3 Results

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_c$</td>
<td>$13 \text{ Wm}^{-1}\text{K}^{-1}$</td>
</tr>
<tr>
<td>$dn/dT$</td>
<td>$9.86 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\eta_{abs}$</td>
<td>0.95</td>
</tr>
<tr>
<td>$w_P$</td>
<td>275 $\mu$m</td>
</tr>
</tbody>
</table>

**Table 3.1:** Table of constants used in fitting thermal lens power vs pump power.

![Plot](image)

**Figure 3.4:** Tm$^{3+}$:YAG thermal lens power in m$^{-1}$ for given absorbed pump power in W with line plots fitted for $\gamma$.

thermal conductivity of the laser material, $\eta_{abs}$ is the absorption efficiency (fraction of pump power incident that is absorbed), $w_P$ is the pump waist radius, $dn/dT$ is the change in refractive index with respect to change temperature, $P_P$ is the incident pump power.

A sample calculation of a typical thermal lens focal length is given on 18.

The following tables take the values from the plots and their gradients and determine the thermal lens focal length using equation 2.9 the implied values for $\gamma$.

We can see that the data with a small offset ($Y_0 \neq 0$) fits the data better that with the constraint of $Y_0 = 0$. For the case of Tm$^{3+}$:(Lu,Y)AG the curve fits imply that for the higher output coupler the gamma is lower. This is thought to be an error in the measurements resulting in a greater variance in the data points of the
### 3.3 Results

<table>
<thead>
<tr>
<th>Output Coupler</th>
<th>$Y_0$</th>
<th>$a$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>-0.37</td>
<td>0.87</td>
<td>0.29</td>
</tr>
<tr>
<td>6</td>
<td>-1.37</td>
<td>1.07</td>
<td>0.35</td>
</tr>
<tr>
<td>10</td>
<td>-0.99</td>
<td>1.15</td>
<td>0.38</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.87</td>
<td>0.29</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1.07</td>
<td>0.35</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>1.15</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Table 3.2: Table of implied $\gamma$ (fraction of absorbed pump power contributing to heating) for different Tm$^{3+}$:YAG laser output couplers and fitting parameters.

![Graph](image)

Figure 3.5: Tm$^{3+}$:(Lu,Y)AG thermal lens power in $m^{-1}$ for given absorbed pump power in W with line plots fitted for $\gamma$.

<table>
<thead>
<tr>
<th>Output Coupler</th>
<th>$Y_0$</th>
<th>$a$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>-1.47</td>
<td>1.39</td>
<td>0.46</td>
</tr>
<tr>
<td>6</td>
<td>2.11</td>
<td>1.30</td>
<td>0.43</td>
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<tr>
<td>10</td>
<td>6.89</td>
<td>1.08</td>
<td>0.36</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1.39</td>
<td>0.46</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1.30</td>
<td>0.43</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>1.09</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Table 3.3: Table of implied $\gamma$ (fraction of absorbed pump power contributing to heating) for different Tm$^{3+}$:(Lu,Y)AG laser output couplers and fitting parameters.
Tm$^{3+}$:(Lu,Y)AG data relative to the Tm$^{3+}$:YAG data set. Little can be concluded from this data set from the linear fits for gamma.

The calculation of implied $\gamma$ for the data assumes $K_c = 13Wm^{-1}K^{-1}$, $dn/dT = 9.86 \times 10^{-6} K^{-1}$ for YAG and the measured pump spot-size $w_p = 275 \times 10^{-6}m$.

The results of the curve-fitting are given in 3.2 and 3.3

It is of interest to look at the resonator $dw/df$ characteristics for these lasers in the context of the power scaling strategy. Figure 3.6 shows these characteristics as a plot of laser mode size at the thin lens position in the rod against the thermal lens focal length.

Under low pumping operation near threshold we would expect the laser to have a very weak thermal lens and hence long thermal lens focal lengths. However as we see in figure 3.6, at long focal lengths the resonator tries to support a laser mode size much larger that the pump spot-size ($w_L \approx 400 \mu m$ vs $w_p \approx 275 \mu m$ for these experiments). This mode-mis-match increases the threshold which increases the threshold inversion density for the $^3F_4$ manifold population. The rate of upconversion de-populating the $^3F_4$ manifold is proportional to the relevant cross-section times the population squared ($N_L^2$). If the upconversion processes increase the heat load then the thermal lens focal length will decrease and the
corresponding laser mode size is reduced as shown in figure 3.6. As the thermal lens focal length is reduced and the laser mode spot-size at the rod is reduced, the pump - laser mode overlap is increased and the threshold pump power is reduced allowing threshold to take place.

The laser cavity $w_L - f_{\text{therm}}$ response does not indicate expected good performance from the plane-plane resonator. However the resonator was chosen for ease of re-alignment, mirror distance repeatability and repeated threshold optimisation necessary for measurements from a known intracavity waist. It is difficult to infer information on the upconversion processes and cross-relaxation efficiencies from such a laser with such possible cyclic dependencies and dynamics.

3.4 Summary

The thermal lens in two materials has been investigated and evaluated. Values for $\gamma$, the fraction of absorbed pump power contributing to heating have been evaluated and show a dependency on the laser losses. This implies a dependency on the laser inversion density and hence possible heating due to upconversion processes contributing to heat. $\gamma$ is noted to be larger for Tm$^{3+}:(\text{Lu,Y})$AG than Tm$^{3+}$:YAG indicates that either the doping of lutetium replacing yttrium in the host effects the upconversion cross-sections or the thermo-mechanical properties are poorer in Tm$^{3+}:(\text{Lu,Y})$AG than Tm$^{3+}$:YAG.

Future work should be directed at an interferometric analysis of the thermal lensing in these materials for a wider range of pump spot sizes and laser losses. Interferometry can provide information on the change in phase due to a particular path through a point in the thermal lens and hence provides much greater resolution of the actual profile. Of interest with such an experiment would be to investigate the difference in pump beam quality and profile and verify the improvement expected between a Gaussian shaped profile to a top-hat shaped profile. A resonator designed to keep the expected thermal lens focal length constant for a large range of thermal lenses would be appropriate to de-couple the effects of varying resonator sustained modes effecting the results. Inclusion of an acousto-optic modulator for an output coupler or variable, measurable loss could be advantageous.
References


Chapter 4

Power-Scaled CW Tm$^{3+}$:YAG Lasers

4.1 Introduction

High power Tm$^{3+}$:YAG lasers have many applications such as medical applications like arthroscopy, lithroscopy, orthopaedics and angioplasty; free-space communications systems requiring high powers and eye-safety and as sources for many different types of lidar. As discussed in the Introduction and Preface, the lasers demonstrated here are intended to be developments on a route to a coherent lidar source though many could be directly used with few modifications for free-space communications systems.

For many years the low powers available from laser diodes provided output powers of $\sim$10-100 mW from the respective diode-pumped Tm$^{3+}$:YAG lasers. Whilst these low power lasers (high power results of their time!) demonstrated the principles of many of the applications, these results showed that higher powers were required.

The potential tunability of a Tm$^{3+}$:YAG laser [Stoneman90] combined with the fine structure of water absorption allows Tm$^{3+}$:YAG lasers to be used for applications where either weak or strong water absorption is required. Strong absorption is required for medical applications where absorption and heating in tissue is wanted whilst weak water absorption is required for free-space communications, remote-
sensing and lidar. It has already been pointed out in chapter 1 that Ho$^{3+}$:YAG is more favourable than Tm$^{3+}$:YAG for atmospheric transmission though there have been many demonstrations of successful lidar systems using a Tm$^{3+}$:YAG source [Henderson93, Grund97, Storm91]. These excellent demonstrations show what has been achieved with the powers available and yet point to the possible applications that would be made possible by further power-scaling. Higher pulse energies and higher average powers increase a lidar’s range (pulse energy) and resolution (repetition rates) and hence its suitability for certain applications.

Very high power Tm$^{3+}$:YAG lasers have been demonstrated, notably [Honea97] reporting $\sim 115\text{W}$ with $M^2$ values of $\sim 14$-23 from an end-pumped Tm$^{3+}$:YAG laser and [Lai00] producing $\approx 120\text{W}$ by a side-pumping arrangement. [Lai02] is due to report at a forthcoming conference an improvement on this result to $\sim 150\text{W}$ of output power.

Compact, microchip and monolithic devices provide excellent sources of stable single-frequency $2\mu\text{m}$ radiation [Kane90],[Storm91] and [Svelto99]. These compact lasers are high suited as seed and reference lasers for Tm$^{3+}$:YAG based lidars but are difficult to scale to higher powers whilst maintaining their advantages.

Crystal waveguide devices have also been scaled to high powers [Mackenzie01] producing $\sim 15\text{W}$ at $2\mu\text{m}$ and showing efficient wavelength conversion from available diode-bar wavelengths. It is hard to maintain the beam quality of a crystal waveguide laser with the planar slab waveguide geometry as the lack of guiding in one dimension reduces the brightness achievable by such devices.

The brightness of a source in $\text{W sr}^{-1}\mu\text{m}$ is given by [Tropper99]

$$B = \frac{P}{\lambda^2M_x^2M_y^2}$$  \hspace{1cm} (4.1)

where $P$ is the power of the source, $\lambda$ is the wavelength and $M_x^2$ and $M_y^2$ are the $M^2$ values for orthogonal planes.

Comparisons between different the brightness of different laser sources in the literature are given in table 4.1

The experiments described in this chapter follow on from the work carried
out by Bollig and is detailed in his thesis [Bollig97] and several publications [Bollig96, Bollig98]. The author’s role with this laser was to help Bollig in some of the data analysis with the experiment. The maximum room-temperature power scaled laser of the Tm$_{3+}$:YAG work in [Bollig97] is [Bollig98], a Tm$_{3+}$:YAG laser providing >4W of output at 2.013μm pumped by a beam-shaped 20W diode-bar delivering 13.5W of incident pump power. This laser gave excellent beam quality with $M^2$ values of 1.2 and 1.4 in orthogonal planes and was operated at a heat sink temperature of $\sim$20°C. However the resonator consisted of only 2 mirrors and was extremely short allowing for no other components or flexibility.

Development of a high power intracavity pumped Ho$_{3+}$:YAG lasers requires power scaling of the available Tm$_{3+}$:YAG lasers. One of the aims of the author’s work was to facilitate power scaling with good beam quality but also to develop more flexible lasers with longer resonators that still accommodate the strongly aberrated thermal lens in Tm$_{3+}$:YAG making use of the resonator design strategy outlined in chapter 2. These lasers were then intended to be used as platforms for the more complex intracavity pumped Ho$_{3+}$:YAG lasers.

### 4.2 Spectroscopy

The spectra and energy levels of Tm$_{3+}$:YAG have been characterised by Gruber et al [Gruber89]. The energy levels for Tm$_{3+}$:YAG are given in figure 4.1. This diagram with the maximum and minimum energy of each manifold to scale in cm$^{-1}$ and the data was collected from [Gruber89]. Note that the $^3P_0$ level (35372 cm$^{-1}$) is within the $^1I_6$ multiplet and that the higher energy $^1S_0$ level at 79604 cm$^{-1}$ is not shown.
Figure 4.1: Energy level diagram to scale for Tm$^{3+}$:YAG (in cm$^{-1}$). Data from [Gruber89].
4.2 Spectroscopy

Figure 4.2: Tm³⁺:YAG (³H₄ → ³F₄ and ³H₆ → ³F₄) cross-relaxation efficiency for different values of N_{1/2}.

The pumping and lasing processes have already been discussed in chapter 2 but are recapped here. The laser transition is the emission from ³F₄ → ³H₆. The pump process is the absorption ³H₆ → ³H₄ but is followed by the inter-ionic ³H₄ → ³F₄ and ³H₆ → ³F₄ with an efficiency \( \eta_{cross} \) determined by equation 4.2.

The efficiency of the two-for-one cross-relaxation (³H₄ → ³F₄ with ³H₆ → ³F₄) can be calculated by equation 4.2 and is defined as the fraction of thulium ions excited to the ³H₄ manifold that co-operatively transfer to the ³F₄ manifold.

\[
\eta_{cross} = \frac{(N_{Tm}/N_{1/2})^2}{1 + (N_{Tm}/N_{1/2})^2}
\] (4.2)

where \( N_{1/2} \) is the Tm³⁺ dopant concentration to give 50% efficiency and \( N_{Tm} \) is the Tm³⁺ dopant concentration. Figure 4.2 shows a plot of the cross-relaxation efficiency for different Tm³⁺ atm. doping concentrations.

Taking a value for \( N_{1/2} \) of 0.011 from [Armagan92] this gives a cross-relaxation efficiency of 0.89 for a 3% atm. doped Tm³⁺:YAG rod.

The absorption spectrum shown in 4.3 was measured using a Perkin Elmer Lambda 9 photospectrometer with a ~ 3nm resolution. This experiment was conducted by C. Bollig [Bollig97] with the author assisting with preparatory setup and hence the figure is repeated here for the convenience of the reader.
The emission spectrum of Tm$^{3+}$:YAG can be related to the absorption spectrum by using the McCumber/reciprocity theory [Payne92], [McCumber64]. The emission spectrum was calculated from the absorption spectrum for Tm$^{3+}$:YAG and is shown in figure 4.4.

It is instructive to have values for the typical phonon energies in Tm$^{3+}$:YAG. Caird et al. [Caird75] provides a value for phonon energy of 700 cm$^{-1}$ and Basiev et al. [Basiev96] provides a value of 850 cm$^{-1}$. Throughout this work the value of 850 cm$^{-1}$ is used.

The $^3F_4 \rightarrow ^3H_5$ transition could be achieved by accepting a lasing wavelength photon or by non-resonant inter-ionic co-operative upconversion ($^3F_4 \rightarrow ^3H_5$ with $^3F_4 \rightarrow ^3H_6$). If the transition were achieved by inter-ionic co-operative upconversion then the energy mis-match between levels would provide $\sim$2 phonons to be given to the lattice as heat as the ion relaxes to the upper Stark level of the $^3H_5$ manifold. This energy would be equivalent to $\sim$1700 cm$^{-1}$. Note that the cross-section for this transition should be small due to the need to interact with $\sim$2 phonons but the rate is increased due to the long $^3F_4$ lifetime, large intracavity field and the relatively small laser emission cross-section from the $^3F_4$ level. Additional heating can then occur as the ion relaxes by fast non-radiative decay through the Stark levels releasing a maximum of 543 cm$^{-1}$ (top Stark level to lowest Stark level)
before continuing to non-radiatively decay to the upper laser manifold $^3F_4$. It is possible that another escape route for an excited ion, inhabiting a Stark level in the $^3H_5$ manifold exists. It can undergo excited state pump absorption to the $^1G_4$ manifold and then radiatively decay to the ground state emitting the characteristic visible blue fluorescence seen from the pumped laser rod in the experiments. In YAG the $^3H_5$ manifold is short lived with a lifetime of $\sim 15\mu$s [Caird75]. In the case of non-radiative decay from the $^3H_5$ manifold to the $^3F_4$ manifold, this provides at least 3 additional phonons with $\sim 2550 \text{ cm}^{-1}$ of energy given to the lattice.

The tunability seen in Tm$^{3+}$:YAG lasers [Stoneman90] indicates that the transitions in Tm$^{3+}$:YAG are phonon broadened and assisted. There are a low number of phonons required for these non-resonant upconversion transitions to the $^3H_5$ and this increases their probability dramatically and the likelihood of the subsequent heating to the lattice.

Should this be the main population mechanism and escape route for the $^1G_4$ manifold then there is little additional heating due to this excited state pump absorption process. The radiative decay from the lowest Stark level in the $^1G_4$ manifold coupling to the top of the ground state emits an energy of 20040 cm$^{-1}$ with a wavelength of 499nm and results in a maximum additional heating of 765 cm$^{-1}$. This maximum additional heating assumes the relaxation from the top Stark level
### Table 4.2: Table of Tm\(^{3+}\):YAG properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>pump wavelength</td>
<td>(\lambda_p)</td>
<td>785</td>
<td>nm</td>
<td>-</td>
</tr>
<tr>
<td>laser wavelength</td>
<td>(\lambda_L)</td>
<td>2013</td>
<td>nm</td>
<td>-</td>
</tr>
<tr>
<td>pump frequency</td>
<td>(\nu_p)</td>
<td>3.82\times10^{14}\ \text{Hz} | \lambda_p</td>
<td>c/\lambda_p</td>
<td>-</td>
</tr>
<tr>
<td>laser frequency</td>
<td>(\nu_L)</td>
<td>1.49\times10^{14}\ \text{Hz}  | \lambda_L</td>
<td>c/\lambda_L</td>
<td>-</td>
</tr>
<tr>
<td>doping Concentration</td>
<td>Conc.</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>doping Concentration</td>
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<td>-</td>
<td></td>
</tr>
<tr>
<td>laser cross-section</td>
<td>(\sigma)</td>
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<td>- [Payne92]</td>
<td></td>
</tr>
<tr>
<td>upper laser level lifetime</td>
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<td>ms</td>
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<tr>
<td>upper level fractional population</td>
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<td>-</td>
<td>- [Bollig97]</td>
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<td>lower level fractional population</td>
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<td>-</td>
<td>- [Bollig97]</td>
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<td>(\mu m)</td>
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<td>(w_L)</td>
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<td>(\mu m)</td>
<td>-</td>
</tr>
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<td>-</td>
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</tr>
<tr>
<td>absorption coefficient ((\lambda = 785\ \text{nm}))</td>
<td>(\alpha)</td>
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<td>m(^{-1})</td>
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<tr>
<td>pump absorption efficiency</td>
<td>(\eta_{abs})</td>
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<td>-</td>
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<tr>
<td>re-absorption loss 2(N_o)(\lambda)(f_L)</td>
<td>0.11</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</table>

* From \(\sigma_{em}/f_U\)  
† Calc'd with effective absorption cross-section \(\sigma_{abs} = 0.5\times10^{-20}\ \text{cm}^2\) and 3\% atm. doping Tm\(^{3+}\)

in the ground state to the lowest Stark level though the ion should relax with a temperature dependent Boltzmann distribution within the manifold.

Table 4.2 gives a summary of the values that are used in calculations throughout this chapter unless stated otherwise.

### 4.3 High Power > 14W CW Near Diffraction Limited Tm\(^{3+}\):YAG Laser

In order to test some of the the power scaling strategies discussed in section 2 on page 9, a high power cw Tm\(^{3+}\):YAG laser was developed. This laser incorporates a resonator that fulfils the \(dw/df\) characteristics of increasing \(dw/df\) near the strongest thermal lens expected for the laser at the highest pump powers as
discussed in chapter 2. To recap, at the shortest focal lengths expected from the
rod thermal lens, the resonator supports an increasing laser mode size preferrably
increasing the laser mode size to $\sim 0.8 w_p$. The TEM$_{00}$ mode should occupy this
transverse position through the rod with the shortest thermal lens whilst the higher
order modes compete for gain in the wings of the pump where the expected aber-
rations of the thermal lens result in a longer focal length. As the heat loading of
the rod increases the thermal lens power for all the transverse profile is increased
and the resonator supports a larger TEM$_{00}$ mode. The TEM$_{00}$ mode can then
compete with the the higher order modes for the available gain.

4.3.1 Resonator Design / Power Scaling Design

An ABCD round-trip model incorporating the cavity elements (which will be de-
scribed later) has been coded into MapleVR4 code to calculate the laser mode size
and stability of the resonator for a varying thermal lens focal length. The code
was similar MapleVR4 listing to that given in appendix B. The plot shown in fig-
ure 4.5 shows the calculated response of the laser mode size ($w_{Tm}$) at the thermal
lens position within the resonator to a change in the thermal lens ($f$). Note that
the thermal lens is modelled as a thin lens placed 6mm from the rod face nearest
mirror $m1$ in figure 4.6. The resonator design will be discussed more fully in
section4.3.2.

We can see that the laser mode size at the thermal lens position in the cavity
increases dramatically as the thermal lens focal length $\rightarrow \sim 20$mm. We can
approximate the expected thermal lens focal length using equation 2.9. Taking the
$\gamma$ parameter from the results in section 3.3 (in chapter 3) as 0.27 and $\eta_{abs} = 0.9$ and
the values for YAG for $K_c$ and $dn/dT$ of 13Wm$^{-1}$K$^{-1}$ and 9.86 K$^{-1}$ respectively
then for the maximum available pump power of 53.4W we calculate a thermal lens
$f_{th} \approx 51$mm. Note that the resonator will support a stronger thermal lens than
this down to $f_{th} \sim 24$mm. This is to accommodate an increase in effective $f_{th}$ in the
model to compensate for additional thermal effects such as rod-face bulging and
increased upconversion related heating. Risk [Risk88] shows that for the ratio of
$w_P/w_L > 0.2$ that the inversion density of the laser transition in quasi-three-level
lasers is greater than 1 as the normalised pumping rate above threshold increases.
This shows that the upper laser level population is not clamped at the threshold level and this indicates that the upconversion rate is not uniform for increasing pump power. As a result of this the laser was designed to accommodate a stronger thermal lens than expected from the results in chapter 3 though they provide a starting point for the design. If we were to take $\gamma$ to be 0.35 then we have a thermal lens focal length of $\sim39\text{mm}$ and $\gamma$ of 0.40 gives $f_{th}\sim34\text{mm}$. What is difficult to estimate with these analytical models is the self-fuelling contribution to heating from increasing upconversion in these lasers and what is intended here is to provide the reader with some understanding of how the analytical models give a good first approximation for the laser design and expected performance whilst allowing for some discrepancy due to the additional features of the lasers’ dynamics to be approximated within the models.

### 4.3.2 Experimental Setup

The laser was pumped by two Coherent Inc (B1-785-40C-19-30-A) 40W diode-bars. The bars used Ga-As active regions that were aluminium free. The removal of aluminium from the active region is intended to reduce oxidation of the output facets though no greater than expected lifetime performance was observed. Each bar was a linear array of 19 emitters. Each emitter output facet was $150 \times 1\ \mu\text{m}$ and
the emitters were spaced 500μm apart. The array was 1 cm long. The diode-bars were housed in a metal container and a continuous low pressure supply of Nitrogen was purged through the housing to reduce the likelihood of condensation forming on the bars and their emitter facets. The bars had a spectral width of \( \sim 2.5 \) nm Full-Width-Half-Maximum (FWHM) centred near 787nm and 789nm respectively and the centre wavelength was temperature tuned to the Tm\(^{3+}:YAG\) absorption feature at 785nm. The diode-bars could be temperature tuned by \( \sim 0.3 \) nm/degree. The diode-bars’ beam divergences were specified as \( \lesssim 10^\circ \) for the slow axis and \( \lesssim 35^\circ \) in the fast axis.

The Coherent diode-bars appeared to have improved ‘smile’ characteristics generating a more consistent curvature when compared with bars from other manufacturers (notably Opto-Power Corporation [OPC sales-brochure]) which were used for lower-power, earlier experiments on Tm\(^{3+}:YAG\) and Ho\(^{3+}:YAG\) (section 6.1). However, reliability was more of a problem with the Coherent diode-bars as catastrophic failure occurred on several occasions requiring replacement bars. The bars were a new product line at the time of the experiments and were the first commercially available 40W rated diode-bars to have aluminium free junctions.

The output from the diode-bar was collimated with a fibre lens and then the emitters were imaged onto the second mirror of the beam-shaper (see figure on page 27. The two-mirror beam-shaper developed by W.A.Clarkson was used to equalise the \( M^2 \) values for both planes of the diode-bar output. A more complete description of the action of the beam-shaper is given in [Clarkson96]. The beam-shaper cuts the image up and overlaps the output into a single output beam thereby reducing the \( M^2 \) in one plane whilst increasing the \( M^2 \) value for the other plane with only a slight reduction in brightness. The output \( M^2 \) values in orthogonal planes from the beam-shaper were \( \sim 75 \) and \( \sim 68 \).

The output beam from the beam-shaper was then collected and focussed into a 250μm diameter multi-mode fibre with an Numerical Aperture (N.A.) of 0.22, length 1.5m and was used to deliver or couple the pump light to the pump focussing arrangements. The fibre delivery coupler provided very easy access to the pump light whilst again only slightly reducing the brightness of the pump. The \( M^2 \) after the fibre coupler was 78 and 79 in orthogonal planes.
One lens of focal length \( f = 50 \text{ mm} \) was used to collimate the output from the fibre coupler and another of focal length \( f = 150 \text{ mm} \) was used to finally focus the pump light into the \( \text{Tm}^{3+}:\text{YAG} \) rod through the input coupler. This arrangement was repeated on at each end of the \( \text{Tm}^{3+}:\text{YAG} \) rod. The final focussing lenses brought the pump to a focus of \( 400 \mu\text{m} \) in both orthogonal planes with \( M^2 \) of 78 and 79. This gives a rayleigh range \( z_R \) in YAG of 14.8 mm and was close to the optimum focussing waist size of \( \sim 325 \mu\text{m} \) given by equation 4.3.

\[
\overline{w_{p,\text{min}}}^2 = \frac{l \lambda_p M^2}{\pi n \sqrt{3}}
\]  

(4.3)

All the pump spot-sizes and \( M^2 \) were measured using a Merchantek Beamscope with a Si detector head along the axis or propagation of the measured beam and fitting the Gaussian beam propagation equation (equation 3.2) to the results. Fine adjustment and optimisation of the pump waist position inside the rod was achieved by translating the final focussing lens.

### 4.3.2.1 Laser Experiment

The laser cavity is shown in figure 4.6.

Mirrors \( m1 \) and \( m2 \), the input couplers for pump1 and pump2 respectively were both plane-plane mirrors with Anti-Reflection (AR) coatings to the pump wave-
length ($\sim$ 785nm) and the lasing wavelength ($\sim$2-2.1$\mu$m) on one side. The mirrors were also Highly Transmitting (HT) at the pump wavelength whilst Highly Reflecting (HR) across the 2.0-2.1$\mu$m wavelength region on the side internal to the cavity. The mirrors transmitted 94% of the pump light incident and were $\geq$ 99.9% reflecting at the lasing wavelength when perpendicular to the incident radiation. Mirror m2 was at an angle of incidence of $\sim$20° to the pump /laser path axis and the coatings on m2 were not designed for angles of incidence other than 90°. This resulted in a small reduction in reflectivity at the lasing wavelength to between $R_{\text{max}}$ = 99.8% and $R_{\text{min}}$ = 98.5%. The reflectivity varied slightly due to transverse position as well as angle hence the approximate minimum and maximum reflectivities given above. The distance from m1 to the laser rod face was $\sim$1mm with the distance from the other rod face to m2 being 34mm. Mirrors m1 and m2 were 1" in diameter to facilitate easier pumping particularly through m2 which was angled by $\sim$ 20°. The 3% atm.doped Tm$^{3+}$ laser rod was 17mm long and 3mm in diameter and mounted in a copper heat-sink that was in good thermal contact and bolted to a further water cooled copper heat sink. The rod coatings were AR (Reflectivity $R \lesssim 0.01\%$) to both the pump radiation and the laser radiation (2.0-2.1$\mu$m region). Mirror m3 was plano-concave with and internal radius of curvature $R_c$ = 100mm. The concave surface was AR coated to the pump whilst HR coated for the lasing wavelength region ($\sim$ 99.9% reflecting). The distance from mirror m3 to mirror m2 was 32mm with the distance between mirror m3 and m4 being 200mm. Mirror m4 was also plano-concave with a radius of curvature of 300mm with the same coating specifications as mirror m3. The output coupling mirror m5 was transmitting(T) $\sim$ 5.8 % of incident 2.0-2.1$\mu$m radiation and the distance between m5 and m4 was 165mm. All the measurements of distances had a tolerance of $\sim$ ± 0.5 mm and were measured internal to the cavity. i.e. from internal mirror face to mirror face. All the internal cavity angles were kept to a minimum to reduce astigmatism. The largest angle of $\sim$ 20° between m1m2 - m2m3 was as small as the rod heat-sink and mirror mounts would allow whilst preserving the distances required by the resonator design. The laser rod mount was kept at $\sim$20 °C by the water cooling.

The pump power transmitted through the laser rod was measured. This power was of interest because of concerns of pump feedback into the second pump and for a measure of pump absorption efficiency. For given pump power incident on
4.3 High Power > 14W CW Near Diffraction Limited Tm$^{3+}$:YAG Laser

<table>
<thead>
<tr>
<th>$P_{inc} [W]$</th>
<th>$T_{rod}$</th>
<th>$\eta_{abs}$</th>
<th>$\alpha_{abs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8</td>
<td>0</td>
<td>1</td>
<td>0.2070 †</td>
</tr>
<tr>
<td>10.1*</td>
<td>0.04</td>
<td>0.97</td>
<td>0.2063</td>
</tr>
<tr>
<td>11.9</td>
<td>0.042</td>
<td>0.958</td>
<td>0.1865</td>
</tr>
<tr>
<td>19.6</td>
<td>0.123</td>
<td>0.877</td>
<td>0.1233</td>
</tr>
<tr>
<td>26.4</td>
<td>0.104</td>
<td>0.896</td>
<td>0.1331</td>
</tr>
</tbody>
</table>

* At Lasing threshold
† Calc'd with $\alpha_{abs} = 0.5.10^{-20}cm^2$ and 3% atm. doping Tm$^{3+}$

Table 4.3: Table of pump power incident on rod from one pump source only with transmission and absorption efficiency $\eta_{abs}$.

The laser rod, the power transmitted through the alternative pump's input coupler was measured (i.e. pump power leaking through m1 for pumping with Pump2). These measurements, though obviously not real-time whilst conducting the laser experiments, allowed the respective pump diode-bars to be temperature tuned to the maximum Tm$^{3+}$:YAG absorption for the highest available drive current. This pump wavelength tuning was conducted whilst the laser was lasing to reduce the risk of thermal fracture to the rod though no fractures were observed throughout these experiments. The results of this experiment are given in table 4.3. The rod used for this absorption experiment was 17mm long 3% atm. doped Tm$^{3+}$:YAG.

4.3.3 Results

Threshold measurements were conducted using the chopped output from the laser, incident on a PbS detector. This clearly showed the change from amplified spontaneous emission (ASE) build up to threshold and was much more sensitive than using the Molelectron thermal power meter for threshold measurements. Threshold was achieved for ~10 W incident pump power from diode-bar pump1 and ~12W incident pump power when pumped independently by pump2. The higher threshold resulting from pumping by pump2 can be explained by the slightly astigmatic pump beam (due to transmission through the tilted cavity mirror m2) and more importantly the position of the strongest section of the thermal lens in the Tm$^{3+}$:YAG rod. The resonator was designed to accommodate the thermal lens position (albeit with a thin lens approximation) close to the input coupling mirror.
m1. This small difference in the initial position of the thermal lens, when pumping with pump2 only, results in an alternative $w_L$ to $w_P$ overlap at low powers and the response of the resonator causes a higher threshold.

The change in output power with incident pump power is shown in 4.7. The output powers were measured using a Molelectron PM150-50C and EPM1000 thermal power meter and a Coherent LM45 thermal power meter. Both meters gave identical results $\pm$ 0.05W. The $M^2$ values of the laser in both orthogonal planes were $= 1.3$. The $M^2$ values were measured using a Merchantek Beamscope with InS detector head translated along the axis of beam propagation at a focus of the laser output beam. The Merchantek Beamscope, using an InAs detector, scans two orthogonal slits across the beam propagation direction and electronically determines the variational beam profile to find the second moment of the beam. At least five measurements of spot-size were made within 2 times the Rayleigh Range in accordance with the ISO standard [ISO:11146:1999].

The laser operated at a wavelength of 2.013µm throughout the experiments. This was verified with a 300 lines/mm Bentham Monochromator and a Burleigh WA-1000 Wavemeter. The laser showed good temporal stability with the maximum power maintained and repeatable over several hours with power fluctuations $\lesssim 2\%$.

The maximum combined pump power of 53.4W incident on the rod yielded a laser output power of 14.2W at 2.013µm. The output beam was unpolarised and near-diffraction-limited with measured orthogonal $M^2=1.3$. The laser shows a slope efficiency of $\sim 34\%$ with a threshold of $\sim 10W$ of incident pump power.

Mirror m2 was used at an angle for which the coatings were not designed and this may have reduced the laser efficiency. Optimisation with corrected coatings and a re-design of the copper rod mount and heat-sink should reduce the laser loss and the angle of reflection bringing a small increase in performance.

### 4.3.3.1 Pumping Efficiency

It is common to choose the laser rod length to be $\approx 2$ absorption lengths ($L_{abs} = 1/\alpha_{abs}$) and hence the absorption efficiency $\eta_{abs}$ will be high at $\sim 0.87$. 
4.3 High Power > 14W CW Near Diffraction Limited Tm³⁺:YAG Laser

![Graph showing output power at 2 μm vs. total pump power incident on rod faces with slope efficiency of 0.34%](image)

**Figure 4.7:** Output power of unpolarised high power Tm³⁺:YAG laser with good beam quality.

It can be seen from table 4.3 that the absorption efficiency decreases slightly at higher pump powers. It is thought that this is why the 17mm rod length selected was more successful than other shorter rods available even though the rod was >3 times the expected pump absorption length of $L_{abs} = 4.8\text{mm}$ (taking the small signal pump absorption coefficient to be $2.07\text{cm}^{-1}$ from an absorption cross-section $\sigma_{abs} = 0.5 \times 10^{-20}\text{cm}^{-1}$ and the 3% atm doping concentration $N_0 = 4.14 \times 10^{20}\text{cm}^{-3}$). We might expect the threshold for this laser to be unduly high due to the re-absorption loss is proportional to the length of the laser rod.

However the table 4.3 shows that at the higher pump powers the absorption length increases and the absorption efficiency reduces. This is thought to be due to some ground-state bleaching at the pump wavelength due to the high pump intensities.

In a four-level-laser there is no restriction on the rod length as due to reabsorption loss but with quasi-three-level lasers there is an optimisation to be made between rod length and absorption. Fan and Byer [Fan87] determined this to be given by a minimisation of $P_{th}$ in equation 2.3 which yields the condition given by equation 4.4.

\footnote{though pump beam quality may largely dictate acceptable rod lengths in accord with equation 4.3.}
Figure 4.8: Plot of $P_{\text{threshold}}$ for a Tm$^{3+}$:YAG laser vs rod length.

\[
\frac{(L + T + 2N_0 l \sigma_{em} f_L) e^{-\alpha l}}{1 - e^{-\alpha l}} - 2\frac{N_0 f_L \sigma_{em}}{\alpha} = 0
\]  

Using the parameters in table 4.2 with an output coupling $T$ of 0.058 and $L = 0.02$ then we can solve equation 4.4 to give an optimum rod length of $\sim 8\text{mm}$. Note that if we take the reduced absorption coefficient from the experiments as $\alpha \approx 132 \text{ m}^{-1}$ then the optimum length is lengthened to $10.5\text{mm}$.

Figure 4.8 shows the change in expected pump threshold against change in laser rod length. The small signal absorption coefficient assumes that the population density in the ground state $N_0 \gg N_{\text{excited}}$ populations in excited states.

### 4.3.3.2 Threshold Pump Power

Using the values from table 4.2 and equation 2.3 and taking the output coupling as 0.058 and other cavity losses as 0.02 then we can calculate a value for the expected threshold of the laser of $P_{\text{th}} \approx 2.3W$.

However the experimental result was a threshold of $\sim 10W$ incident on the rod from pump source 1. Upconversion is one explanation for this increase in the
threshold relative to the calculation. [Rustad96] shows that upconversion can more than double the threshold though this calculation does not take into account the additional cyclic heating effects and loss below threshold.

The resonator was not quite optimal as the laser mode size for very long thermal lens focal lengths was higher than the pump mode size. This would increase the threshold due to poor initial mode-matching which in turn increases the upconversion and heating associated with the upconversion. The resulting shorter focal length thermal lens increases the laser-pump mode-matching and hence relatively reducing the threshold but at the higher inversion density.

Visible fluorescence was observed from the pumped region of the Tm$^{3+}$:YAG rod though this was not measured. As discussed earlier in the chapter, this fluorescence is thought to be emission from the $^4G_4$ manifold to the ground state. The population of this manifold is thought to be due to excited-state pump absorption from the upper laser level.

### 4.3.4 Summary

This experimental result brings together several of the power scaling strategies discussed earlier in the thesis. Excellent pump beam quality from the beam-shaper provides the platform to control the pump light to enable good thermal management with pump spot-size choice and tight focussing allowing optimal pumping of the low gain transition. The resonator design incorporates the $dw/df_{\text{thermal}}$ characteristics of increasing laser spot size for shortening thermal lens focal length and the good beam quality from the laser indicates that this strategy is in part successful.

The laser shows high efficiency and power output combined with good beam quality. The laser also had a longer resonator than previously available [Bollig98a] which gives more flexibility to any further developments to intracavity pumped Ho$^{3+}$:YAG lasers.

The threshold was higher than the expected threshold from calculations and some improvement should be made to reduce this. Upconversion is thought to be the main cause for the high threshold [Rustad96] but the dopant concentration cannot
be justifiably reduced as this would start to reduce the cross-relaxation efficiency. The resonator may be able to be further optimised to reduce the mode size at longer thermal lens focal lengths as this is thought to be a cause for increased upconversion near threshold. Unfortunately due to failure of the diode-bar pump sources, further optimisation of the laser was not possible. The lengthening of resonator arm m3-m4 should result in a smaller laser mode size at very long thermal lens focal lengths and this should reduce the threshold.

4.4 De-Polarisation Loss Compensated Polarised High Power Tm$^{3+}$:YAG Laser

4.4.1 Introduction

Many applications of Tm$^{3+}$:YAG lasers require linearly polarised output. Chapter 6 of this thesis describes work conducted on Ho$^{3+}$:YAG lasers intracavity pumped by Tm$^{3+}$:YAG lasers. One of the proposed designs for an intracavity pumped Ho$^{3+}$:YAG laser in section 6.5 requires a polarised Tm$^{3+}$:YAG laser.

Thermally induced birefringence in the diode-bar pumped Tm$^{3+}$:YAG laser rod causes a disturbance to the linear polarisation state defined by the linearly polarising element of the laser (usually a Brewster plate). Upon a round-trip the disturbed polarisation states that do not match the linearly polarising elements cause a loss to the laser and reduce the performance of the laser. This additional loss is called de-polarisation loss. There have been several strategies to compensate for this de-polarisation loss and these have been discussed in chapter 2. The compensation scheme used here is the simple inclusion of a Quartz quarter-wave plate between the laser rod and a near mirror [Clarkson99].

In this section two lasers are described which show the effectiveness of the de-polarisation compensation scheme. The author did not contribute to the development of the scheme but to the best of the authors knowledge this is the first demonstration of the compensation schemes applied at the longer wavelength of 2.013μm.
4.4.2 Experimental Setup

Two Tm\(^{3+}\):YAG lasers were developed to compare the performance of a laser suffering de-polarisation loss and the performance of a laser with the same conditions but using the compensation scheme briefly shown above. Both lasers were developed using some of the power scaling strategies detailed in 2.

Both lasers, compensated and un-compensated, were near identical to the laser experiment detailed in section 4.3.2.

The primary differences are the inclusion of a Brewster angled thin glass plate.

The resonator \(dw/df\) characteristics were as before chosen to give both good slope efficiency and high output power whilst maintaining good beam quality. The resonator mirrors and distances between mirrors were the same as in the previous laser experiment as were the pump lasers and the pump coupling optics.

The uncompensated laser was similar to the resonator shown in figure 4.10 the only difference being the removal of the quarter-wave plate. The 17mm long, 3mm diameter, 3% atm. doped Tm\(^{3+}\):YAG rod was mounted in a copper heat sink which in turn was mounted to a water-cooled copper block. The rod was end-pumped from both ends by 2 coherent 40W diode-bars. Each diode-bar was beam-shaped to equalise the \(M^2\) between the two orthogonal directions parallel and perpendicular to the plane of the diode junction. This facilitated high efficiency coupling of the output beam into a multi-mode 250\(\mu\)m core fibre coupler of length 1.5m. The fibre coupler provided easy access to the pump light across the optical bench. The laser rod mount was kept at \(\sim\)20 °C by the water cooling.

In order to compare the compensated laser with the uncompensated laser, the resonator was required to be comparable for a large range of thermal lens focal lengths without a severe change in the laser mode size at the lens. This would ensure that should the uncompensated laser suffer a large de-polarisation loss at high pump powers, the resonator response (changes in laser mode-size) should not be a significant factor in any performance differences between the two lasers.

The uncompensated laser was first optimised and the threshold, change in output power with pump power and power reflected from the Brewster plate was mea-
4.4 Depolarisation Loss Compensated Polarised High Power Tm$^{3+}$:YAG Laser

Figure 4.9: Resonator design for the high power de-polarisation compensated Tm$^{3+}$:YAG laser incorporating a quarter-wave plate.

The quarter-wave plate was inserted between mirror m1 and the laser rod face with its fast and slow axes aligned parallel or perpendicular to the preferred plane of polarisation defined by the polariser. The compensated laser was then characterised in the same way as for the uncompensated laser. The beam quality was quantified for both lasers using a Merchantek Beamscope to measure the $M^2$ of the focussed output from the lasers for the highest sustainable pump powers.

The power reflected from the intracavity Brewster plate was measured and compared with the power emitted from the laser output coupler. The comparison then gives a relative measure of half (there are two reflections from the Brewster plate, one for each intracavity field direction) the loss to the laser due to depolarisation caused by the thermal effects in the laser rod. If the laser were perfectly linearly polarised by the Brewster plate and the state of polarisation were not disturbed by any intracavity components then no power should be observed reflected from the plate. This means that errors in the measurement of depolarisation loss due to the laser rod are also susceptible to imperfect alignment of the Brewster plate and polarisation changes due to off-axis mirrors etc. Any errors in the alignment of the Brewster plate was constant for both lasers and the resulting loss to the laser would be independent of any thermally induced de-polarisation loss from the laser rod polarisation effects.
4.4 De-Polarisation Loss Compensated Polarised High Power Tm$^{3+}$:YAG Laser

![Graph showing output power and efficiency.]

Figure 4.10: Output power and slope efficiencies for the high power de-polarisation compensated Tm$^{3+}$:YAG laser incorporating a quarter-wave plate and its comparison laser without compensation.

4.4.3 Results

The output powers with change in incident pump powers are given in figure 4.10. The uncompensated laser had a threshold of 11.7W compared with the 10.5W incident threshold pump power for the compensated laser. The maximum power output from the compensated laser was 11.5W for 53.7W of incident pump power combined from both the diode-bars. This gives an approximate slope efficiency of $\sim 27\%$. The maximum power output from the uncompensated laser was 8.39W for 49.9W giving a slope efficiency of $\sim 22\%$ before the laser action ceased. Pumping above these levels resulted in the cessation of laser action as shown in the figure 4.10.

The beam quality of the two lasers was near identical with $M^2$ values of 1.2 and 1.4 in orthogonal directions.

The measurements of the loss from the Brewster plate showed that for the uncompensated laser the round-trip loss was $\sim 5\%$ or higher which prevented lasing whilst the compensated laser depolarisation loss was $\lesssim 0.4\%$.

It was thought that the increased loss to the laser from depolarisation, increased the inversion density at and above threshold. The upconversion rate is dependent on the upper laser level population. The increased upconversion relative to the
compensated laser results in additional heating and thermal effects such as lensing and birefringence. The laser can then suffer a runaway effect as the increasing thermal load increases the loss until the laser losses equal the maximum gain and the lasing action ceases.

4.4.4 Summary

This experiment has resulted in 11.5W linearly polarised output at 2.013μm with good beam quality ($M^2 \sim 1.2$ and 1.4).

These lasers show the benefits of the de-polarisation loss compensation scheme applied to a 2μm system. The inclusion of the quarter-wave plate reduces the loss by an order of magnitude and allows the resonator to support the increased pump power.

4.5 Summary

The unpolarised high power Tm$^{3+}$:YAG laser in section 4.3 shows a combination of the power scaling strategies discussed in chapter 2 in action. The use of the beam-shaper to control the pump source and the $d\omega_1/d\omega_{thermal}$ characteristics resonator design have both been shown to be successful.

We can see that the brightness of this laser, shown as [Hayward01] in table 4.1 shows the relative brightness between this laser and the much higher power lasers at this wavelength. Brightness is critical for applications such as nonlinear optical conversion and pumping of other lasers.

The polarised output from the thermally induced birefringence related depolarisation compensated laser has also been successful. The compensation scheme for thermally induced birefringence has already been shown at other wavelengths ($\lambda \sim 1\mu m$) to be highly effective and now it has been shown here at 2μm to be extremely effective, enabling a high power polarised laser. The relative increase in the depolarisation loss at this longer wavelength compared with 1μm sources shows the value of using such a simple to implement scheme.
4.5 Summary

The design of the resonators for the lasers in this chapter were still not optimal and this points to a deficit in this power scaling strategy that the lasers must operate near the limits of their thermal lenses with the correct mode sizes. The current models of heat loading and the subsequent self-feeding losses to the lasers from the coupling between upconversion related heating and heating related losses are not fully understood and this causes some errors in the resonator design which makes optimal design still difficult. Yet if these factors are known then the thermal effects can be partially compensated for and used with this $dw_l/df_{\text{thermal}}$ power scaling strategy.

Further study into the causes of the thermal loading and their impact on losses to the laser could bring the $dw_l/df_{\text{thermal}}$ strategy more improvements.

These Tm$^{3+}$:YAG lasers are high power efficient sources in their own right and provide a good base for pump sources in the development of high power intracavity pumped Ho$^{3+}$:YAG lasers as a bulk route for obtaining high powers at 2.097$\mu$m.

References


4.5 Summary
electronics Research Centre, University of Southampton, UK (1997).


4.5 Summary


Chapter 5

High Power $\text{Tm}^{3+}:(\text{Lu},\text{Y})\text{AG}$ Laser and a comparison with $\text{Tm}^{3+}:\text{YAG}$ Laser

5.1 Introduction to $\text{Tm}^{3+}:(\text{Lu},\text{Y})\text{AG}$

The suitability of materials for 2μm applications has already been discussed. Atmospheric lidars require a laser with an output wavelength corresponding to one where there is high atmospheric transmission. The typical peak gain from $\text{Tm}^{3+}:\text{YAG}$ lasers at an output wavelength of 2.013μm has poor transmission (-1.3dBkm$^{-1}$) and often $\text{Tm}^{3+}:\text{YAG}$ lasers are tuned to ~2.020μm as the atmospheric transmission is better -0.8dBkm$^{-1}$ (see table on page 6).

Thulium doped lutetium-yttrium aluminium garnet ($\text{Tm}^{3+}:(\text{Lu},\text{Y})\text{AG}$) is a material whereby a percentage of the yttrium ions have been replaced by lutetium ions. Previous experiments [Kmetec94] have shown that this has the effect of shifting the room-temperature peak operating wavelength of a laser operating on the $\text{Tm}^{3+} {^3}H_4 \rightarrow {^3}H_6$ transition from ~2.013μm (form 0% Lu$^{3+}$ replacement) towards 2.025μm. A precise mechanism for this effect has not been determined in either this, or previous works. [Kmetec94] suggests that there is some inconsistency in the peak emission wavelength shift with different lutetium doping concentrations.
There may be variations in wavelength shifts between crystal boules although this is difficult to determine without a large number of boules.

Lutetium is a member of the rare-earth lanthanides with a atomic weight of 174.967 (most stable isotope). When compared with yttrium (atomic weight 88.906) we can see that the lutetium replacement is a much heavier body. If the yttrium is completely replaced in-site by a lutetium ion then this can be a source of stress in the crystal thus changing the host field that interacts with the active thulium ion. This then modifies the energy level splitting of the Tm$^{3+}$ and results in the characteristic peak laser emission wavelength $\sim 2.022 \mu m$.

Co-doped Ho$^{3+}$ with Tm$^{3+}$ [Kushawaha96c] 2μm lasers have also been demonstrated with lutetium doping for lutetium concentrations varying from 0% to 100%. Low temperature 77K Ho$^{3+}$:Tm$^{3+}$:LuAG lasers [Kushawaha96c] have produced cw 2.1μm output power of 1.38W with a slope efficiency of $\sim 35\%$. This shows that co-doped materials can exhibit high cw efficiency at Ho$^{3+}$ wavelengths. However co-doped Tm$^{3+}$ and Ho$^{3+}$ LuAG or Lu,YAG suffers from the same Ho$^{3+}$ $^5I_7 \rightarrow ^5I_8$ transition lifetime quenching as seen in co-doped Tm$^{3+}$:Ho$^{3+}$:YAG lasers.

[Grund97] provides a field tested demonstration of a doppler lidar application using a diode-pumped Q-switched Tm$^{3+}$:(Lu,Y)AG laser. The laser developed for [Grund97] was diode-pumped by two sets of 5 × 3W 785nm laser diodes which were fibre coupled and focussed into the ends of the Tm$^{3+}$:Lu,YAG laser rod. The laser was injection-seeded by a single frequency Tm$^{3+}$:YAG via a 100MHz AO Modulator which also served to Q-switch the laser. The laser produced 1.2mJ pulses with a pulse duration of 300ns (injection seeded) and a repetition rate of 1kHz. This performance was observed consistently in a marine field test. Laboratory performance was reported to be $\sim 5$mJ. This paper shows that a high level of pulsed performance was possible from the the material. [Grund97] also shows the suitability of Tm$^{3+}$:(Lu,Y)AG for doppler lidar applications. The expected performance was $\sim 10$mJ and the explanation given for the lower than expected output pulse energy was thermal lensing induced laser mode narrowing resulting in high fluences on the rod faces (and presumably subsequent damage).

In this chapter a laser resonator optimised for power output was developed in order to compare the power output and efficiency of Tm$^{3+}$:YAG and Tm$^{3+}$:(Lu,Y)AG
5.2 High Power Tm\(^{3+}\):(Lu,Y)AG Laser Optimised For Efficiency

Figure 5.1: Resonator dw/df characteristics for the high power Tm\(^{3+}\):(Lu,Y)AG and Tm\(^{3+}\):YAG lasers.

Lasers. This is of interest because of the apparent similarities between the two laser media. By looking at the power performance and efficiency from a high power laser in a resonator designed to be stable for a large range of thermal lens focal length equivalences it is hoped that the suitability for further power scaling and investigation can be commented upon and compared with the better known material Tm\(^{3+}\):YAG.

5.2 High Power Tm\(^{3+}\):(Lu,Y)AG Laser Optimised For Efficiency

As we have seen for many of the lasers presented in this work and in other works that there is often a compromise between output beam quality and power. In order to easily measure and compare the efficiencies between Tm\(^{3+}\):YAG and Tm\(^{3+}\):(Lu,Y)AG a resonator was designed to be stable and to maintain a constant laser mode size in the rod for a large range of thermal lens focal lengths. Maintaining a constant laser mode size for a large range of thermal lens focal length (for a thin lens approximation) ensures that the laser mode size \(w_L\) to pump mode size \(w_P\) overlap is approximately constant for all available pump powers and the gain volume to laser mode overlap was not influenced by resonator dynamics.

Good beam quality at the highest available powers was not expected due to the
small laser mode size to pump mode size ratio for the short thermal lens focal lengths.

5.2.1 Experimental Setup

The pump setup was similar to the setup for the experiments in chapter 4 on page 48.

The lasers were pumped by two Coherent Inc (B1-785-40C-19-30-A) 40W diode-bars. Each bar was a linear array of 19 emitters. Each emitter output facet was $150 \times 1$ μm and the emitters were spaced 500μm apart. The array was 1 cm long. The diode-bars were housed in a metal container and a continuous low pressure supply of Nitrogen was purged through the housing to reduce the likelihood of condensation forming on the bars and their emitter facets. The bars had a spectral width of $\sim 2.5$ nm FWHM centred near 787nm and 789nm respectively and the centre wavelength was temperature tuned to the Tm$^{3+}$:YAG absorption feature at 785nm. The diode-bars could be tuned by $\sim 0.3$nm/degree. The diode-bars' beam divergences were specified as $\lesssim 10$ ° for the slow axis and $\lesssim 35$ ° in the fast axis.

The output from the diode-bar was collimated with a fibre lens and then the emitters were imaged onto the second mirror of the beam-shaper (see figure 2.5. The two-mirror beam-shaper developed by Clarkson was used to equalise the $M^2$ values for both planes of the diode-bar output. A more complete description of the action of the beam-shaper is given in [Clarkson96]. The beam-shaper cuts the image up and overlaps the output into a single output beam thereby reducing the $M^2$ in one plane whilst increasing the $M^2$ value for the other plane with only a slight reduction in brightness. The output $M^2$ values in orthogonal planes from the beam-shaper were $\sim 75$ and $\sim 68$.

The output beam from the beam-shaper was then collected and focussed into a 250μm diameter multi-mode fibre with an Numerical Aperture (N.A.) of 0.22, length 1.5m and was used to deliver or couple the pump light to the pump focussing arrangements. The fibre delivery coupler provided very easy access to the pump light whilst again only slightly reducing the brightness of the pump. The $M^2$ after the fibre coupler was 78 and 79 in orthogonal planes.
5.2 High Power Tm\textsuperscript{3+}:(Lu,Y)AG Laser Optimised For Efficiency

Figure 5.2: Resonator setup for the high power Tm\textsuperscript{3+}:(Lu,Y)AG and Tm\textsuperscript{3+}:YAG laser.

One lens of focal length $f = 50$ mm was used to collimate the output from the fibre coupler and another of focal length $f = 150$ mm was used to finally focus the pump light into the Tm\textsuperscript{3+}:YAG rod through the input coupler. This arrangement was repeated on at each end of the Tm\textsuperscript{3+}:YAG rod. The final focussing lenses brought the pump to a focus of 400 $\mu$m in both orthogonal planes with $M^2$ of 78 and 79.

The experimental setup is given in figure 5.2 on page 79. There were two lasers developed to compare the performance between Tm\textsuperscript{3+}:(Lu,Y)AG and Tm\textsuperscript{3+}:YAG. The only difference between the lasers was the replacement of a Tm\textsuperscript{3+}:(Lu,Y)AG rod with a Tm\textsuperscript{3+}:YAG rod. Both rods were 3mm diameter, 17mm long and 3% atomic doped with Tm\textsuperscript{3+}.

The resonator arm lengths were $\sim$1mm between the input coupling end mirror and the rod, 35mm from the rod to the first plane-plane turning mirror, $\sim$46mm from the turning mirror to the 150mm radius of curvature concave mirror and the final distance was 129mm to the plane-plane output coupling end mirror.

The output power and threshold were measured with change in incident pump power. The laser output wavelengths $\lambda_L$ were measured using a Bentham monochromator and a Burleigh Wavemeter WA-1000. No intracavity elements were introduced to define the laser wavelength.

5.2.2 Results

The threshold pump power for the Tm\textsuperscript{3+}:(Lu,Y)AG laser was 5.6W and the Tm\textsuperscript{3+}:YAG laser had a slightly lower threshold of 5.2W. The output power with
change in pump power for both lasers is shown in figure 5.3. The slope efficiency of the Tm\(^{3+}:(\text{Lu,Y})\)AG laser was 38% with the Tm\(^{3+}:\)YAG laser showing 37% efficiency.

Laser output wavelength varied with small alignment adjustments to the resonator and pump power. The Tm\(^{3+}:(\text{Lu,Y})\)AG laser showed a range of output wavelengths \(\lambda_L\) from 2.0197 to 2.0264 \(\mu\)m with 2.0215 \(\mu\)m being the most frequent. At low incident pump powers the laser operated at the shorter wavelengths (~2.0197\(\mu\)m whilst for higher pump powers it operated at the longer wavelengths (~2.0215-2.0223\(\mu\)m). The laser would require wavelength definition and stabilisation to perform as a lidar source.

### 5.2.3 Summary

These results show that Tm\(^{3+}:(\text{Lu,Y})\)AG lasers are capable of high powers with thermal stability and high efficiencies. Direct comparison between the two Tm\(^{3+}\) lasers shows that this particular Tm\(^{3+}:(\text{Lu,Y})\)AG laser to have a slightly higher efficiency and output power. The small difference in performance could be a due to slight variations in alignment and laser rod heat-sinking. The result indicates that the material Tm\(^{3+}:(\text{Lu,Y})\)AG has very similar characteristics to Tm\(^{3+}:\)YAG even
at high powers and is suitable for power scaling using the techniques described elsewhere in this thesis. To the best of the authors knowledge this experiment reports the highest power Tm\(^{3+}:(\text{Lu,Y})\)AG laser yet reported.

5.3 Summary

The material provides a viable alternative to Tm\(^{3+}:\text{YAG}\) as a laser medium suitable for eyesafe lidar lasers in the 2022nm region. Tm\(^{3+}:(\text{Lu,Y})\)AG has become commercially available providing easy access to the material. The small but welcome wavelength advantage over Tm\(^{3+}:\text{YAG}\) with no discernable disadvantages suggest that Tm\(^{3+}:(\text{Lu,Y})\)AG lasers deserve further consideration. There would be merit in developing a Q-switched, cw diode-bar pumped Tm\(^{3+}:(\text{Lu,Y})\)AG laser using the power scaling strategies discussed elsewhere and this would provide an excellent source for numerous lidar applications.

It should be noted that in the context of this thesis, this laser is the only laser that is not aimed towards the development of a high power Ho\(^{3+}:\text{YAG}\) source for lidar but is included as an source of interest in its own right.

References


4.5 Summary

Chapter 6

Intracavity-Pumped Ho$^{3+}$:YAG Lasers

6.1 Introduction

Holmium lasers operating at $\sim$2.1$\mu$m have many applications including coherent laser radar and as a pump source for nonlinear generation across the 3-5$\mu$m wavelength region. Ho$^{3+}$:YAG is a material of particular interest as the peak emission wavelength corresponds with a region of high atmospheric transmission with a large $\sigma$($\tau$ product compared with Tm$^{3+}$:YAG. The long upper level lifetime of $\tau$ $\sim$8.9ms provides a potentially large energy storage suitable for high pulse energy $Q$-switched operation required for long range coherent lidar. The YAG host (Y$_3$Al$_5$O$_{12}$) has well known robust properties as seen with Tm$^{3+}$:YAG lasers elsewhere in this work and in the literature of high Knoop strength, good thermal conductivity, high optical quality, consistent boule standards and a large thermal shock parameter $R$ ($\sim$7.9 Wcm$^{-1}$) compared to other materials such as YLF or YALO.

Efficiently pumping Ho$^{3+}$ lasers to operate with high powers at 2.1$\mu$m has proven difficult and various pumping schemes have been reported.

As discussed in chapter 2, co-doping Ho$^{3+}$ with Tm$^{3+}$ in a crystal host is a path to pumping Ho$^{3+}$:YAG and careful selection of the doping concentrations and laser
design has shown high cw efficiency and output powers [Fan88]. Unfortunately co-doping restricts the potential energy storage in Ho\(^{3+}\):YAG by providing cooperative energy transfers between neighbouring Tm\(^{3+}\) and Ho\(^{3+}\) ions which reduce the inverted population in the Ho\(^{3+}\) ions and hence reduce the energy storage. This means that co-doping is an unfavourable route for developing a high pulse energy Q-switched Ho\(^{3+}\):YAG laser suitable for coherent lidar applications.

Direct diode laser pumping of Ho\(^{3+}\):YAG is also difficult due to the unavailability of high power diode-lasers at suitable wavelengths (\(\sim 1.95\)\(\mu\)m). Nabors et al [Nabors95] demonstrated a laser providing \(\sim 0.7\)W at 2.1\(\mu\)m for 3.6W of pump power where the Ho\(^{3+}\):YAG laser was operated at a temperature of -53 \(^{\circ}\)C. The Ho\(^{3+}\):YAG laser was pumped by 6 angle-multiplexed and polarisation coupled diode-lasers operating at 1.9\(\mu\)m each providing a pump power of \(\sim 0.7\)W. The laser showed good slope efficiency of \(\sim 35\)%.

The laser output power was noted to drop to \(\sim 0.2\)W for room temperature operation at \(\sim 15\) \(^{\circ}\)C due to the increased lower laser level population at the higher temperatures. Despite the modest powers, direct diode-laser pumping is presently restricted by the powers of the diode-laser pump source. Should high power diode-bars become available for the required wavelength range 1.9-1.98\(\mu\)m then direct diode-bar pumping would be enable increased Ho\(^{3+}\):YAG laser efficiencies.

However direct pumping by an external diode-pumped Tm\(^{3+}\) based laser has been shown to be effective and efficient. Budni et al [Budni00] show high powers and efficiencies from a Tm\(^{3+}\):YLF laser and demonstrate direct pumping of a Ho\(^{3+}\):YAG laser producing 9.5W of output power for \(\sim 20\)W of incident power from the Tm\(^{3+}\):YLF laser. The beam quality of the Ho\(^{3+}\):YAG laser was reported to have an \(M^2\) of 1.22. The Ho\(^{3+}\):YAG laser was then used to pump a ZnGeP\(_2\) (ZGP) optical parametric oscillator (OPO) to provide efficient high power \(\sim 4.2\)W of the combined signal (3.8\(\mu\)m) and idler (4.6\(\mu\)m).

Both of the above direct pumping routes can access singly doped Ho\(^{3+}\):YAG and are able to isolate the energy storage within the Ho\(^{3+}\) ions. Intracavity (IC) pumping of Ho\(^{3+}\):YAG within a cavity of a Tm\(^{3+}\):YAG laser is an alternative method for efficiently pumping singly doped Ho\(^{3+}\):YAG. The IC pumped laser that generated much of the interest for this work is that of Stoneman and Esterowitz
[Stoneman92]. In that work they used a Ti:Sapphire pumped Tm$^{3+}$:YAG laser to intracavity pump a Ho$^{3+}$:YAG laser producing 120mW of output at 2.091μm from the Ho$^{3+}$:YAG laser with a slope efficiency of 42% from Ho$^{3+}$:YAG laser output to 785nm pump power absorbed. This demonstration showed that the combination of laser materials also used in this work could operate efficiently in an intracavity (IC) pumping scheme and offered an alternative route to pumping Ho$^{3+}$:YAG.

6.1.1 Intracavity Pumped Lasers

IC pumping lasers can provide novel laser sources for as range of wavelengths and a number of interesting features. IC pumping lasers consist of a laser (primary laser) that is pumped within the cavity of the pump laser (secondary laser). The output coupling for the secondary pump laser is the absorption of the primary laser and the output coupling for the primary laser is the wanted useful emission, typically from a partially reflecting mirror.

Several IC pumping schemes have been demonstrated with a range of primary and secondary hosts and geometries. Anthon et al [Anthon93] describes a wide ranging and general patent on the IC pumping schemes and [Anthon90] shows a Nd:YAG laser intracavity pumping an Yb-sensitised Er:phosphate glass. An interesting feature of this laser is that because the IC pump laser wavelength (secondary laser wavelength, Nd:YAG) and the primary Er:glass laser wavelength are distinct (1.064μm vs 1.536μm) the laser cavities could easily be separated by dichroic coatings on the rod faces. This example fits into what will be called a "de-coupled" intracavity pumped laser (see figure 6.1) as the primary laser does not share a cavity with the secondary laser and hence is de-coupled.

Spariosu and Birnbaum reported [Spariosu94] an Er:YAG laser operating at 1.634μm by IC pumping from a flashlamp pumped Er:glass laser. This is an example of a "Coupled" IC pumped laser because the primary laser shares the cavity with the secondary laser (see figure 6.2). Another example of a coupled IC pumped laser is Abraham et al [Abraham92] where an erbium doped fibre laser was pumped within the cavity of a diode-laser by making the back facet (the other side of the diode-laser from the fibre) highly reflecting to the erbium laser wave-
6.1 Introduction

Figure 6.1: General schematic of a de-coupled intracavity (IC) pumped laser. Note: the Primary Laser does not share a cavity with the Secondary laser.

Figure 6.2: General schematic of a de-coupled intracavity pumped laser. Note: the primary laser shares the cavity with the secondary laser.

length. An another interesting example of an IC pumped laser is the pumping of Tm$^{3+}$:YAG within a Nd$^{3+}$:YAG laser [Phua00]. This interesting application of the IC pumping scheme provides both 1μm and 2μm radiation and a maximum 2μm output power of 4.7W.

It should be noted that the laser of Stoneman and Esterowitz [Stoneman92] was also an example of a coupled IC pumped Ho$^{3+}$:YAG laser as the wavelengths of both the primary and secondary are so close together (2.013μm to 2.097μm) that it is difficult to manufacture dichroic coatings on the Ho$^{3+}$:YAG laser rod that has the required very low loss T>99.99% at 2.097μm whilst also providing very high transmission for the Tm$^{3+}$:YAG laser pump at 2.013μm.

The IC scheme enables strong pumping by using the high IC laser field of one laser with the the absorption feature of another laser. The absorption feature can have a very weak absorption cross-section relative to a feature suitable for extra-cavity pumping. Extracavity pumping of such a weak absorption would normally result in poor efficiency and require an extremely long absorption length. This would be prohibitive in the case of quasi-three-level lasers where absorption medium
length must be optimised whilst minimising re-absorption losses. The IC scheme
overcomes this by pumping with the IC field which can often be several orders
of magnitude higher than the useful output available through a laser’s output
coupling. For this reason the IC design can allow access to low gain laser transitions
that require intense pumping.

A feature of IC pumping Ho$^{3+}$:YAG by a Tm$^{3+}$:YAG laser is that the Ho$^{3+}$:YAG
laser is pumped inband (the pump transition and the laser transition are between
different Stark levels in the same two multiplets/manifolds). This has the advan-
tage of a potentially very small minimum quantum defect heating fraction ($\frac{\nu_p-\nu_4}{\nu_p}$)
arising from heating by non-radiative decay between the upper pump level and
the upper laser level and between the lower laser level and the ground state
assuming a quantum pump efficiency of 1(every pump photon absorbed results in a
lasing photon). For the Tm$^{3+}$:YAG laser pumping at 2.013$\mu$m and the Ho$^{3+}$:YAG
laser operating at 2.097$\mu$m this gives us a quantum defect heating fraction of only
4% compared with 24% for Nd:YAG ($\lambda_L=1.064\mu$m and $\lambda_P=808\text{nm}$) and 22% for
Tm$^{3+}$:YAG with 100% efficient two-for-one cross-relaxation (taking $\frac{\nu_p-2\nu_4}{\nu_p}$ with
$\lambda_L=2.013\mu$m and $\lambda_P=785\text{nm}$). A low quantum defect heating is an advantage to
power scaling as the lower the thermal loading for a given absorbed pump power
the lower the relative thermal effects are for a comparable laser with a higher defect
heating.

There are more benefits to be sought by power scaling IC pumped lasers. Not
only is inband pumping a common benefit with regard to heat generation, there
is also a de-coupling of the thermal effects between the diode-pumped Tm$^{3+}$:YAG
pump laser and the IC pumped Ho$^{3+}$:YAG laser. This should give more tolerance
in the design of the Tm$^{3+}$:YAG laser allowing optimisation for power as the beam
quality of the Tm$^{3+}$:YAG laser should provide much lower $M^2$ than direct diode-
bar pumping whether beam-shaped or not. The IC pump scheme also lends itself
well to pumping the IC laser rod over a long length due to the characteristically
low absorption and long absorption lengths. This distributes the heat loading over
a longer length allowing a greater surface area of the rod to be cooled. The IC
pump scheme also enables pumping of low doping concentrations efficiently and
the doping concentration can be tailored to lower upconversion effects.
There are some drawbacks to intracavity pumping. On obvious problem that must be addressed is the coupling of the Tm$^{3+}$:YAG and Ho$^{3+}$:YAG laser cavities. As the eventual aim is a high pulse energy $Q$-switched Ho$^{3+}$:YAG laser the cavity $Q$ must be switched for the Ho$^{3+}$:YAG laser whilst maintaining the $Q$ for the Tm$^{3+}$:YAG laser. This is necessary to maintain the cw Tm$^{3+}$:YAG pumping of the Ho$^{3+}$:YAG rod as the energy storage is built to take advantage of the long upper level $^5I_7$ lifetime of the Ho$^{3+}$ ion.

Another possible drawback is the inherent coupling of the inversion and photon population dynamics of the two lasers. Instabilities in one of the lasers (primary or secondary) could affect the dynamics of the other due to possible changes in intracavity powers or Ho$^{3+}$:YAG absorption may disturb the spectral and power outputs of the Ho$^{3+}$:YAG laser. This would have detrimental effects on the performance of a lidar based on one of these lasers. The possible effect of this behaviour will be addressed throughout the chapter.

6.1.2 Previous 2$\mu$m Diode-Bar Power-Scaling

The aims of this work were to develop power scaled Ho$^{3+}$:YAG lasers, intracavity pumped by diode-bar pumped Tm$^{3+}$:YAG lasers. Additional aims were to investigate resonators that de-couple the primary and secondary lasers. Earlier work on power scaling an intracavity pumped Ho$^{3+}$:YAG laser reported a diode-bar pumped Tm$^{3+}$:YAG laser intracavity pumping a Ho$^{3+}$:YAG laser [Bollig98] producing 2.1W for 9.2W incident on the Tm$^{3+}$:YAG rod. The beam quality was measured to be good with $M^2$ of 1.6 in both orthogonal planes. The author assisted with the preparation for this experiment and some of the analysis. The cavity design is given in figure. 6.3.
Figure 6.3: Intracavity pumped Ho$^{3+}$:YAG laser experimental setup producing 2.1W of near diffraction limited output at 2097nm.

6.2 Spectroscopy

6.2.1 Energy Levels

Figure 6.4 shows many of the levels of Ho$^{3+}$:YAG. The levels are drawn to scale. The level structure for Ho$^{3+}$:YAG is split into the Stark levels by the host. The main manifolds of interest to us are the $^5I_8$ and $^5I_7$, the ground state manifold and upper laser manifold respectively. The ground state manifold is split into 17 Stark levels with energies from 0 to 536 cm$^{-1}$. For a temperature greater than 0K the number of ions in the ground state will be Boltzmann distributed with the fraction of the total number of ions in that state $f_{m,s}$ (where the indices $s$ denotes the Stark level within the manifold $m$) and is given by equation 2.1 on page 10 ([Fan87]).

6.2.2 Fractional Populations of the Laser Manifolds

The Boltzmann fractional populations for the $^5I_8$ ground state are given in table 6.1 for different crystal temperatures. The Stark level energies used to calculate the fractions were taken from [Gruber89] and [Bollig97].

The upper laser Stark level is the lowest Stark level of the $^5I_7$ manifold and the lower, 1st laser Stark level is the 12th of the $^5I_8$ manifold for emission at 2.097μm. It can be seen from the equation for quasi-three-level lasers (equation(2.3) on page 11) that the threshold is proportional to the ratio of lower laser level to upper laser level Boltzmann population fractions $f_L/f_U$. We can calculate from tables 6.2 and 6.1 that this fraction increases from 0.1109 to 0.2373 (a 210% increase) for a temperature change from -20°C to 100°C. This suggests that the
Figure 6.4: The lowest 6 energy levels of Ho$^{3+}$:YAG with the energies in cm$^{-1}$. a) shows the pump transition when pumped by Tm$^{3+}$:YAG, b) the Ho$^{3+}$:YAG laser, c) the main upconversion route from the upper laser level, d) a possible diode pump absorption at 785nm and e) observed green emission.
### Table 6.1: $^5S$ fractional Boltzmann populations for a range of temperatures $T$ (in Kelvin).

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change in Boltzmann fractional populations from increased strong thermal loading can have a significant effect on these lasers.

### 6.2.3 Co-operative Ionic Processes

Figure 6.4 also shows some of the transitions of interest to this work. The pump transition a) \( ^5I_8 \rightarrow ^5I_7 \) is accomplished in IC pumping by photon absorption from the Tm\(^{3+}\):YAG laser in contrast to inter-ionic co-operative energy transfer in co-doped Tm\(^{3+}\),Ho\(^{3+}\):YAG systems. The laser transition b) \( ^5I_7 \rightarrow ^5I_8 \) is typically from the lowest Stark level of the \( ^5I_7 \) manifold to the 11th (2.091\( \mu \)m), 12th (2.097\( \mu \)m) and for some Ho\(^{3+}\):YAG lasers the 15th (2.123\( \mu \)m) Stark levels of the \( ^5I_8 \) manifold. The values in brackets are the corresponding emission wavelengths of these transitions. c) is the main co-operative Ho\(^{3+}\)-Ho\(^{3+}\) upconversion route from the upper laser level. The maximum possible energy overlap of a transition is the energy of a transition between the lowest energy Stark level of the lower manifold and the highest energy level of the upper manifold. For the transition \( ^5I_7 \rightarrow ^5I_6 \) this corresponds to a range of transition energies from 3231 cm\(^{-1}\) to 3725 cm\(^{-1}\).
corresponding to an optical transition wavelengths of ~3.09-2.68\mu m. The transfer energy from the \(5I_7 \rightarrow 5I_6\) transition could provide to a co-operative upconversion energy of 4693 \(\rightarrow\) 5490 cm\(^{-1}\). For the co-operative upconversion \(5I_6 \rightarrow 5I_7\) and \(5I_6 \rightarrow 5I_7\) then the direct energy overlap with the minimum difference in energies of 968 cm\(^{-1}\) (4693 cm\(^{-1}\) - 3725 cm\(^{-1}\)) and the maximum difference of 2259 cm\(^{-1}\) (5490 cm\(^{-1}\) \(\rightarrow\) 3231 cm\(^{-1}\)). If we take a value for a typical phonon energy of 850 cm\(^{-1}\) for YAG [Basiev96] then this requires that 1 to 3 phonons must be coupled into the crystal lattice generating heat in addition to the quantum defect heating discussed earlier (section 6.1). Shaw et al [Shaw94] gives the energy transfer probability (or transfer rate) for nearest neighbour ions to undergo the \(5I_8 \rightarrow 5I_7\) and \(5I_7 \rightarrow 5I_6\) process as \(W = (1.7 \pm 0.4) \times 10^5\) sec\(^{-1}\). This transfer rate is large compared to the similar co-operative transition in Tm\(^{3+}\):YAG \(3F_4 \rightarrow 3H_6\) and \(3F_4 \rightarrow 3H_6\) which has a value [Shaw94] of \(W = (3.2 \pm 0.8) \times 10^4\) sec\(^{-1}\) but is small relative to the co-operative transfer giving the two-for-one cross-relaxation process in Tm\(^{3+}\):YAG of \(W = (6.4 \pm 1.5) \times 10^6\) sec\(^{-1}\) (where the high probability is wanted for high efficiency). However, in the Ho\(^{3+}\):YAG laser experiments presented here the ratio of Ho\(^{3+}\):YAG to Tm\(^{3+}\):YAG dopant concentrations is 0.5/3 \(\approx\) 0.167 and the difference in dopant concentration modifies the number of nearest-neighbour donor-acceptor sites and hence the upconversion parameters from the values given here.

### 6.2.4 Absorption and Emission Spectra

Figure 6.5 shows the cross-sections for absorption and emission of Ho\(^{3+}\):YAG for the wavelength region 1.8 to 2.2 \mu m and figure 6.6 shows the absorption spectrum over a wider wavelength range. We can see the absorption feature at 2.013\mu m that is pumped by the Tm\(^{3+}\):YAG laser emission in an IC pumping scheme. The absorption cross-section for this feature is \(\sim 0.093 \times 10^{-20}\) cm\(^2\) which if in a 0.5% at. doped laser rod would require a rod length of \(\sim 155\) mm to efficiently (\(\sim 95\%\)) absorb the pump from an external Tm\(^{3+}\):YAG pump laser!
Figure 6.5: Ho$^{3+}$:YAG absorption and calculated emission spectrum [Bollig97]. Calculation of emission spectrum was obtained by Reciprocity or McCumber theory [Payne92].

Figure 6.6: Ho$^{3+}$:YAG absorption spectrum showing absorptions from 0.6μm to 2.2μm [Bollig97].
6.3 High Power Collinearly Intracavity Pumped Ho³⁺:YAG Producing > 7W

The 2W laser developed by Bollig [Bollig98] had only a short cavity (≈30mm) (figure 6.3) which would be restrictive for further development with regard to the necessary de-coupling of the two cavities. Longer resonators were required that would still accommodate the strong thermal lens in the Tm³⁺:YAG rod. For simplicity, the resonator of the Tm³⁺:YAG lasers developed earlier (chapter 5) was used, differing only by the inclusion of a Ho³⁺:YAG rod. This resonator satisfied the need for a longer resonator but was not optimised for beam quality.

6.3.1 Experimental Setup

The resonator design used is shown in figure 6.8 and is based on the Tm³⁺:YAG laser resonator shown in section 5.2.

The Tm³⁺:YAG laser was pumped by the same diode-bar setup as in chapter 5. Note that the Tm³⁺:YAG rod was pumped through the Ho³⁺:YAG rod from one end. We can see from figure 6.5 that there is a very small overlap between the diode-bar pump photon energy 12738.85 cm⁻¹ and the ⁵I₇ → ⁵I₄ transition (energy range from 12752 to 13811 cm⁻¹). This would require absorption from the highest energy 17th Stark level in the ⁵I₇ manifold (E ≈ 536 cm⁻¹) to the lowest level of the
\(^{5}I_{4}\) manifold possibly even requiring assistance from a crystal lattice phonon. The very low Boltzmann fractional population of the 17th \(^{5}I_{8}\) Stark level \((f \sim 0.0117\) at 25°C) also reduces the probability of the diode-pump absorption. However if this pump absorption were to occur then it is likely that the resulting relaxations from the \(^{5}I_{4}\) manifold would result in addition crystal heating thus increasing the Boltzmann fractional population and perpetuating the process.

The final focusing lenses brought the pump to a focus of 400 \(\mu m\) in both orthogonal planes with \(M^2\) of 78 and 79 giving a rayleigh range \(z_R\) in YAG of 14.8 mm.

The 3% atm.doped Tm\(^{3+}\):YAG laser rod was 17mm long and 3mm in diameter and mounted in a copper heat-sink that was in good thermal contact and bolted to a further water cooled copper heat sink kept at 17°C. The rod coatings were AR (reflectivity \(R \lesssim 0.01\%\)) to both the pump radiation and the laser radiation (2.0-2.1\(\mu m\) region).

The 0.5% at. Ho\(^{3+}\)-doped YAG rod (9mm long), mounted in a water-cooled copper heat-sink and was maintained at a temperature of 17°C. As can be seen from the figure 6.8 that the Ho\(^{3+}\):YAG rod was in close proximity to the Tm\(^{3+}\):YAG rod as they were both mounted to the same heat exchanging copper block for convenience.

The cavity mirrors had high reflecting (HR) coatings (internal to the cavity) for 2-2.1\(\mu m\) apart from the output coupler which were specified as HR (2.0~2.06\(\mu m\)) and \(~6\%\) Transmission at 2.08~2.15\(\mu m\). The external coatings were all anti-reflection (AR) coated for the laser wavelengths (\(T > 99.99\%\)) and were highly transmitting \(T > 85\%\) for the pump wavelength.

### 6.3.2 Results

The Ho\(^{3+}\):YAG laser reached threshold for a diode power of \(~10\)W incident on the Tm\(^{3+}\):YAG rod, and produced a maximum power of 7.2\(W\) at 2.097\(\mu m\) for 53.4\(W\) of incident pump power, corresponding to a slope efficiency with respect to incident diode power of 17.5\%. The output beam had \(M^2\) values in orthogonal planes of \(~5\) and \(~6\). This relatively poor beam quality resulted from the use of a resonator designed for a high power Tm\(^{3+}\):YAG laser presented in section 5.2 rather than optimised for good beam quality. The Ho\(^{3+}\):YAG laser beam also experiences some
beam aberration due to thermal distortion and lensing in the Tm$^{3+}$:YAG rod.

The laser provided a slope efficiency of 17.5% at 2.097μm output for incident 785nm pump radiation. This compares with 25% for the earlier, simpler, 2W output power IC laser results (section 6.1.2). The 4 mirror cavity of this experiment introduces increased losses due to mirror "leakage" (~2 × the loss per mirror to the laser compared to the simple 2 mirror cavity of section 6.1.2) and this affect the performance and efficiency of both lasers.

Double pumping the Tm$^{3+}$:YAG rod through the Ho$^{3+}$:YAG rod is not optimal and although experimentally simple has the disadvantages of the small possible ground state 785nm diode-bar absorption and restricts the flexibility for future decoupling the Ho$^{3+}$:YAG and Tm$^{3+}$:YAG lasers.

### 6.3.3 Summary

This demonstration of a high power IC pumped Ho$^{3+}$:YAG laser shows that the IC pumping scheme is capable of power scaling to the high powers achieved by direct pumping [Budni00]. However the beam quality is poor partly due to the strong thermal effects in the Tm$^{3+}$:YAG rod.
To access the full benefits of the low fractional heating in the Ho^{3+}::YAG laser rod it is necessary to decouple the Ho^{3+}::YAG and Tm^{3+}::YAG cavities, so that the Ho^{3+}::YAG laser beam does not propagate through the Tm^{3+}::YAG rod. This should allow a significant improvement in efficiency and beam quality. Further optimisation was problematic due to stability of the diode-bar pump lasers.

6.4 Non-Collinear De-Coupled Lasers

6.4.1 Introduction

One method for de-coupling the primary and secondary IC lasers is to operate the primary, Ho^{3+}::YAG laser axis at an angle to the pumping axis of the secondary, Tm^{3+}::YAG laser. This provides the necessary de-coupling of the two lasers cavities but does result in an increase in the threshold for the primary laser due to increased re-absorption loss from the unpumped region of the Ho^{3+}::YAG rod.

6.4.2 Experimental setup

The experimental setup is given by figure 6.9. The Tm^{3+}::YAG rod was pumped by a single 20W diode-bar operating at 785nm O(PC-A020-785-CS, Opto-Power Corporation [OPC Sales-brochure]). The diode-bar had 24 emitters which had facet apertures of approximately 1µm by 200µm and
Table 6.3: Mirror distances and radii of curvature for the mirrors in the non-collinear intracavity pumped Ho$^{3+}$:YAG laser.

<table>
<thead>
<tr>
<th>distance</th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 - Tm:YAG rod</td>
<td>1</td>
</tr>
<tr>
<td>Tm:YAG rod - M2</td>
<td>84</td>
</tr>
<tr>
<td>M2 - M3</td>
<td>443</td>
</tr>
<tr>
<td>M3 - Ho:YAG rod</td>
<td>263</td>
</tr>
<tr>
<td>Ho:YAG rod - M4</td>
<td>293</td>
</tr>
<tr>
<td>M5 - Ho:YAG rod</td>
<td>298</td>
</tr>
<tr>
<td>Ho:YAG rod - M6</td>
<td>294</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mirror</th>
<th>RoC [mm]</th>
<th>Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>plane</td>
<td>HR(2-2.1μm)</td>
</tr>
<tr>
<td>M2</td>
<td>100</td>
<td>HR(2-2.1μm)</td>
</tr>
<tr>
<td>M3</td>
<td>300</td>
<td>HR(2-2.1μm)</td>
</tr>
<tr>
<td>M4</td>
<td>300</td>
<td>HR(2-2.1μm)</td>
</tr>
<tr>
<td>M5</td>
<td>300</td>
<td>HR(2-2.1μm)</td>
</tr>
<tr>
<td>M6</td>
<td>300</td>
<td>HR(2-2.02μm)+3%T(2.05-2.14μm)</td>
</tr>
</tbody>
</table>

a facet spacing of $\sim$400μm. The diode-bar was beam-shaped [Clarkson96] and then focussed by into the Tm$^{3+}$:YAG rod through the input coupling mirror as shown in figure 6.9. The Tm$^{3+}$:YAG rod was 3% at. doped, 17mm long and 3mm diameter. The Ho$^{3+}$:YAG rod was 0.5% at.doped, 13.5mm long and 5mm diameter. Both rods were coated with AR coatings across the 2-2.1μm regions ($T>99.999\%$). The distances between components and mirror curvatures are given in table 6.3.

There were difficulties during the experiment with laser stability. To reduce the threshold of the Ho$^{3+}$:YAG laser, the Tm$^{3+}$:YAG laser mode in the Ho$^{3+}$:YAG rod was required to be small ($\sim$100μm). This placed stringent restrictions on the Ho$^{3+}$:YAG laser resonator which was required to operate at the edge of stability to provide such a small laser mode size. This not only negates some of the argument for this non-collinear pump scheme but also meant that alignment and optimisation of the cavity was problematic. This was exacerbated by the lack of viewers available for the 2μm wavelength region.
6.4 Non-Collinear De-Coupled Lasers

6.4.3 Results

The threshold pump power was \( \sim 5 \text{W} \) of diode-bar 785nm pump power incident on the Tm\(^{3+}\):YAG rod. The maximum output power at 2.091\( \mu \text{m} \) was 1.6W. This compares to the 2.1W maximum output power from the shorter 2-mirror (for both lasers) collinear laser of section 6.1.2. The reduction in output power and higher threshold are attributed to the non-collinear pumping and the increased losses from the additional mirrors and their leakage (unwanted transmission from imperfect highly reflective coatings). From observation the output beam viewed on a Thermal 80 InVision thermal camera showed the beam quality to be \( \sim 70\% \) elliptical indicating that the non-collinearity of the pump distribution forms an elliptical cross-section lens for the Ho\(^{3+}\):YAG laser mode and this may be a drawback of non-collinear IC pumping.

Unfortunately the laser was disturbed and mis-aligned before further measurements were possible. As a result it is difficult to draw a great deal further from the results other than to comment on the difficult alignment and alignment stability of this laser.

One of the disadvantages of decoupling the Tm\(^{3+}\):YAG and Ho\(^{3+}\):YAG resonators is the requirement for independent resonator mode-matching. The collinear pump scheme self-satisfies this to some degree by sharing the same propagation axis. The requirement of the non-collinear pump scheme to reduce the threshold by reducing the Ho\(^{3+}\):YAG laser spot-size and Tm\(^{3+}\):YAG laser spot-size in the pumped regions (which has the benefits of reducing threshold and increasing the overlap due to increased beam divergence from the waist planes) makes resonator design and alignment difficult. The Ho\(^{3+}\):YAG resonator needed to operate on the edge of stability to reduce the laser mode waist size to keep the threshold pump power low. If the 2-mirrors of the Ho\(^{3+}\):YAG laser resonator were to be moved closer together then it is problematic to determine if the laser is not operating due to mis-alignment of the mirrors or poor mode-matching. Not only must the angular orientation of the two mirrors be correct but also the two mirrors are required to be translatable in the plane of the Ho\(^{3+}\):YAG rod face to pick out the region and axis of the Tm\(^{3+}\):YAG pump laser.
6.4.4 Summary

The experiment indicated poor beam quality possibly originating from the non-collinear pumping scheme producing an elliptical thermal lens seen by the Ho$^{3+}$:YAG laser beam in the Tm$^{3+}$:YAG rod. This problem would be increased by poor mode-matching the in the plane of the face of the Ho$^{3+}$:YAG rod (though this mode-matching overlap could be optimised by optimising the output of the laser).

The results of the working laser were quite close to expectations with 1.6W of output power compared to the basic laser result of 2.1W but the extreme difficulty with alignment made the laser impractical as a route to de-coupling the Ho$^{3+}$:YAG and Tm$^{3+}$:YAG lasers.

6.5 Collinear De-Coupled Ho$^{3+}$:YAG Laser

Earlier discussion of the IC pumping scheme has highlighted the problem of coupled Tm$^{3+}$:YAG and Ho$^{3+}$:YAG cavities when looking to $Q$-switch such lasers. One scheme to de-couple the lasers was to non-collinearly pump the Ho$^{3+}$:YAG laser thus spatially separating the laser modes and resonators to enable $Q$-switching. Non-collinear pumping brings problems of alignment and mode-matching (section 6.4.4). Other methods include collinearly pumping the Ho$^{3+}$:YAG rod and separate the lasers by using other properties such as polarisation or laser emission frequency. It has been noted earlier that for Tm$^{3+}$:YAG pumping Ho$^{3+}$:YAG, frequency or wavelength is difficult to distinguish using dichroic, variable reflectivity mirrors or optical coatings. Dispersion for instance using prisms is also problematic due to the small wavelength separation. Collinear pumping brings advantages of ease of alignment and dispersion diminishes this benefit.

In this proposed experiment, the spatial separation would be achieved by using the walk-off angle, the angle between the k-wavevector of propagating radiation through a birefringent material, and the direction of the energy of the radiation given by the Poynting vector. The walk-off angle changes with the angle of propagating radiation k-wavevector to the uniaxial crystal optical axis of the uniaxial
material.

Unfortunately due to constraints on time, experiments were not conducted on this particular laser. However the laser design is of interest to this work and offers yet another potential route to a $Q$-switched $\text{Ho}^{3+}:\text{YAG}$ laser. The laser is again designed to take the advantages of a high IC power afforded by a $\text{Tm}^{3+}:\text{YAG}$ laser but selects different cavities for the $\text{Ho}^{3+}:\text{YAG}$ laser and $\text{Tm}^{3+}:\text{YAG}$ laser whilst allowing collinear pumping of the $\text{Ho}^{3+}:\text{YAG}$ laser. This separation, or de-coupling of the two lasers would allow $Q$-switching of the $\text{Ho}^{3+}:\text{YAG}$ laser independently of the $\text{Tm}^{3+}:\text{YAG}$ pump laser.

6.5.1 Experimental Design

Again it is stressed that unfortunately this laser experiment was not conducted. The preliminary experimental design is included here to provide further discussion of the potential for IC pumped sources at 2µm.

The advantages of collinear pumping are good mode matching between the primary and secondary IC lasers and easier alignment of the primary laser. In order to separate the cavities whilst retaining the collinear pumping the wavelength difference between the primary laser and secondary lasers must be exploited. For this design, a Quartz birefringent filter would be inserted into the cavity to select and link orthogonal linear polarisation states with the two laser wavelengths. The primary and secondary laser cavities would then be separated by a long birefringent crystal cut to the angle with the maximum walk-off between orthogonal polarisation states. Note that this scheme also provides some definition of the laser wavelengths as the birefringent filter will generate elliptical polarisation states that see a greater loss from the Brewster angled filter selecting the polarisation state. This de-polarisation loss selecting the wavelength may also be a problem for the manufacture of the components because should the birefringent filter select a wavelength combination not at the peak of the primary laser absorption and emission, the overall primary laser efficiency could be poor.

Figure 6.10 shows a planned collinearly IC pumped de-coupled laser design. The design would have used a Quartz birefringent filter that was the correct thickness
to provide the equivalent of a $\lambda/2$ waveplate for the 2.097\,\mu m radiation and a $\lambda$ waveplate for the 2.013\,\mu m radiation thus separating the two wavelengths by their polarisation (including upon reflection from mirror M5 in figure 6.10). One of the advantages of this design for separating the wavelengths is flexibility. By selecting the thickness of the birefringent filter/dual-waveplate then different wavelength pairs for the scheme could be defined. The two polarisations would then be separated spatially by a walk-off crystal. The largest walk-off angle for a material at 2\,\mu m with a high damage threshold was chosen to be alpha-Barium Borate ($\alpha - BBO$) cut to $\sim 45^\circ$. This material is a commonly used nonlinear material that has well known optical properties [Eimerl87], good transmission to 2.2\,\mu m and a high damage threshold ($I_{\text{max}} \approx 1.5\,\text{GW/cm}^2$[Koechner95]. Figure 6.11 shows the change in walk-off angle in $\alpha - BBO$.

$\alpha - BBO$ crystals were specially fabricated (by CASIX, China) at the crystal angle cut of 45$^\circ$ and were 40mm long with an aperture of 5mm$\times$10mm. Though these crystals were not used experimentally, their details are included here to demonstrate availability.
6.5 Collinear De-Coupled Ho\textsuperscript{3+}:YAG Laser

![Figure 6.11: Walk-off angle for $\alpha - BBO.$](image)

### 6.5.2 Summary

The main drawback to the collinearly IC pumped de-coupled Ho\textsuperscript{3+}:YAG laser is the complexity of the resonator components. The faces of the birefringent filter and the walk-off crystal add unwanted losses to the laser. It has already been seen in the non-collinearly IC pumped lasers that the Tm\textsuperscript{3+}:YAG laser pumping efficiency is susceptible to increases in resonator losses as the efficiency is dictated by the relative loss and ratio of the Ho\textsuperscript{3+}:YAG pumping absorption and the other losses to the laser. However the design does enable collinear coupling of the pump Tm\textsuperscript{3+}:YAG laser with the Ho\textsuperscript{3+}:YAG laser ensuring good mode-matching. This design has many advantages when compared with the non-collinearly decoupled lasers of section 6.4. The alignment of the laser should consist of aligning the linearly polarised Tm\textsuperscript{3+}:YAG laser with a plane output coupler (T\textasciitilde{}3% or so with some measurable, optimisable output) in place of the high reflecting mirror of M6 in the final laser. The other components could then be inserted and optimised in turn before replacement of M5 mirror with the high reflector. The Ho\textsuperscript{3+}:YAG laser resonator could be aligned by slight purposeful rotation of the birefringent filter coupling out some power and defining the Ho\textsuperscript{3+}:YAG resonator. The Ho\textsuperscript{3+}:YAG rod would also be near a waist for the Tm\textsuperscript{3+}:YAG pump laser due to proximity to the plane M5 mirror if the curvature of mirror M4 is close to the distance between M4-M5 and this would enable changes in pump spot-size by translation along the laser axis. This would have the disadvantage of increasing both the laser mode divergences through the walk-off crystal possibly requiring an increased aperture.
than available. Another drawback of the design is the proximity of the two spatially separated beams propagating from the walk-off crystal. Careful resonator design is needed to ensure that any beam clipping would be negligible.

6.6 Summary

Several high power IC pumped Ho\textsuperscript{3+}:YAG lasers have been demonstrated. A collinearly IC pumped coupled Ho\textsuperscript{3+}:YAG laser producing 7.2 W of output power at 2.097 μm has been reported which is to the best of the authors knowledge the highest power 2μm intracavity pumped laser to date. The resonator was not optimised for good beam quality and diode-bar pumping through the Ho\textsuperscript{3+}:YAG rod was also not-optimal. The \( \frac{d\omega_l}{df_{\text{thermal}}} \) resonator design strategy was not implemented and so it is not possible to discuss the application here.

One of the features and problems that has arisen from this work is the complexity of intracavity pumped lasers. The non-collinearly pumped de-coupled laser experiment in particular was difficult to design and build.

The IC pumped Ho\textsuperscript{3+}:YAG lasers presented here show that under CW conditions efficiency and high powers are achievable. It is with some regret that there was insufficient time with which to investigate some of the lasers and laser dynamics by the further development of IC pumped lasers and the collinearly IC pumped de-coupled Ho\textsuperscript{3+}:YAG laser of section 6.5 in particular. This laser design may suffer some loss of efficiency due to imperfect components causing additional losses but the increased alignment sensitivity and low thermal loading in the Ho\textsuperscript{3+}:YAG laser would make interesting future investigations.

Intracavity pumped lasers have interesting physical features associated with the strong coupling between the two laser systems but do not appear to be the best route to a high pulse energy Q-switched Ho\textsuperscript{3+}:YAG laser suitable for lidar as discussed as an aim throughout this work. The increased complexity and strong coupling make robust resonator design and alignment difficult, weakening the argument for this route.
References


Chapter 7

Double Clad Tm$^{3+}$:Alumino-Silica Fibre Laser

7.1 Introduction

Fibre lasers and fibre amplifiers have proven essential in telecommunications. The advantages are obvious; excellent beam quality, robust geometry, easily controllable output for coupling with modulators and single facet diode-pump lasers. High power 2µm fibre lasers have applications in remote sensing, medical applications, free-space communications and as a pump source for nonlinear frequency conversion by an Optical Parametric Oscillator (OPO) to the 3-5µm wavelength region with both the signal and idler outputs.

For many of these applications the need for high power and high efficiency is frequently accompanied by a requirement for good beam quality. This combination of operating characteristics becomes increasingly difficult to achieve at high pump powers in conventional ‘bulk’ solid-state lasers due to strong thermal effects, in particular, strong and highly aberrated thermal lensing, which degrades both beam quality and efficiency (see chapter 2 and chapter 3).

Fibre lasers provide an attractive alternative with the advantages that the heat generated due to the laser pumping cycle can be dissipated over a long length of fibre thus minimising the risk of thermally induced damage, and the output beam
characteristics are determined by the waveguiding properties of the active ion doped core, which can easily be tailored to produce a single-spatial-mode output. However high power diode pump sources with diffraction limited beam quality that are required to couple into mono-mode fibres are currently unavailable. High powers are available from diode-bar lasers but with poor brightness and inconvenient output $M^2$ as has been discussed earlier in chapter 2 and couple inefficiently into mono-mode fibres. To overcome the problem of coupling diode-bar pump light into the fibre, an additional 'inner' cladding can be added in fabrication. The inner-cladding is non-absorbing and is designed to guide the pump radiation which then couples into the doped, absorbing fibre core. The inner-cladding provides de-coupling between the need for large fibre numerical apertures (N.A.) to accept the pump light and the N.A. and mode-size of the core which dictates the beam-quality of the laser. Cladding-pumping has been shown to be both robust and efficient [Dominic99].

1μm Yb-doped double-clad fibre lasers have been scaled to very high powers of $\sim$110W [Dominic99]. This fibre possessed a rectangular inner cladding cross-section and was pumped by $4 \times \sim$45W polarisation-coupled end-pumping diode-bars. Side-pumping of a double-clad fibre laser has been demonstrated [Goldberg97] with an Er/Yb laser showing that there are alternatives to the standard end coupling of pump laser light. However all of the work presented here uses the more conventional end-pumping of the fibre and makes use of the two-mirror beam-shaper [Clarkson96] to equalise the $M^2$ values of the diode-bars. This enables the use of near circular inner-cladding which are easier to fabricate than square or rectangular geometries.

Tm$^{3+}$-doped fibre lasers and amplifiers have been demonstrated in several host glasses including silica [Hanna88, Barnes90, Hanna90a] and fluoride glasses [Carter92, Smart91, Percival92] and have shown great tunability [Barnes90, Hanna90a, Percival92] from 1.77 - 2.05μm. Q-switched operation of a Tm$^{3+}$-doped fibre laser was demonstrated in 1993 producing 4W peak pulse power in 130ns pulses at 1.945μm with a 4kHz repetition rate [Myslinski93]. The fibre laser was end-pumped through a dichroic mirror by 110mW absorbed pump power from a Ti:sapphire laser. The dynamics and gain-switching of a Tm-doped sil-
ica fibre laser have been investigated [Jackson99a, Jackson98a]. More recently there has been work reporting tunable pulsed operation from a diode-bar pumped Tm$^{3+}$:alumino-silica fibre laser [Barnes00]. The work reported in this thesis uses an alumino-silica glass host for thulium and investigates cw power-scaling, efficiency and tunability.

Power scaled cw 2$\mu$m silica fibre laser work has shown steady progress. In 1990 Hanna et al demonstrated the high power result from a Tm$^{3+}$:Silica monomode fibre laser producing 1.35W of output power pumped by 4.5W absorbed power from a 1.064$\mu$m Nd:YAG laser [Hanna90b].

Jackson and King [Jackson98b] demonstrated 5.4W of output power from a cladding pumped Tm$^{3+}$-doped silica fibre laser. The laser showed a slope efficiency of 31% with respect to launched pump power. At the start of the research described in this thesis, this result [Jackson98b] was the highest power Tm$^{3+}$-fibre 2$\mu$m laser reported to the authors knowledge. The laser had a rectangular inner-cladding cross-sectional area and was pumped by a combination of sixteen 2W diode lasers. Jackson and King [Jackson99b] have also modelled the relative merits and performance of pumping Tm-doped silica fibre lasers with a range of different wavelengths showing some of the versatility of this type of laser.

In this work efficient high-power diode-bar pumped Tm$^{3+}$-fibre lasers are reported. In keeping with the rest of the thesis the power-scalability of the lasers is discussed and the results put in context with the aims of the work.

7.2 Fabrication

Fabrication of the fibre was carried out by P. W. Turner in-house. The Tm$^{3+}$-doped aluminate silica fibre was pulled from a preform fabricated in-house using the standard modified chemical vapour deposition and solution-doping technique [Townsend87]. The resulting preform had a thulium concentration of $\sim$2.2% by weight. This equates to $\sim 1.72 \times 10^{26} \text{ions/m}^3$ or $\sim 22000 \text{ppm}$.

The trend in previous demonstrations of silica based Tm$^{3+}$ fibre lasers seems to indicate that increasing the aluminium concentration allows greater thulium ion
concentration. Prior to the experiments here it was thought that the efficiency for the cross-relaxation process ($^3H_4 \rightarrow ^3F_4$ and $^3H_6 \rightarrow ^3F_4$) was negligible [Jackson98b]. High Tm$^{3+}$ doping concentrations increase the probability of any two-for-one cross-relaxation between neighbouring ions as (seen with Tm$^{3+}$ in crystal hosts). The inclusion of aluminium was also thought to increase the lifetime of the upper laser level $^3F_4$ in silica host.

The preform had an outer diameter of 11.79mm and a core diameter of 1.23mm. This was then milled on an arbitrary cross-sectional tangent down towards the core by 0.3mm and then rotated by $\sim 30^\circ$ and milled down towards the core by 0.86mm. The milling changes the cross-section of the inner cladding that guides the pump in the finished fibre.

The fibre was then pulled and coated in a silicate polymer coating which provides a lower refractive index than the inner cladding to enable the inner cladding to guide.

The pulled fibre had a core diameter of $\sim 20\mu\text{m} (\pm 1\mu\text{m})$ and an inner cladding diameter of $\sim 200\mu\text{m} (\pm 4\mu\text{m})$. The area ratio ($\frac{A_{\text{core}}}{A_{\text{clad}}}$) was then 0.011 with only $\sim 4\%$ of the inner cladding area being removed by the preform milling process.

### 7.3 Fibre Geometry

#### 7.3.1 Cladding Cross-Section and Layout Geometry

Several geometries have been tried with great success using square or rectangular pump guiding cladding (see figure 7.1(c)). Rectangular geometries have the advantage of increasing the overlap between the typical focused asymmetric output beam of a diode-bar and the pumped cross-sectional area of the fibre end. By using the beam shaper to equalise the $M^2$ in orthogonal planes of the diode output, focusing into a circular geometry can be far more efficient. A completely concentric and circular geometry (where the core and claddings sit on concentric radii as in fig 7.1 a)) suffers from a reduction in pump absorption due to a significant amount of injected pump power not passing through the fibre core and hence never being
absorbed. Ray analysis confirms that some injected rays, called ‘skew rays’, are totally internally reflected by the inner cladding-outer cladding interface indefinitely and yet never cross the core. This has the effect of reducing laser power output and efficiency. Three main strategies have been employed to counter this skew ray problem; altering the geometry by off-setting the core from the centre of concentric claddings as in figure 7.1 (b); manufacturing the fibre to have a non-symmetric inner pump-guiding cladding cross-section; taking a concentric design (figure 7.1(a)) but exerting external twisting and bending.

Off-setting the core [Muendel96] increases the probability that the skew rays will intercept the core which increases the core absorption efficiency. The core absorption efficiency is the efficiency of pump power successfully launched into the cladding and core which is then absorbed in the core. Off-setting the core results in a small reduction in the pump launched into the fibre but this reduction is generally much smaller than the increase in the core absorption efficiency and hence overall pumping efficiency (the fraction of pump power incident on the fibre end resulting in ions excited to the upper laser level). The main disadvantage with this geometry is the difficulty of manufacture. Fibre pre-form milling or novel fibre pulling methods to preserve a circular pump cladding are time consuming and can be difficult.

Rectangular cross-section pump claddings [Jackson98b] have been demonstrated with a Tm$^{3+}$:silica fibre laser. The non-circular cladding prevents skew rays by passing them through the core and hence increases the pump absorption efficiency (the fraction of pump power launched into the inner cladding and core that is absorbed into the gain media). A rectangular geometry also improves the pump launch efficiency for standard diode-bar pumping but requires significant preform
milling and careful fibre-end orientation and alignment to the axis of the pump laser.

Muendel et al [Muendel96] also determined that many polygon shaped inner cladding cross-sections for a double clad fibre will enforce all propagating pump skew rays to eventually pass through the core. In a 4-level laser this is an ample requirement but in a quasi-3-level or 3-level laser system there is an optimisation to be made between pump absorption efficiency and the minimising the length of the laser to reduce the loss due to re-absorption from the ground level back to the upper laser level manifold \((^{3}H_6 \rightarrow ^{3}F_4)\). Polygon cross-sections can also be difficult to manufacture requiring specific angles and preform milling depths.

The geometry employed in our experiments used a new asymmetrical inner cladding design to increase the pump absorption efficiency. The fabrication process was described in section 7.2. and a schematic of the fibre cross-section is given in figure 7.1 (d). The geometry also has a small effect of displacing the core from the centre of the inner cladding.

This geometry also benefits from being simple to manufacture (a small mill of the preform followed by a rotation followed by another simple mill) and provides the necessary disturbance to the circular symmetry of typical concentric double-clad fibre designs. The near circular cross-section should also be easy to splice to other fibres and connections.

Many double-clad fibre designs have needed to take the elongated asymmetrical shape of a focused diode-bar beam into account to enable high pump launch efficiencies. A beam-shaped [Clarkson96] diode-bar as a pump source demonstrates the benefits of near symmetrical \(M^2\) values in orthogonal planes to enable high pump launch efficiency into circular or near circular double-clad fibre ends.

Twisting and bending can be applied to all the manufactured geometries including the basic concentric design. By bending and twisting, the fibre undergoes micro-bends and small changes in the Total-Internal-Reflection (TIR) angles (within the ray model of propagation) to displace skew rays from their normal path. This irregular displacement increases the likelihood of any particular ray passing though the core.
7.3 Fibre Geometry

7.3.2 Core-Cladding Sizes and Ratio

The robust nature of optical fibre dictates that fibre laser performance is largely set in the fabrication process. Pump absorption is a critical factor in laser performance particularly with quasi-three-level laser transitions where there is a trade-off between pump absorption length and laser re-absorption loss. This re-absorption loss is really a volume (or separate volumes) of laser media that is insufficiently pumped to reach transparency or gain for the laser radiation. The potentially non-uniform distribution of absorption in the double-clad fibre laser geometry can pose some problems for quasi-three-level lasers.

The core to cladding cross-sectional area ratio provides a simple relationship between the core absorption (the absorption of the pump guided by the core) and the approximate absorption of the launched pump power (guided by the core and the inner cladding).

The effective absorption of a double-clad fibre can be approximated using 7.1 from [Muendel96].

\[ \alpha_{\text{effective}} = \alpha_{\text{core \, abs}} \frac{A_{\text{core}}}{A_{\text{clad}}} \]  

(7.1)

where \( A \) is the respective cross-sectional area and \( \alpha_{\text{core \, abs}} \) is the absorption coefficient of the core.

The core of the Tm\(^{3+}\) doped fibre used in the experiments was chosen to be \( \sim 20\mu m \) in diameter with the inner cladding outer diameter to be \( \sim 200\mu m \). This gives us an \( \sim \frac{A_{\text{core}}}{A_{\text{clad}}} \) ratio of 0.01. It is difficult to estimate the pump absorption derived from the fibre or preform composition and so experiments were conducted to establish the different absorption measurements (see the following section 7.4). However as has been mentioned earlier, the Tm\(^{3+}\) doping concentration was chosen to be high to increase the probability and efficiency of any two-for-one-cross-relaxation between neighbouring Tm\(^{3+}\) ions. Increasing the concentration also has the effect of increasing upconversion rates from the upper laser level due to closer proximity of nearest-neighbour Tm\(^{3+}\) ions. Increasing the Tm\(^{3+}\) ion concentration also reduces the potential device length. We will discuss the consequences on performance of these different factors in later sections.
The core diameter influences the number of modes that the fibre laser will support. The relationship between the commonly quoted 'V' number of a near monomode fibre and the core diameter is given in equation 7.2 (see pages 74-92, Chapter 3 of [Yariv91]).

\[ V = \frac{\pi d}{\lambda} N.A. \]  \hspace{1cm} (7.2)

where \( d \) is the core diameter the fibre and the fibre is classed as mono-mode (only guiding a single transverse mode) if \( V \leq 2.405 \).

and the Numerical Aperture (N.A.) is given by

\[ N.A. = \sqrt{n_1^2 - n_2^2} \]  \hspace{1cm} (7.3)

where \( n_1 \) is the refractive index of the inner guiding layer (often the fibre core) and \( n_2 \) is the refractive index of the outer guiding layer (often the cladding).

From measurements of cross-sectional refractive index change carried out on the fibre by P. W. Turner at the ORC. The refractive indices at 633nm were determined to be:

<table>
<thead>
<tr>
<th>Guiding Layer</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>core</td>
<td>1.4632 ± 0.002</td>
</tr>
<tr>
<td>inner cladding</td>
<td>1.4585 ± 0.002</td>
</tr>
<tr>
<td>outer coating</td>
<td>1.375 ± 0.02</td>
</tr>
</tbody>
</table>

From equation 7.3 the core N.A. was 0.117 and the inner cladding N.A. was 0.49.

Taking the N.A. to be 0.117 and the core diameter to be 20\( \mu \)m and the wavelength \( \lambda \) to be 1.98\( \mu \)m we obtain a value for the V-number of 3.72. This indicates that the resulting fibre lasers should have multimode output and hence not near diffraction limited output (where diffraction limited output has \( M^2 < 1.1 \)). From [Yariv91], this indicates that higher order modes are supported (linearly polarised \( LP_{02} \) or \( LP_{12} \) modes). Note that the measurements for refractive index were taken at
633nm and dispersion to 2μm has not been taken into account. It is possible that there is a slow differential variation between the core and inner cladding refractive indices towards longer wavelengths due to the different doping concentrations, and the increasing background silica glass host absorptions at 2μm.

7.4 Spectroscopy

As with all lasers it is necessary to have measurements of the laser system in order to properly understand the physics. A laser’s performance is dependent on how easily it can be induced to stimulated emission (the στ product) and how easily the active component can absorb the pump energy. The following sections describe experiments to determine the lifetime and the pump absorption. The emission spectrum of the fluorescence of a diode-bar pumped fibre section was also taken as an indication of the tunable range.

7.5 Effective Lifetime

A measurement of the effective radiative lifetime of the upper laser level is of interest for several reasons. Such a measurement can be used to estimate laser threshold and efficiency. A measurement of the lifetime is also needed to indicate whether such a laser is capable of storing sufficient energy for high energy pulsed Q-switched operation. This points to the lasers suitability as a lidar source. The Tm³⁺:silica fibre laser is a potentially suitable candidate for tuning to a favourable wavelength region for atmosphere transmission. The laser has many advantages of scalability whilst preserving beam quality yet may not be suitable for high energy pulsed operation.

7.5.1 Experimental Setup

The fibre of length 200 mm was pumped as detailed in figure 7.2 by a single diode-bar. The output from the diode-bar was beam-shaped, collimated and then
brought to a focus in the plane of the optical chopper. The focus was then collected and re-collimated before final focussing and coupling into the end of the test fibre. The test fibre was a length of the same Tm-doped alumino-silica double-clad fibre as used in all of the following fibre experiments. The intermediate focus was put into the set-up in order to reduce the rise-time and fall-time of the pump which would otherwise distort the lifetime measurements.

The average pump power incident was varied by modifying the diode-bar drive-current and the 2μm signal fluorescence decay was measured. The throughput pump radiation was also measured. The correlation between the pump throughput and the 2μm signal allowed the signal fluorescence decay curve to be isolated. An exponential decay curve was then fitted to the results and the lifetime of the decay estimated from the fitting parameters.

In order to determine whether there is any effect due to pump pulse frequency there were two experimental sets of data. The pump pulse duration for experiment set 1 was 5.54 ms with a frequency of 7.794 Hz determined by measurements of the pump throughput and the chopper signal frequency. The pump pulse duration for experiment set 2 was 14.92 ms with a frequency of 2.865 Hz.
7.5 Effective Lifetime

<table>
<thead>
<tr>
<th>Pump power incident on chopper [W]</th>
<th>Average pump power incident on fibre end [W]</th>
<th>Lifetime Measured[ms] Error[ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.65</td>
<td>0.41</td>
<td>0.43</td>
</tr>
<tr>
<td>20.03</td>
<td>0.81</td>
<td>0.35</td>
</tr>
<tr>
<td>27.59</td>
<td>1.15</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Table 7.1: Pump power and lifetime results for Tm$^{3+}$:Silica fibre laser at chopper speed 1, pulse duration 5.54 ms.

<table>
<thead>
<tr>
<th>Pump Power Incident on Chopper [W]</th>
<th>Average Pump Power Incident on Fibre End [W]</th>
<th>Lifetime Measured[ms] Error[ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.58</td>
<td>0.44</td>
<td>0.37</td>
</tr>
<tr>
<td>20.05</td>
<td>0.80</td>
<td>0.38</td>
</tr>
<tr>
<td>27.43</td>
<td>1.05</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Table 7.2: Pump power and lifetime results for Tm$^{3+}$:silica fibre laser at chopper speed 2, pulse duration 14.92 ms.

7.5.2 Results

Tables 7.1 and 7.2 summarise the results from the different experiments. Each table displays the change in measured lifetime at different pump powers. The two tables are for a results set with a different pump pulse duration.

A typical experimental results set is displayed in 7.3. From these the pump pulse duration, rise time and fluorescence decay can be measured.

From these results we can see that the measured effective lifetime is $\sim$0.3 to 0.4ms. This is in broad agreement with published values [Barnes90] where they state a value for the Tm$^{3+}$ $^3H_4$ lifetime of $\sim$0.3ms in a GeO$_2$-SiO$_2$ host and a value of $\sim$0.5ms in Al$_2$O$_3$-SiO$_2$. The test fibre may be lifetime shortened due to the very high Tm$^{3+}$ ion concentration increasing co-operative upconversion branches out of the upper laser level. However, should there be a systematic error in the measurements it is expected that the lifetime measurements would indicate a longer lifetime value than the actual values due to the end-pumping and end-measurement experimental setup in section 7.5.1 as a result of radiation trapping.

This measured lifetime for Tm$^{3+}$ in silica ($\sim$0.3ms) is much shorter than the typical
lifetime of Tm$^{3+}$ in a bulk host such as YAG (Tm$^{3+}$:YAG $\tau \sim 7$ms).

7.6 Absorption Measurements

Correctly determining the absorption coefficient of a length of double-clad fibre is a complicated and unreliable experiment. Ordinarily, 'cut-back' measurements of transmission can be carried out to determine the absorption length of a single-clad fibre with great certainty. Such a measurement on a single-clad device yields the core absorption coefficient, and as the pump is also guided within the core the pump mode and the doped, absorbing core overlap efficiently. However in a double-clad fibre the pump is guided by another guiding interface and only part of the pump mode overlaps with the doped core region. Thus the absorption coefficient of the core is an unreliable guide to the effective absorption seen by a potential pump source such as a diode-bar. The absorption length is not constant for arbitrary lengths of fibre because under pumping conditions, the interaction between core and cladding modes is itself inconsistent. Also, the physical external layout of the fibre has a bearing on the absorption as does the core-cladding ratio/core geometry (which although fixed for a length of fibre interacts with the two modes differently in separate lengths of fibre). The physical layout of the fibre influences
the conversion of pump propagating in the cladding to propagation and possible absorption in the core. Pressure and torsion also affect the effective absorption of a double-clad fibre, producing 'micro-bending' effects in the fibre that disturb the modes almost randomly. The finite bandwidth of the output from a diode-bar and the overlap with the absorption feature also determines the effective absorption coefficient.

Diode-bar pumping adds yet another relatively small error to any measurement of absorption. The typical output of the sum of emitters from a diode-bar has a spectral bandwidth of ~3nm FWHM. In practice this effect can be optimised with pump coupling and fibre layout adjustments and is a small effect relative to the changes in absorption due to core-absorption, area geometry, micro-bending, pressure and torsion. For all these reasons, measurements of double-clad fibre pump absorption are prone to errors.

### 7.6.1 Core Absorption Experiment

The experiment was conducted by P.W. Turner but as it is unpublished is added here for completeness. The fibre outer coating was stripped off with a solvent and then the fibre was bathed in index matching fluid to strip out any cladding modes so that the only guided light was within the core. A background corrected white light source is then coupled into the 65mm long fibre and a spectrum analyser determines the loss across the 600 - 900 nm spectrum.

Figure 7.4 provides an absorption value of ~215 ± 5 dBm\(^{-1}\). Using equation 7.1 and a \(\frac{A_{core}}{A_{clad}}\) ratio of 0.011 then these measurements give an effective absorption of ~2.365 ±0.01 dBm\(^{-1}\).

### 7.6.2 White Light Source Experiment

White light absorption in a double-clad fibre provides a simple indication of the absorption of a diode-bar pump source. A white light source was proximity coupled into a 3m length of standard silica fibre of approximately the same cladding diameter and then coupled into an Anritsu M59001A optical spectrum analyser.
Figure 7.4: Tm$^{3+}$:alumino-silica double-clad fibre core absorption over 65mm length vs wavelength.

Figure 7.5: Double-clad Tm$^{3+}$:alumino-silica fibre white light absorption vs wavelength.

This spectrum was taken as a background reading and provides some offset from the spectral imperfections of the white light source. The white light source was then coupled into the 3m length of HD570 Tm$^{3+}$ doped aluminate silica double clad fibre which was then coupled into the spectrum analyser. The spectrum analyser was suitably screened from direct collection from the white light source. The results of this scan are given in 7.5.

Assuming that the white light power is insufficient to cause any bleaching effects this measurement should be a good measure of the relative absorption over a given length. The measured absorption coefficient depends on the fibre length.
7.6 Absorption Measurements

The experiment provided a value for the peak absorption of $\sim 17 \text{dB}$ across a fibre length of 3m at a wavelength of 787.5nm. This gives a value for absorption at 787.5nm of 5.67 dBm$^{-1}$.

7.6.3 Cut-Back Experiment

Pump light from a beam-shaped diode-bar was coupled into a length of the Tm$^{3+}$ doped double-clad fibre and transmission at the pump wavelength measured. The fibre length was 'cut-back' to shorter and shorter lengths to determine an approximate absorption coefficient for the double-clad fibre. This method illuminates errors in absorption measurement due to coupling losses and inconsistent skew-ray absorption.

<table>
<thead>
<tr>
<th>Fibre Length [m]</th>
<th>Absorption [dBm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.75</td>
<td>4.86 ±0.1</td>
</tr>
<tr>
<td>2.00</td>
<td>4.39 ±0.1</td>
</tr>
<tr>
<td>1.75</td>
<td>4.65 ±0.1</td>
</tr>
</tbody>
</table>

These values give an average absorption coefficient value of 4.63 dBm$^{-1}$.

7.6.4 Summary

From the different absorption experiments in sections 7.6.1, 7.6.2 and 7.6.3 we have values and estimates for the absorption coefficient of the double-clad Tm$^{3+}$:alumino-silica fibre of: 2.365 dBm$^{-1}$, 5.67 dBm$^{-1}$ and 4.63 dBm$^{-1}$ respectively. There is a factor of $\sim 2$ between the estimation derived from the core absorption/core-cladding ratio and the measured absorption values from light launched into the double-clad fibre. The cross-sectional geometry and external fibre geometry is thought to account for this difference.

The peak of the absorption of interest for diode-bar pumping in the following experiments was $\sim 787.5 \text{nm}$ with the Full-Width-Half-Maximum (FWHM) $\sim 20 \text{nm}$.

Note also that there is a background absorption from a standard silica host at
\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure7_6.png}
\caption{Tm$^{3+}$:alumino-silica double-clad fibre fluorescence spectrum.}
\end{figure}

\~2\mu m of approximately 100dBkm$^{-1}$ which is a small round-trip loss to any laser device given a typical device length of < 10m.

\section{Fluorescence Spectrum}

A spectrum of the emission from a length of the fibre under diode-bar pumping is shown in figure 7.6. The spectrum shown was to give an indication of the possible tuning range available for later experiments. This result cannot be reliably used for a determination of emission cross-section for a number of reasons. The spectrum was taken from the output from the fibre end which would result in the emission spectrum lineshape being shifted towards longer wavelengths due to emission re-absorption by the lower laser level transition population. A detailed experiment to determine the emission cross-section would require the use of an integrating sphere to collect the total emitted power from the fibre.
7.8 Singly Diode-Bar Pumped High Power Tm$^{3+}$:Alumino-Silica Fibre Laser

7.8.1 Introduction

This first experiment was aimed at achieving a simple high-power high-brightness, high efficiency Tm$^{3+}$:alumino-silica fibre laser. This laser was then to be further scaled higher powers with tunability to pick the optimum lasing wavelength for pumping the 1.905μm absorption peak in Ho$^{3+}$:YAG.

7.8.2 Experimental Setup

A simple single-end-pumped laser arrangement was chosen and is shown in figure 7.7.

The laser was pumped by a single Coherent Inc [Coherent Sales-Brochure] (B1-785-40C-19-30-A) 40W rated diode-bar and is shown as 'Diode A' in figure 7.7. The diode-bar was a linear array of 19 emitters. Each emitter output facet was 150 x 1 μm and the emitters were spaced 500μm apart. The array was 1 cm long. The diode-bar was housed in a metal container and a continuous low pressure supply of Nitrogen was purged through the housing to reduce the likelihood of condensation forming on the bar and its emitter facets. The bar had a spectral width of ~ 2.5 nm FWHM centred near 787nm which matched the peak of the Tm$^{3+}$:alumino-silica fibre absorption feature at 787nm (see section 7.6.4).

The diode-bar was beam-shaped [Clarkson96] and the output collimated by a 100 mm focal length cylindrical lens.

The final focussing lens was a plano-convex Gradium® [GRADIUM Sales-Brochure] lens with a focal length of 25 mm. Gradium® Lenses have a concentrically graded refractive index distribution in addition to the air-glass interface of the plano-convex surfaces. This refractive index distribution is designed to compensate for the aberrations suffered by an incident collimated beam when focussing. The pump beam was brought to a focussed to a
Figure 7.7: Single diode-bar pumped double-clad Tm\(^{3+}\):alumino-silica fibre laser experimental setup. HT: Highly Transmitting. HR: Highly Reflecting.

\(\sim 150\mu m \times 160\mu m\) waist radii in orthogonal planes, with \(M^2\) values of \(\sim 74\) and 76 respectively. The pump ray NA was \(\sim 0.42\) which is less than the NA of the inner cladding (section 7.3.2). The maximum pump power available at the focus was \(\sim 28W\). The incoupling efficiency was estimated to be \(\sim 80\%\) by measurements of transmitted pump power for different lengths of fibre. Taking account of the various in-coupling losses, a maximum of \(\sim 19W\) of pump was coupled into the fibre.

The fibre has been described in the preceding sections of this chapter and was 2m long. The fibre end was cleaved perpendicular to the axis of the fibre core and then butted against a plane-plane dichroic mirror with an anti-reflection coating that was highly transmitting (T>99%) at the pump wavelength (\(\sim 787nm\)) on one side (the side closest to the pump). The side that was directly butted to the fibre was highly reflecting (R>99.9%) in the wavelength region 1.8\(\mu m\) to 2.1\(\mu m\) and highly transmitting (T>85%) at 787nm. The other end of the fibre was butted to an anti-reflection coated output coupler. The output coupling mirror transmitted 92% of the incident 2\(\mu m\) radiation.

The coiled fibre was placed level with the ends (height fixed by XYZ-positioners) on a metal breadboard to aid heat removal.

### 7.8.3 Results

The threshold for laser oscillation was reached at an incident pump power of \(\sim 3W\) (i.e. \(\sim 2W\) launched) and at the maximum available pump power, an output of
Singly pumped Tm\textsuperscript{3+}:alumino-silica fibre laser output power vs launched pump power.

6.7W at 2 \textmu m was obtained as shown in figure 7.8. The slope efficiency for output power to launched pump power was \textasciitilde40.6\% demonstrating high efficiency relative to the bulk Tm\textsuperscript{3+} lasers of chapters 4 and 5.

The laser output wavelength was measured with a Burleigh WA-1000 Wavemeter against change in pump power incident on the fibre end (shown in figure 7.9. The change in wavelength with pump power is characteristic of quasi-three-level lasers. For low pump powers the Tm\textsuperscript{3+} peak emission wavelength is determined by the re-absorption loss which increases the laser wavelength. The emission cross-section is lower at the longer wavelengths but the loss is also lower. Increasing pump power saturates the re-absorption loss allowing the laser to operate efficiently at the lower wavelengths with the relatively higher emission cross-sections.

7.8.4 Summary

A single 40W diode-bar was used to pump a Tm\textsuperscript{3+}:alumino-silica double-clad fibre laser producing 6.7W of output power at 1.987\textmu m with a high slope efficiency of \textasciitilde40.6\%. The laser also provided excellent beam quality with \( M^2 \) of <1.1 in both
orthogonal planes at the highest output powers.

7.9 Doubly Diode-Bar Pumped High Power Tm$^{3+}$:Alumino-Silica Fibre Laser

7.9.1 Introduction

The fibre laser geometry offers a straightforward method for further power scaling of the laser described in section 7.8 by pumping both ends of the fibre. The problem that this presents is the necessity for extracting the output of the laser from one end. In this experiment, a second, identical beam-shaped diode-bar was coupled into the other end of the fibre whilst the setup of the first fibre end was kept as for the single diode-bar pumped laser.
7.9.2 Experimental Setup

The experimental set-up is shown in figure 7.10.

The double-clad fibre fabrication and geometry have been detailed in sections 7.2, 7.6 and 7.3.1 of this chapter.

The fibre was pumped by two Coherent diode bars temperature tuned to operate at \( \sim 787 \text{nm} \) which corresponds to a measured effective absorption coefficient of \( \sim 4.6 \text{dB/m} \) as given in section 7.6.3. The output from each bar was re-formatted using a two-mirror beam shaper [Clarkson96] to equalise the \( M^2 \) values in orthogonal planes and so allow tight focussing into the inner cladding.

The maximum combined pump power incident on the fibre ends was 48W, of which approximately 38.3W was launched into the fibre. The feedback for laser oscillation was provided by a dichroic mirror, with reflectivity \( > 99.8\% \) at \( \sim 2\mu\text{m} \) and high transmission \( (> 93\%) \) at the pump wavelength, butted to one of the fibre ends and by the Fresnel reflection at the other, uncoated, fibre end. The fibre laser output was collimated by a lens of focal length 20mm (which also focuses the pump from one of the diode bars into the fibre), and was then incident on a second dichroic mirror to provide access to the output beam. The pump focusing lens was coated for high transmission \( (> 99\%) \) at the pump wavelength and was found to have a transmission of only 74\% at 2 \( \mu\text{m} \).

By coupling two diode-bars into either end of the fibre the maximum pump power available was coupled into the fibre with one diode-bar achieving threshold before the second pump drive-current increased. By varying which diode-bar pump brought the laser to threshold, the threshold and coupling efficiency was optimised.

The maximum output power and efficiency was obtained for a fibre length of 4.5m. Care had to be taken to ensure that minimal unabsorbed pump was not coupled back into the opposite diode-bar pump.

The laser output beam was brought to a focus and the using a Merchantek Beamscope the second moment spot-size was measured at \( > 5 \) points though the confocal region (2 times the rayleigh range of the focus). The results were then plotted and the gaussian beam equations were fitted to the data to determine the \( M^2 \) of the
beam and hence the beam quality.

7.9.3 Results

The slope efficiency and threshold for the laser is given in figure 7.11. The threshold pump power incident on the fibre end (from diode-bar pumping through the dichroic mirror) was $\sim$7.6W or 5.8W launched pump power. At the maximum available incident pump power of 47.5W or 36.5W launched pump power, the fibre produced 10.3W of usable output power or 14W exiting from the fibre end (i.e. before the collimating lens). Using a Merchantek beam scope the output beam was measured to have $M^2$ values in orthogonal planes of $<1.1$ providing excellent beam quality. The power stability at high powers was measured to be good with short term fluctuations $<3\%$. Of particular note is the slope efficiency of $\sim$45% with respect to launched pump power. Comparing this result with equation 2.6 and taking the maximum values for $\eta_{STOKES} = 0.39$, $\eta_{PL} \sim 1$, $\eta_{abs} \sim 1$ and the ratio $\frac{T}{T+L} \sim 1$ then re-arranging gives a minimum value for the effective quantum pumping efficiency $\eta_q = 1.17$. This implies that on average for every pump photon absorbed, 1.17 ions are excited to the upper laser manifold. A value for $\eta_q > 1$ implies that there is an increase in efficiency due to the “two-for-one” cross-relaxation process ($^3H_4 \to ^3F_4$ combined with $^3H_6 \to ^3F_4$).

If we take non-optimal values for the efficiencies $\frac{T}{T+L} \sim 0.95$ ($T=0.96$ and $L=0.05$), $\eta_{PL} \sim 1$, $\eta_{abs} \sim 0.95$ then this provides a quantum pumping efficiency $\eta_q = 1.28$. 

Figure 7.10: Experimental setup for high power double diode-bar pumped Tm$^{3+}$:alumino-silica fibre laser.
Figure 7.11: Output power vs calculated coupled pump power at peak wavelength for high power double diode-bar pumped Tm$^{3+}$:alumino-silica fibre laser.

This result indicates a significant contribution to the overall efficiency due to cross-relaxation. It is thought that the contribution from cross-relaxation observed in this fibre is from the high Tm$^{3+}$-doping concentrations.

A typical measurement of the beam quality of the laser is shown in figure 7.12. The spot-size is measured for different positions throughout the waist along the direction of propagation and the $M^2$ value is determined by fitting the gaussian propagation equation.

7.9.4 Summary

This double diode-bar pumped laser produced 14W of output power with a slope efficiency of $\sim$46% and beam quality of $M^2 <1.1$. The slope efficiency provides evidence of significant efficiency from the “two-for-one” cross-relaxation process seen in Tm doped crystal lasers [Becker89] thought to be due to the high Tm dopant concentration in the fibre core. If this cross-relaxation process were 100% efficient, then the process has the effect of providing two Tm$^{3+}$ ions excited to the upper laser level for every absorbed pump photon. 100% efficient two-for-one cross-relaxation has effect improving the quantum pumping efficiency to 200% and
improves upon the upper limit on slope efficiency from the Stokes efficiency \( \frac{\eta_{\text{laser}}}{\eta_{\text{pump}}} \) when pumped at 787nm. This points to the possibility of improvements to the efficiency and performance of Tm\(^{3+}\) doped double-clad fibre lasers by optimisation of the doping concentration. There is expected to be a compromise between high doping concentrations increasing the \( ^3H_4 \rightarrow ^3F_4 \rightarrow ^3H_6 \rightarrow ^3F_4 \) cross-relaxation process whilst also attempting to minimise the unwanted upconversion processes such as \( ^3H_4 \rightarrow ^3H_6 \) with \( ^3F_4 \rightarrow ^1G_4 \).

To the best of the authors knowledge, at the time of this research this laser showed a combination of the highest reported output power and the highest reported efficiency from a thulium doped fibre laser.

## 7.10 Tunable Tm:Silica Fibre Laser

Tunable Tm\(^{3+}\):silica fibre lasers have been demonstrated [Barnes90, Hanna90a, Percival92] showing tuning from 1.77 - 2.05\( \mu \)m depending on the glass host and concentrations.

The tunability of the Tm-Fibre laser is potentially a significant advantage over
7.10 Tunable Tm\textsuperscript{3+}:Silica Fibre Laser

![Diagram of laser setup](image)

Figure 7.13: Tunable Tm\textsuperscript{3+}:alumino-silica fibre laser experimental setup.

bulk crystal lasers with regard to the aim of pumping singly doped Ho\textsuperscript{3+}:YAG lasers. The tunability over a large region of the 2μm spectrum would enable tuning and selection of the optimal absorption peak of Ho\textsuperscript{3+}:YAG. Selection of the pump wavelength for a Ho\textsuperscript{3+}:YAG laser, provides control over some of the ground state bleaching effects of in-band pumping of Ho\textsuperscript{3+}:YAG in the 2μm region.

The emission spectrum experiment in section 7.7 gave an indication that this laser might be tuneable over a large spectral region, potentially >200nm.

7.10.1 Experimental setup

The experimental laser setup is shown in figure 7.13. Due to the feedback required from the grating and for ease of alignment, only one pump source was used to pump the laser through the fibre end that the 2μm output radiation was emitted. The pump was coupled into the fibre end through an uncoated Gradium lens with f=20mm. No suitable coated lens (AR at 787nm and AR across the 2μm wavelength region) was available.

The fibre laser length was 1.7m with the grating at an angle of ~33° between the retro-reflection angle and the grating normal. The grating was gold coated with 600 lines/mm and was ~340mm from the collimating lens. The grating provided ~69% reflectivity in retro-reflection. With the other re-coupling losses back into the fibre the total feedback from the grating was ~52%.
7.10 Tunable Tm\textsuperscript{3+}:alumino-silica fibre laser maximum output power [W] vs tuned wavelength [nm].

![Graph showing output power vs peak lasing wavelength.]

**Figure 7.14:** Tunable Tm\textsuperscript{3+}:alumino-silica fibre laser maximum output power [W] vs tuned wavelength [nm].

### 7.10.2 Results

Figure 7.14 shows the output powers for the laser when tuned across the lasers wavelength range.

The output power of the tunable laser optimised for the peak wavelength was taken providing a maximum output power of 2.93W with a threshold at \(\sim 4.5\) W of launched pump power giving a slope efficiency of \(\sim 21\%\). The pump launch efficiency was \(\sim 80\%\) of incident pump power. This can be compared with the laser performance when operating with no feedback from the grating and just lasing off of the ‘bare’ cleaved fibre end reflections. These results are shown in figure 7.15.

The tunable wavelength range of the laser should be compared with the possible emission spectrum given in section 7.7. As expected the laser output wavelength range is shifted towards the longer wavelengths of the emission spectrum due to the loss to the laser from re-absorption.

The experimental setup was by no means optimised. A simple improvement to the tunable laser would be to retro-reflect from the grating via a turning mirror.
Figure 7.15: Tunable Tm\(^{3+}\):alumino-silica fibre laser output power [W] vs launched pump power [W]. (a) Peak wavelength with grating (b) No grating feedback - bare fibre-end laser.

This mirror should be coated to transmit at the pump wavelength and reflect at 2\(\mu\)m thus allowing a second pump source to be coupled into the second fibre end. The second pump with an associated adjustment to fibre length should bring a significant increase in output power to >5W. The grating was not optimised for Littrow configuration (blazed for retro-reflection) at this wavelength.

### 7.11 Summary

Continuous-wave operation of a double-clad Tm-doped silica fibre laser at 2\(\mu\)m pumped by one beam-shaped diode bar, provided 6.7W of output power in a single-mode \((M^2 < 1.1)\) beam for 19.1W of launched pump power at 787nm. The slope efficiency with respect to launched diode power was \(\sim 41\%\). Continuous-wave operation of a double-clad Tm-doped silica fibre laser at 2\(\mu\)m pumped by two beam-shaped diode bars, yielded an output power of 14W in a single-mode \((M^2 < 1.1)\) beam for 36.5W of launched pump power at 787nm. The slope efficiency with respect to launched diode power was \(\sim 46\%\). To the best of the author’s knowledge, this result combines both the highest power and highest efficiency in
the 2μm spectral region thus far reported for a fibre laser.

Tunable operation of a double-clad Tm-doped silica fibre laser showed an output power of >1.8W across a grating tuned wavelength range from 1870 to 2030nm for ~19W of pump power.

The beam quality for all these fibre lasers was better than expected from the fabricated design. This was thought to be due in part to some “mode-cleaning” from the fibre twisting, pressure and torsion applied externally to the laser. Note that if some mode-cleaning were present then in order to maintain brightness there would have to have been some loss to the potential output power.

The results of this work provide strong indication that some “two-for-one” cross-relaxation is evident. This brings some interesting areas of further research to the fore. Experimentation with Tm doping concentration to optimise the efficiency of the cross-relaxation process and characterise the effects on upconversion due to high Tm-doping concentrations should bring improvements in output power and efficiency.

There are also improvements to be made in the pump in-coupling optics and their coatings. Many of the coatings on lenses, mirrors and the grating were not optimal.

The incorporation of fibre Bragg gratings in the core would also define the emission wavelength without the need for a grating. This would provide an excellent pump source for a hybrid fibre pumped Ho³⁺:YAG bulk laser. Fibre Bragg gratings could also be used to define the wavelength for cw nonlinear frequency conversion using PPLN. This could generate high powers with good beam quality at 980nm as is much sought after for telecommunications applications.

Given advances in diode-bar technology there is a lot of scope for power scaling this double-clad Tm³⁺ fibre laser to very high powers ≥100W. Heat sinking of the fibre to remove excess heat would be needed. Despite the significant advantage that the distributed heat absorption of fibre brings over bulk lasers, heat-sinking would improve performance by lowering the lower laser level Boltzmann population and would not be too difficult. Heat-sinking of the fibre ends would enable longer term stability, reduce thermally-induced core-end effects and improve performance in a similar way to the rest of the fibre but this is difficult to implement.
The ability to pump the double-clad fibre laser other than through the fibre ends would also be a significant break-through in the area of high power fibre lasers and allow power scaling to very high powers >200W.

The lasers demonstrated in this chapter provide an excellent base for further work in a number of areas, particularly in the direction of this thesis with regard to cw pumping bulk Ho$^{3+}$:YAG crystal lasers for pulsed operation and compares favourably with alternative pump sources for this application [Budni00].

References


[Dominic99] V. Dominic, S. Macomack, R. Waarts, S. Sanders, S. Bicknese, R. Dohle, E. Wolak, P. S. Yeh and E. Zucker,


R. G. Smart, J. N. Carter, A. C. Troppé and D. C. Hanna, "Continuous-wave oscillation of Tm³⁺-doped fluorozirconate fiber lasers at around 1.47-μm, 1.9-μm and 2.3-μm when pumped at 790 nm," *Optics Communications*, vol. 82 (5-6), pp. 563–570 (May 1 1991).


Chapter 8

Conclusions and Future Work

8.1 Conclusions

2\textmu m lasers have numerous applications with the prospect of more applications for compact efficient higher power 2\textmu m lasers. The focus of this work has been to develop a 2\textmu m lidar system based around a power-scaled diode-bar end-pumped Ho\textsuperscript{3+}:YAG laser. Direct diode-pumping of Ho\textsuperscript{3+}:YAG is problematic due to the unavailability of suitable high-power diode-bars. Historically co-doping of Ho\textsuperscript{3+} and Tm\textsuperscript{3+} ions into a crystal host has enabled the use of diode wavelength absorptions in the Tm\textsuperscript{3+} ion and ‘two-for-one’ cross-relaxation efficiently transferring the excitation energy to the Ho\textsuperscript{3+} ions. However this route suffers due to ionic-transfer back to the Tm\textsuperscript{3+} ions from the Ho\textsuperscript{3+} ions which reduces energy storage-time and limits the applicability of this route. An alternative route is to directly pump Ho\textsuperscript{3+}:YAG with a Tm\textsuperscript{3+}:YLF or Tm\textsuperscript{3+}:YALO laser which has been shown to power-scale successfully.

In this work two new routes have been investigated.

One route is intracavity pumping Ho\textsuperscript{3+}:YAG within a high power Tm\textsuperscript{3+}:YAG laser. This scheme requires the power scaling of a diode end-pumped Tm\textsuperscript{3+}:YAG laser and this was the subject of chapter 4. In order to achieve a high power Tm\textsuperscript{3+}:YAG laser several problems had to be identified and approached. These problems and the strategies for overcoming them were the subject of chapter 2. Chapter 3
quantifies one the thermally induced lensing in Tm$^{3+}$:YAG and Tm$^{3+}$:(Lu,Y)AG and the information this provided was used to model the resonator responses of the Tm$^{3+}$:YAG laser in chapter 4.

The high-power high-brightness Tm$^{3+}$:YAG laser of chapter 4 provided a base for the high-power intracavity pumped Ho$^{3+}$:YAG laser presented in chapter 6. The increases in power of the Tm$^{3+}$:YAG laser have enabled a greater than four-fold increase in the previous highest power intracavity pumped Ho$^{3+}$:YAG laser and so has been successfully power-scaled to >5W power levels. However in order for this route to provide a lidar source, the Ho$^{3+}$:YAG and Tm$^{3+}$:YAG lasers must be decoupled. Efforts to decouple the lasers proved to be difficult with the non-collinear de-coupling scheme. The non-collinear laser was difficult to align and repeat and was not considered successful. An alternative collinear de-coupled scheme which should be easier to align has been suggested but the experiment was not conducted due to constraints on time. Though the intracavity pumping route has produced some interesting high power laser sources it was not considered to be the optimal route and so the experimental direction was changed to an alternative direct pumping scheme.

The second route investigated was directly pumping a Ho$^{3+}$:YAG laser by a power-scaled Tm$^{3+}$:alumino-silica fibre laser developed in chapter 7. To the author's knowledge this laser produced the highest power and brightness Tm$^{3+}$ fibre laser to date exhibiting excellent beam quality and high efficiency. The efficiency was higher than may have been expected and this was thought to be due to a significant efficiency of the two-for-one cross-relaxation process between Tm$^{3+}$ ions. A significant two-for-one efficiency is believed to be due to the high dopant concentrations present in the fibre. The laser was then modified to allow frequency tuning producing multi-watt powers over a broad wavelength range. Although tunability is not required for direct pumping of Ho$^{3+}$:YAG, the ability to select the peak of the Ho$^{3+}$:YAG absorption near 1.96µm is highly desirable from the fibre laser. The progression for this laser towards the eventual goal of a Ho$^{3+}$:YAG lidar is discussed in the future work section below.

A high-power laser was investigated in chapter 5 which could provide an alternative base laser for a lidar source. Tm$^{3+}$:(Lu,Y)AG lasers operate at the more
favourable longer wavelength of 2.022μm compared to the 2.013μm of Tm\(^{3+}\):YAG. Lidars based on Tm\(^{3+}\):YAG generally tune the laser to the longer wavelength for the better atmospheric transmission with a small reduction of emission cross-section. Tm\(^{3+}\):(Lu,Y)AG offers the preferable wavelength at the peak of the emission cross-section. The thermal lens of Tm\(^{3+}\):(Lu,Y)AG was determined and compared with Tm\(^{3+}\):YAG in chapter 3. The thermal lensing was found to be slightly stronger than Tm\(^{3+}\):YAG but the effects of the stronger lensing did not prevent the Tm\(^{3+}\):(Lu,Y)AG laser from matching the performance of the comparison Tm\(^{3+}\):YAG laser in chapter 5. Unfortunately it was not possible to perform the necessary spectroscopy and thermo-mechanical experiments to fully characterise the material.

Although work on developing new power-scaling schemes has not been the direct focus of this research, the implementation of several strategies and the identification of areas where 2μm lasers offer unique opportunities has been successful. The use of the 2-mirror beam-shaper (on page 25) and the resonator design strategy (on page 26) have shown great merit at 2μm as with other wavelength regions. The control of the diode-bar output provided by the beam-shaper enabled intense pumping to overcome some of the spectroscopy deficiencies of Tm\(^{3+}\):YAG. The resonator design strategy was particularly successful when applied to the Tm\(^{3+}\):YAG lasers of chapter 4. Despite the broad approximations made when designing the resonators by using the thin-lens approximation and treating the thermal lens aberrations as a range of thin-lens focal lengths these approximations have enabled progressions in resonator length, flexibility and high powers whilst retaining excellent beam quality. The birefringence compensation scheme (on page 28), when applied to the Tm\(^{3+}\):YAG laser of chapter 4 also showed itself to be almost essential for obtaining linearly polarised output though the reduction of the depolarisation loss is lower for these longer wavelengths than when applied to near 1μm sources.

The work presented in this thesis provides a strong base for further development towards the stated aim of a Ho\(^{3+}\):YAG based lidar. However the lasers here fall short of this aim and so the progress must be objectively assessed. The intracavity route shows many interesting features and novel laser dynamics. The thermal and spectroscopic de-coupling of the Tm\(^{3+}\) and Ho\(^{3+}\) lasers and the low intrinsic
heating from inband pumping provides many benefits. However the problems faced in de-coupling the two lasers proved more difficult than first thought. The work here shows that relatively simple intracavity lasers can be power-scaled to high powers successfully but one of the de-coupling schemes investigated (on page 97) was unsuccessful. The resonators required to operate the non-collinear pumped laser and overcome the added losses needed to be too close to the stability edge and this caused extreme alignment problems. The collinear scheme put forward in section 6.5 would solve this but at the expense of additional intracavity components which may reduce the efficiency.

The hybrid Tm\(^{3+}\):fibre direct pumping bulk Ho\(^{3+}\):YAG route is simpler and currently more attractive. The efficiency of the laser detailed in chapter 7 approaches the bulk Tm\(^{3+}\):YAG lasers and provides a more robust, higher brightness pump source displaying the advantages of fibre lasers. The efficiency is in part due to the design of the core-cladding ratio and novel cladding cross-section design. The beam-shaped diode-bar enabled a small cladding-core area ratio with a near circular cladding that is difficult to couple into with the standard output of a diode-bar. The fibre geometry absorbs many of the problems of the unfriendly diode-bar output and generates excellent 2\(\mu\)m pump beam quality to any subsequent bulk Ho\(^{3+}\):YAG laser. The emission wavelength for the fibre laser would require some tuning and control to hold the maximum Ho\(^{3+}\):YAG absorption.

This work satisfies much of the initial argument carried through the thesis that 2\(\mu\)m lasers offer many interesting avenues for compact high-power efficient laser sources. In certain cases 2\(\mu\)m lasers have the potential to retain parity, with the more mature 1\(\mu\)m based technology and can provide unique opportunities.

### 8.2 Future Work

There are many projects and experiments that lead on from the work presented here. Some experiments are a logical progression of the work here regarding the aims discussed above.

The thermal lensing measurements on all the laser crystals used should be refined
8.2 Future Work

using an interferometric method to ascertain the aberrations of the lens under a range of pump conditions. From this information it would be hoped that more inferences could be made on the upconversion related heating in the laser media. Upconversion related heated can have a marked effect on laser design for Q-switched lasers as the laser must operate with a high inversion density for a period before the cavity $Q$ is switched. This course of research may also lead to some quantification of the loss of the aberrated thermal lens which would greatly aid laser design. The cyclic dependency between thermally-induced laser losses and upconversion related heating is a problem for modelling a laser as the increased loss not only affects the inversion density but also the thermal lens strength.

To continue the preliminary Tm$^{3+}$:(Lu,Y)AG laser experiments, a characterisation of the material is required. The thermo-mechanical properties and spectroscopy are important as we have seen in this work. $Q$-switching a laser could provide an interesting high pulse energy source.

The intracavity pumping scheme still offers a wide range of further work. The implementation of the collinear de-coupled intracavity pumped Ho$^{3+}$:YAG laser is an obvious direction.

Q-switched operation of the intracavity pumped Ho$^{3+}$:YAG laser would bring a novel and interesting high-power laser. The interaction of the Ho$^{3+}$:YAG absorption characteristics and the Tm$^{3+}$:YAG output coupling also brings in a fascinating regime of laser dynamics. Future experiments should work towards bringing an increased understanding of the amplitude and frequency stability of these lasers in view of these laser dynamics, an area which has not yet been investigated. Active stabilisation of a $Q$-switched Ho$^{3+}$:YAG laser may be needed but would connect well with 1μm work using a pre-lase.

Single-frequency experiments would be of great interest for the lidar applications as well as allowing the potential for narrow-linewidth, high-power OPO devices reaching into the 3 to 5μm region. An optimised 2.1μm, high-power, eyesafe, coherent source could be used to efficiently pump mid-IR OPO's as lidar sources. Novel mid-IR OPO devices would be of great interest in atmospheric sensing and spectroscopy.
8.2 Future Work

The powers achieved by the fibre laser in this work approach those necessary for cw pumping of a cw OPO reaching across the 3-5\(\mu\)m region with both the OPO signal and idler. This would be a unique and attractive source due to cw coverage of the wide mid-IR atmospheric transmission region.

A high power Tm\(^{3+}\):aluino-silica laser producing \(\sim 20\)W of output at 1.960\(\mu\)m could be used to generate a second harmonic at 980nm, a highly attractive wavelength for telecommunications if combined with excellent beam quality. CW second harmonic generation via periodically-poled lithium niobate (PPLN) could be one route to this wavelength but would require high cw Tm\(^{3+}\):fibre laser powers. A stable cw pump 980nm source for erbium-doped fibre amplifiers would attract a great deal of attention as current 980nm diode sources are both expensive and hard to scale. With advances in the poling of fibres to generate a \(\chi_2\) nonlinearity then an all fibre source could be investigated.

A high-power broadly tunable 2\(\mu\)m fibre source only touched on by the work here could readily be improved with the use of a more suitable grating and suitable optical coatings on the coupling launch-exit optics. An adjustment in the experimental design would also enable access to both fibre ends to allow additional pumping bringing increased efficiencies and output powers across a wide wavelength range.

The hybrid Ho\(^{3+}\):YAG laser is another highly attractive area of further research leading on from this work. To achieve this the Ho\(^{3+}\):YAG laser would require output wavelength definition of the fibre laser to correspond to a strong Ho\(^{3+}\):YAG absorption. Ultimately this could be achieved using refractive-index Bragg gratings in the core or possibly (with lower efficiency) in the inner cladding. Another attractive feature of the hybrid fibre-bulk scheme is the convenience of powerscaling the double-clad fibre laser whilst retaining the excellent beam quality. This contrasts with using a direct bulk laser pump such as Tm\(^{3+}\):YLF or Tm\(^{3+}\):YALO where the thermal lensing problems arise again. Additionally, fibre lasers could be added in a bundle arrangement as the pump for the Ho\(^{3+}\):YAG laser for a modest reduction in brightness still far in advance of a direct diode pump. Double-clad fibre sources are excellently suited to extremely high power cw operation if the pump power can be successfully launched. The hybrid scheme would use these advantages with the advantages for energy storage and \(Q\)-switching in the bulk
8.2 Future Work

geometry. The hybrid laser scheme should also allow further power-scaling of 2μm lasers by side-stepping many of the thermal effects that are proving to be such a problem for bulk lasers.

The fibre laser was to a great extent limited by available pump power. The need for increased pump power is continually being addressed with improvements in diode-bar and diode-bar stack output powers. However, there is a problem facing linear arrays of emitters for which the two-mirror beam-shaper provides such an elegant solution. This leaves us looking once again for a scheme that will facilitate the shaping of the output from a 2-dimensional stack of linear arrays or similar. Current schemes use collector optics but offer little ability to shape the $M^2$ of the stack output and hence offer little control over the brightness that the pump provides. This pump control must be present to enable the knock on effects in efficiency and thermal management and as pump powers increase then the need for brightness control will become more evident not less.

In order to significantly power-scale the bulk lasers whilst maintaining good beam quality further compensation schemes and strategies must be devised. The strategy in this work was to attempt to use the resonator response to partially compensate for the thermal lens aberration but this requires operation near the stability limits and is unlikely to allow significant further power-scaling. Non-linear methods such as phase-conjugation are generally limited to high gain transitions and so do not lend themselves to the lasers of interest here. Intracavity compensating elements may provide some of the answers but currently such schemes use diffractive elements and introduce significant losses to achieve the compensation. Careful resonator design and pump management as part of cohesive strategies will still be required for future power scaling.

The development and power scaling of fibre lasers is already starting to encounter the thermal problems that the area has for so long side-stepped with its advantageous thermal geometry. Whilst the area will continue to benefit from the inherent thermal management of the distributed geometry, the limitations in energy storage and thermal strains in immediately pumped sections will require fresh thought regarding thermal management. The most promising scheme advocated here would be that of the hybrid approach (fibre-bulk) for Q-switched and pulsed operation
and the fibre for cw operation in this wavelength region. The energy storage in the materials discussed in this work is potentially enormous and the advantage bulk has over the fibre geometry is energy storage over a large volume and large cross-section. The fibre geometry currently suffers from the Amplified Spontaneous Emission (ASE) causing inefficient extraction and repetitive build-up of pulses of large average powers (as required for lidar) in fibres may push them to destruction. This in mind, the high average powers in a hybrid bulk laser may again result in thermal loading issues requiring solutions. The area of power-scaling diode-pumped solid-state lasers continues to push the boundaries back a little further. Conducting experiments on 2μm laser sources is challenging, yet there are excellent rewards to be gained.
Appendix A

Example MapleVR4 Resonator Design Program

The following is example maple code for plotting the stability and spotsizes for different resonator lengths, mirror curvatures and thermal lens focal lengths. Note that the thermal lens is modelled as a simple thin lens but that the change in resonator mode spot size is plotted for changes in the simple thin lens approximation thermal lens.

In Folded ZZ Resonator (tan and sag resolved) FILE : \ZZCAV77b.mws

Introduction
> with(linalg);
> with(plots):setoptions(axes=boxed, thickness=2,titlefont=[TIMES,ROMAN,18]):

BASER ON FILE:\ZZCAV1.mws
Author: R.A.Hayward

Date: 27/7/98

Basic Resonator Layout :
Pump--> | input mirror (rin) -- space (d) -- Tm 3+thermal lens (ftm)
BLACK--- space(11) --
    | mirror (r1, theta1) -- space (12) -- mirror (r2,theta2)
    | space (13) -- Ho3+thermal lens(ths) -- Ho rod --
    | space(14) --mirror(r3,theta3)--space(15) -- flat mirror |

Includes : M^2 for spot sizes
different thetas for folded arms - allows lenses to replace
    mirrors for theta =0

Units : Units are in mm, W, K and rad unless otherwise stated.

Definition of Constants - Resonator values
    Rod Material Constants
    YAG Material Constants

> nrod:= 1.82:
\[ lrodmt := 12; rrodmt := 3; Lrodmt := lrodmt/10; \]
\[ lrodho := 0; \]
\[ Msq := 1; \]
\[ lambda := 2013E-6; \]

Resonator values

Resonator (mm) ----------------- 11=70, 12=210+100, 13=102+160+12,100, 14=152, 15=300 from independent evaluation: NOTE: A SMALL ADDITION HAS BEEN MADE TO

\[ d := 2; 11 := 82; 12 := 300; 13 := 270; 14 := 300; rin := 1e99; r1 := 100; \]
\[ r2 := 150; r3 := 300; rout := 1e99; theta1 := 5*evalf(Pi)/180; \]
\[ theta2 := 2*evalf(Pi)/180; \]
\[ theta3 := 2*evalf(Pi)/180; \]

\[ d := 2 \]
\[ 11 := 82 \]
\[ 12 := 300 \]
\[ 13 := 270 \]
\[ 14 := 300 \]

\[ rin := .1 10 \]
\[ r1 := 100 \]
\[ r2 := 150 \]
\[ r3 := 300 \]

\[ rout := .1 10 \]
\[ theta1 := .08726646262 \]
\[ theta2 := .03490658504 \]
\[ theta3 := .03490658504 \]

RAH Thermal lens Focal Length value at Rod Centre

My value for thermal lens focal length
\[ fvaltm := 32.34; \]
\[ fvalho := 1e99; \]

\[ fvaltm := 32.34 \]

100
\[ fvalho := .1 10 \]

Matrix Definitions - RTMs

Definition of Matrices

Rod and lens matrices
\[ M_rodho := matrix([[1, lrodho/nrod],[0, 1]]); \]
\[ M_rodmt := matrix([[1, lrodmt/nrod],[0, 1]]); \]
\[ M_lens := (ftm) \rightarrow matrix([[1, 0],[1/ftm, 1]]); \]
\[ M_lensho := (fho) \rightarrow matrix([[1, 0],[1/fho, 1]]); \]

Space matrices
\[ M_d := (d) \rightarrow matrix([[1, d],[0, 1]]); \]
\[ M_11 := (11) \rightarrow matrix([[1, 11],[0, 1]]); \]
\[ M_12 := (12) \rightarrow matrix([[1, 12],[0, 1]]); \]
\[ M_13 := (13) \rightarrow matrix([[1, 13],[0, 1]]); \]
\[ M_14 := (14) \rightarrow matrix([[1, 14],[0, 1]]); \]
Mirror matrices

\[ M_{\text{rin}} := (\text{rin}) \rightarrow \begin{bmatrix} 1 & 0 \\ -2/(\text{rin}) & 1 \end{bmatrix} \]
\[ M_{\text{r1_sag}} := (r1, \text{theta1}) \rightarrow \begin{bmatrix} 1 & 0 \\ -2/(r1 \times \cos(\text{theta1})) & 1 \end{bmatrix} \]
\[ M_{\text{r1_tan}} := (r1, \text{theta1}) \rightarrow \begin{bmatrix} 1 & 0 \\ -2/(r1 \times \cos(\text{theta1})) & 1 \end{bmatrix} \]
\[ M_{\text{r2_sag}} := (r2, \text{theta2}) \rightarrow \begin{bmatrix} 1 & 0 \\ -2/(r2 \times \cos(\text{theta2})) & 1 \end{bmatrix} \]
\[ M_{\text{r2_tan}} := (r2, \text{theta2}) \rightarrow \begin{bmatrix} 1 & 0 \\ -2/(r2 \times \cos(\text{theta2})) & 1 \end{bmatrix} \]
\[ M_{\text{r3_sag}} := (r3, \text{theta3}) \rightarrow \begin{bmatrix} 1 & 0 \\ -2/(r3 \times \cos(\text{theta3})) & 1 \end{bmatrix} \]
\[ M_{\text{r3_tan}} := (r3, \text{theta3}) \rightarrow \begin{bmatrix} 1 & 0 \\ -2/(r3 \times \cos(\text{theta3})) & 1 \end{bmatrix} \]
\[ M_{\text{out}} := (\text{out}) \rightarrow \begin{bmatrix} 1 & 0 \\ -2/(\text{out}) & 1 \end{bmatrix} \]

RTM1 - Ref : Thermal lens

This round-Trip Matrix has the reference plane position
at the thermal lens of the Tm:YAG rod

Round-trip matrix for tangential plane

\[ RTM1_{\text{tan}} := (d1,11,12,13,14,\text{rin},r1,r2,r3,\text{out},\text{f},\text{tm},\text{theta1},\text{theta2},\text{theta3}) \]
\[ \rightarrow \text{evalm}(\#*( \]
\[ M_{\text{d}(d)}, M_{\text{rin}(\text{rin})}, M_{\text{d}(d)}, \]
\[ M_{\text{lens}(\text{f})}, M_{\text{rodtm}}, \]
\[ M_{11(11)}, M_{r1\_tan}(r1, \text{theta1}), \]
\[ M_{12(12)}, M_{r2\_tan}(r2, \text{theta2}), \]
\[ M_{13(13)}, M_{r3\_tan}(r3, \text{theta3}), M_{14(14)}, \]
\[ M_{\text{out}(\text{out})}, \]
\[ M_{14(14)}, M_{r3\_tan}(r3, \text{theta3}), M_{13(13)}, \]
\[ M_{r2\_tan}(r2, \text{theta2}), M_{12(12)}, \]
\[ M_{r1\_tan}(r1, \text{theta1}), M_{11(11)}, \]
\[ M_{\text{rodtm}}, M_{\text{lens}(\text{f})}) \]) ;
\]

\[ A1_{\text{tan}} := (d1,11,12,13,14,\text{rin},r1,r2,r3,\text{out},\text{f},\text{tm},\text{theta1},\text{theta2},\text{theta3}) \]
\[ \rightarrow RTM1_{\text{tan}} \]
\[ (d1,11,12,13,14,\text{rin},r1,r2,r3,\text{out},\text{f},\text{tm},\text{theta1},\text{theta2},\text{theta3})[1,1] ;
\]

\[ B1_{\text{tan}} := (d1,11,12,13,14,\text{rin},r1,r2,r3,\text{out},\text{f},\text{tm},\text{theta1},\text{theta2},\text{theta3}) \]
\[ \rightarrow RTM1_{\text{tan}} \]
\[ (d1,11,12,13,14,\text{rin},r1,r2,r3,\text{out},\text{f},\text{tm},\text{theta1},\text{theta2},\text{theta3})[1,2] ;
\]

\[ C1_{\text{tan}} := (d1,11,12,13,14,\text{rin},r1,r2,r3,\text{out},\text{f},\text{tm},\text{theta1},\text{theta2},\text{theta3}) \]
\[ \rightarrow RTM1_{\text{tan}} \]
\[ (d1,11,12,13,14,\text{rin},r1,r2,r3,\text{out},\text{f},\text{tm},\text{theta1},\text{theta2},\text{theta3})[2,1] ;
\]

\[ D1_{\text{tan}} := (d1,11,12,13,14,\text{rin},r1,r2,r3,\text{out},\text{f},\text{tm},\text{theta1},\text{theta2},\text{theta3}) \]
\[ \rightarrow RTM1_{\text{tan}} \]
\[ (d1,11,12,13,14,\text{rin},r1,r2,r3,\text{out},\text{f},\text{tm},\text{theta1},\text{theta2},\text{theta3})[2,2] ;
\]

Round-trip matrix for sagittal plane

\[ RTM1_{\text{sag}} := (d1,11,12,13,14,\text{rin},r1,r2,r3,\text{out},\text{f},\text{tm},\text{theta1},\text{theta2},\text{theta3}) \]
\[ \rightarrow \text{evalm}(\#*( \]
\[ M_{\text{d}(d)}, \]
\[ M_{\text{rin}(\text{rin})}, \]
\[ M_{\text{d}(d)}, M_{\text{lens}(\text{f})}, M_{\text{rodtm}}, \]
\[ M_{11(11)}, M_{r1\_sag}(r1, \text{theta1}), \]
\[ M_{12(12)}, M_{r2\_sag}(r2, \text{theta2}), \]
\[ M_{13(13)}, M_{r3\_sag}(r3, \text{theta3}), M_{14(14)}, \]
\[ M_{\text{out}(\text{out})}, \]
\[ M_{14(14)}, M_{r3\_sag}(r3, \text{theta3}), M_{13(13)}, \]} }
\[ M_{\text{r2,sag}}(r_2, \theta_2), M_{\text{l2}}(12), \]
\[ M_{\text{r1,sag}}(r_1, \theta_1), M_{\text{l1}}(11), \]
\[ M_{\text{rod}}(r_2, \theta_2), M_{\text{lens}}(f_{\text{tm}}) \):

\[ A_1_{\text{sag}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3) \rightarrow \]
\[ \text{RTM}_{\text{i1}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3)(1,1) \]
\[ B_1_{\text{sag}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3) \rightarrow \]
\[ \text{RTM}_{\text{i1}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3)(1,2) \]
\[ C_1_{\text{sag}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3) \rightarrow \]
\[ \text{RTM}_{\text{i1}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3)(2,1) \]
\[ D_1_{\text{sag}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3) \rightarrow \]
\[ \text{RTM}_{\text{i1}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3)(2,2) \]

Calculations

Stability Calculations

\[ \text{half_trace1}_\tan := \]
\[ (d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3) \rightarrow \]
\[ (\text{abs}(A_1_{\text{tan}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3)+\]
\[ D_1_{\text{tan}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3))/2)) \]
\[ \text{half_trace1}_\sag := \]
\[ (d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3) \rightarrow \]
\[ (\text{abs}(A_1_{\text{sag}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3)+\]
\[ D_1_{\text{sag}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3))/2)) \]

\[ \text{half_trace2}_\tan := \]
\[ (d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3) \rightarrow \]
\[ (\text{abs}(A_2_{\text{tan}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3)+\]
\[ D_2_{\text{tan}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3))/2)) \]

\[ \text{half_trace2}_\sag := \]
\[ (d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3) \rightarrow \]
\[ (\text{abs}(A_2_{\text{sag}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3)+\]
\[ D_2_{\text{sag}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3))/2)) \]

Spot Radius Calculation

This section provides the calculation for determining the spot radii
at the reference planes for different RTM's

Determination for RTM1

\[ v_{\text{rod1}}_{\tan} := \]
\[ (d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3) \rightarrow \]
\[ \text{sqrt}(2*\text{lambda}\times\text{Mg}) \]
\[ \text{abs}(B_1_{\text{tan}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3)) \]
\[ / (F_1)*\text{sqrt}(4-\]
\[ (A_1_{\text{tan}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3))^{2}) \]
\[ D_1_{\text{tan}}(d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3))^{2})) \]
\[ \rightarrow v_{\text{rod1}}_{\sag} := \]
\[ (d_1,11,12,13,14,r_1,r_2,r_3,\text{rout},f_{\text{tm}},\theta_1,\theta_2,\theta_3) \rightarrow \]
\[ \text{sqrt}(2*\text{lambda}\times\text{Mg}) \text{abs} \]
(B1_sag(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1,theta2,theta3)) / 
(Pi*sqrt(4-(A1_sag(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1,theta2, theta3)+B1_sag 
(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1,theta2,theta3))**2));
>
Evaluation
Give Value for f in the evaluation matrices
> ftm:=fvaltm:
Evaluation of RTMs
> RTM1_tan(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1,theta2,theta3):
> RTM1_sag(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1,theta2,theta3):
Evaluation of Stability Parameter - RTM1 (previously checked RTM2)
> 'half_trace1_tan'=
half_trace1_tan(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1, theta2,theta3);
> 'half_trace1_sag'=
half_trace1_sag(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1, theta2,theta3);

half_trace1_tan = 0.9466972810
half_trace1_sag = 0.9234541720

Evaluate spot size w_rod for thermal lens at rod centre
\*Calculate the spot size w_rod for the thermal lens in the centre
(in microns) USES fvaltm and fvalho
> 'w_rod1_tan' = evalf(w_rod1_tan 
(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1,theta2,theta3) 
*1000);
> 'w_rod1_sag' =
evalf(w_rod1_sag 
(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1, theta2,theta3)*1000); #m
>
w_rod1_tan = 148.6685001
w_rod1_sag = 151.8336005

RAH Plots
Stability plot vs Changing Thermal lens f
> ftm:=ftm';fho:=fho';fvaltm;
> plot((half_trace1_sag 
(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1,theta2, theta3),half_trace1_tan 
(d,11,12,13,14,rin,r1,r2,r3,rout,ftm,theta1,theta2, theta3)),ftm =0..2*fvaltm, S =0..1,
 labels=['ftm[mm]','ht'],title='(A+B)/2 vs. 
 ftm (sag/tan)');

ftm := ftm
fho := fho

32.34

Spot size at Tm:YAG vs f
> plot({w_rodi_sag
(d,11,12,13,14,rin,rl,r2,r3,rout,ftm,theta1,theta2,theta3),
w_rodi_tan
(d,11,12,13,14,rin,rl,r2,r3,rout,ftm,theta1,theta2,theta3)},
ftm =0..120, w=0...0.2,
labels=['f[mm]', 'w_Tm'], title='w_Tm vs. f (sag/tan)');

Stability plot vs changing d
> #plot({half_trace1_sag
(D,11,12,13,14,rin,rl,r2,r3,rout,fvaltm,theta1,theta2,
theta3), half_trace1_tan
(D,11,12,13,14,rin,rl,r2,r3,rout,fvaltm,theta1,theta2,
theta3), D =0..2.5+d, S =0...1, labels=['d [mm]', 'ht'],
title=('A+D)/2 vs. d (sag/tan)');

Spot size at Tm:YAG vs changing d
> #plot({w_rodi_sag
(D,11,12,13,14,rin,rl,r2,r3,rout,fvaltm,theta1,theta2,theta3),
w_rodi_tan
(D,11,12,13,14,rin,rl,r2,r3,rout,fvaltm,theta1,theta2,theta3), D =0..2.5+d, w=0...1.0,
labels=['d[mm]', 'w'], title='w vs. d (sag/tan)');

Stability plot vs changing l1
Here, L1 is used to replace l1
( which has already been assigned a value) as a
variable and is varied by 0 to 2 x l1.
> plot({half_trace1_sag
(d,L1,12,13,14,rin,rl,r2,r3,rout,fvaltm,theta1,theta2,
theta3), half_trace1_tan
(d,L1,12,13,14,rin,rl,r2,r3,rout,fvaltm,theta1,theta2,
theta3), L1 =0..130, S =0...1, labels=['l1 [mm]', 'ht'],
title=('A+D)/2 vs. l1 (sag/tan)');

> plot({half_trace1_sag
(d,L1,12,13,14,rin,rl,r2,r3,rout,fvaltm,theta1,theta2,
theta3), half_trace1_tan
(d,L1,12,13,14,rin,rl,r2,r3,rout,fvaltm,theta1,theta2,
theta3), L2 =0..1050, L =0...1, labels=['l2 [mm]', 'ht'],
title=('A+D)/2 vs. 12 (sag/tan)');

Wtm plots
> plot({w_rodi_sag
(d,L1,12,13,14,rin,rl,r2,r3,rout,fvaltm,theta1,theta2,theta3),
w_rodi_tan

(d, l1, l2, l3, l4, rin, r1, r2, r3, rout, fval, tgamma, theta1, theta2, theta3)),
  L1 =60...120, w=0...0.3,
  labels=['l1[mm]', 'w'], title='w vs. l1 (sag/tan)');

> LL2 := 12
> plot((w, r1, r2, r3, rout, fval, tgamma, theta1, theta2, theta3)),
  w, r1, r2, r3, rout, fval, tgamma, theta1, theta2, theta3))},
  L2 =100...350, w=0...0.25,
  labels=['l2[mm]', 'w'], title='w vs. l2 (sag/tan)');

LL2 := 300

> plot((w, r1, r2, r3, rout, fval, tgamma, theta1, theta2, theta3)),
  w, r1, r2, r3, rout, fval, tgamma, theta1, theta2, theta3))},
  L3 =225...290, w=0...0.3,
  labels=['l3[mm]', 'w'], title='w vs. l3 (sag/tan)');

> plot((w, r1, r2, r3, rout, fval, tgamma, theta1, theta2, theta3)),
  w, r1, r2, r3, rout, fval, tgamma, theta1, theta2, theta3))},
  L4 =140...370, w=0...0.3,
  labels=['l4[mm]', 'w'], title='w vs. l4 (sag/tan)');

> 
> 
}
Appendix B

ABCD Matrix for Thermal Lensing Relay

Below is the general ABCD matrix (equation B.1) used in chapter 3 for the optics train 4f relay imaging system following the plane-plane resonator output coupler. It can be used to estimate the error in spot-size measurements given displacements in the arm lengths and lens focal lengths (should a non-4f arrangement be used).

\[
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix}_{4f\text{-relay}}
\]  \hspace{1cm} (B.1)

where

\[
A_{4f\text{-relay}} = 1 - \frac{d_3}{f_2} - \left( d_2 \left( 1 - \frac{d_3}{f_2} \right) + d_3 \right) \frac{1}{f_1}
\]  \hspace{1cm} (B.2)

\[
B_{4f\text{-relay}} = \left( 1 - \frac{d_3}{f_2} - \left( d_2 \left( 1 - \frac{d_3}{f_2} \right) + d_3 \right) f_1^{-1} \right) d_1 + d_2 \left( 1 - \frac{d_3}{f_2} \right) + d_3
\]  \hspace{1cm} (B.3)
\[ C_{4f-\text{relay}} = -f_2^{-1} - \left( 1 - \frac{d_2}{f_2} \right) f_1^{-1} \]  
\[ (B.4) \]

\[ D_{4f-\text{relay}} = \left(-f_2^{-1} - \left( 1 - \frac{d_2}{f_2} \right) f_1^{-1} \right) d_1 + 1 - \frac{d_2}{f_2} \]  
\[ (B.5) \]
List of Publications

Journal Publications


Conference Papers


List of Publications


Other Publications and Articles Related to Work


B.1 Selection of Publications

- Efficient cladding-pumped Tm-doped silica fibre laser with high power singlemode output at 2μm. Published in Electronics Letters., Vol.36, No. 8, p 711-712 (13th April, 2000)

Conclusion: Impairments that have the potential to cause a deter-
iation in conversion bandwidth and efficiency of four-wave-mix-
ing have been discussed and the use of a short fibre to resolve the
impairments has been proposed. We used an HNL-DSF and ver-
ified the discussion experimentally. Despite using a non-PM-HNL-
DSF, we were able to achieve a conversion bandwidth of up to
91 nm using a 100 m long fibre. The only drawback may be the
high-pump power, although this is no longer a serious problem as
very high-power EDFA’s have been developed and commercialised

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Efficient cladding-pumped Tm-doped silica
fiber laser with high power singlemode output
at 2μm
R.A. Hayward, W.A. Clarkson, P.W. Turner,
J. Nilsson, A.B. Grudinin and D.C. Hanna

Continuous-wave operation of a double-clad Tm-doped silica
fiber laser at 2μm, pumped by two beam-shaped diode bars,
yielded an output power of 14 W in a singlemode ($M^2 < 1$) beam
for 36.5 W of launched pump power at 785 nm. The slope
efficiency with respect to launched diode power was 46%.

Introduction: All-solid-state sources producing high output power
in the 'grysal'-2μm spectral region have recently attracted much
interest owing to their numerous applications in areas such as
medicine and LIBAR. These devices also provide an ideal starting
wavelength for efficient nonlinear frequency conversion to the
mid-infrared (3-5 μm) spectral region. For many of these applica-
tions the need for high power and high efficiency is frequently
accompanied by a requirement for good beam quality. This com-
bination of operating characteristics becomes increasingly difficult
to achieve at high pump powers in conventional bulk solid-state
lasers due to strong thermal effects, in particular, strong and
highly aberrated thermal lensing, which degrades both beam qual-
ity and efficiency. Cladding-pumped fiber lasers offer an alterna-
tive route to power-scaling [1], with the advantages that the heat
generated due to the laser pumping cycle can be dissipated over a
long length of fiber thus minimizing the risk of thermally induced
damage, and the output beam characteristics are determined by
the waveguiding properties of the active ion doped core, which
can easily be tailored to produce a single-spatial-mode output.

Previous to the work reported here, the maximum output power
obtained from a cladding-pumped Tm-doped fiber laser in the
2μm regime, reported by Jackson and King [2], was 5.4 W with a
slope efficiency of 31% with respect to the launched pump power.
In this Letter we report a double-clad Tm-doped fiber laser of
improved design with a CW singlemode output power of 14 W for
35.5 W launched pump power, corresponding to a slope efficiency
of 46%. To the best of our knowledge, this result combines both
the highest power and highest efficiency in the 2μm spectral region
thus far reported for fiber lasers.

Experiments and results: The Tm-doped fiber laser used in our experi-
ment was pulled from a preform fabricated in-house using the
standard modified chemical vapour deposition and solution-doping
technique. The resulting preform had a chalcogen concentration
of ~2% by weight, and was machined so that the Tm-doped slab
was slightly offset from the core of the cladding (by roughly half its
diameter) to improve pump absorption [3]. The final fiber had an inner core diameter of ~20μm with a
numerical aperture of 0.12, and an inner cladding of outer dimen-
sion ~200μm. The latter was coated with a low refractive index (n
= 1.35) polymer outer cladding resulting in a nominal numerical
aperture of 0.49. The relatively small inner cladding size was cho-
森 to minimize the cladding-to-core area ratio to maximize pump
absorption, while allowing efficient in-coupling of the diode pump
sources used.

Fig. 1 Tm-doped fiber laser arrangement used with single diode-bar
pump source
HR: high reflectivity, HT: high transmission

Preliminary experiments were conducted using a single diode-
bar pump source (as shown in Fig. 1), which produced a maxi-
mum power of ~35 W at 785 nm. The output beam from the bar
was re-formed by a two-mirror beam shaper (not shown) [4] to
roughly equalize the beam propagation factors ($M^2 
< 70$) in orthogonal planes in order to allow tight focusing and hence effi-
cient coupling into the fiber's inner cladding. The resulting maxi-
mum pump power available at the focal was ~28 W. The in-
coupling efficiency and the effective absorption coefficient for the
pump were determined, via measurements of transmitted pump
power for different lengths of fiber, to be 80% and 4.6 dB/m, re-
spectively. The fiber laser arrangement for our preliminary
experiments used a length of ~2 m. Feedback for laser oscillation
was provided by a plane dielectric mirror with high reflectivity
($>99.8\%$) at the lasing wavelength (~2μm) and high transmission
(83%) at the pump wavelength, burred to the perpendicularly
cleaved pump-in-coupling end of the fiber, and by a dichroic mir-
ror with reflectivity, 8% at 2μm and > 99% at 785 nm, burred to
the opposite cleaved fiber end. The latter served to reflect any
unabsorbed pump light. Taking account of the various in-coupling
losses, a maximum of ~19 W of pump was coupled into the
fiber.

Fig. 1 Tm-doped fiber laser arrangement used with single diode-bar
pump source

HR: high reflectivity, HT: high transmission

Preliminary experiments were conducted using a single diode-
bar pump source (as shown in Fig. 1), which produced a maxi-
mum power of ~35 W at 785 nm. The output beam from the bar
was re-formed by a two-mirror beam shaper (not shown) [4] to
roughly equalize the beam propagation factors ($M^2 
< 70$) in orthogonal planes in order to allow tight focusing and hence effi-
cient coupling into the fiber's inner cladding. The resulting maxi-
mum pump power available at the focal was ~28 W. The in-
coupling efficiency and the effective absorption coefficient for the
pump were determined, via measurements of transmitted pump
power for different lengths of fiber, to be 80% and 4.6 dB/m, re-
spectively. The fiber laser arrangement for our preliminary
experiments used a length of ~2 m. Feedback for laser oscillation
was provided by a plane dielectric mirror with high reflectivity
($>99.8\%$) at the lasing wavelength (~2μm) and high transmission
(83%) at the pump wavelength, burred to the perpendicularly
cleaved pump-in-coupling end of the fiber, and by a dichroic mir-
ror with reflectivity, 8% at 2μm and > 99% at 785 nm, burred to
the opposite cleaved fiber end. The latter served to reflect any
unabsorbed pump light. Taking account of the various in-coupling
losses, a maximum of ~19 W of pump was coupled into the
fiber.
The threshold for laser oscillation was reached at an incident pump power of ~3W (i.e, 12W launched) and at the maximum available pump power, an output of 6.7W at 2m was obtained, corresponding to a slope efficiency with respect to launched power of ~39.5% (Fig. 2). The beam propagation factor, $M^2$, was measured using a Merchandis beam scope to be <1.1, confirming diffraction-limited, single-spatial-mode operation, even though the fibre core can support higher-order modes.

![Fig. 2 Fibre laser output power against launched pump power](image)

**Fig. 2** Fibre laser output power against launched pump power

![Fig. 3 Two-doped fibre laser arrangement used with two diode-bar pump sources](image)

**Fig. 3** Two-doped fibre laser arrangement used with two diode-bar pump sources

To scale to higher output power, a second beam-shaped diode-bar pump was coupled into the fibre using the modified experimental arrangement shown in Fig. 3. In this case feedback for laser oscillation was provided by a single dichroic mirror buttet to one end of the fibre and the by the 3.5% Fresnel reflection from the opposite cleaved fibre end. A longer fibre of length 4.5m was used to ensure sufficient pump absorption and to minimise the risk of damage to the pump diode due to any unabsorbed pump coupling back into the opposing fibre-diode. The fibre laser output was then collimated by a lens of focal length 25mm (which also served to focus the light from the second diode pump source into the fibre), and was then incident on a second dichroic mirror with high reflectivity (>99.8%) at the laser wavelength and high transmission (>95%) at the pump wavelength to provide access to the output beam. The pump focusing lens was coated for high transmission (>99%) at the pump wavelength, but was found to have a transmission of only 74% at 2m. The threshold pump power incident on the fibre laser (from diode A) was measured to be ~7.6W (i.e., 5.8W launched), and at the maximum available incident pump power of 47.5W (i.e., 36.5W launched) the fibre laser produced 10.3W of CW output (i.e., 14W before the collimating lens) in a single-mode beam with $M^2 < 1.1$. The power stability at high power levels was noted to be very good with short term fluctuations of < 3%. A particular interesting feature of the laser's performance (Fig. 4) is that the slope efficiency of ~44% (with respect to the launched pump power) was significantly higher than the Stokes efficiency (~39%), suggesting a significant increase in efficiency due to "two-for-one" cross-relaxation, as is commonly observed in Ti-doped crystal lasers. Taking into account cavity losses we estimate that the pumping quantum efficiency is >1.2. This represents a significant improvement in performance over that which would be expected without cross-relaxation, and is most likely due to the relatively high thulium concentrations used in our fibre. Future studies will be carried out into the effect of Th concentration on performance to see if a further increase in quantum efficiency comparable to that observed in Ti-doped crystals is achievable.

![Fig. 4 Fibre laser output power (before collimating lens) against launched pump power](image)

**Fig. 4** Fibre laser output power (before collimating lens) against launched pump power

Conclusions: We have demonstrated a double-clad Ti-doped fibre laser with a stable CW single-mode output power of 14W for 36.5W of launched diode power. This represents the highest power so far achieved from a fibre laser operating in the 2m regime. Further optimisation of the pump in-coupling optics, fibre design and Ti-doped concentration should yield a significant increase in output power and overall efficiency. The combination of high power, high efficiency and diffraction-limited beam quality provided by Ti-doped fibre lasers in the 2m region should make these sources attractive for a wide range of applications.

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R.A. Hayward, W.A. Clarkson, P.W. Turner, J. Nilsson, A.B. Grishanov and D.C. Hagan (Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom)

E-mail: wacl@orc.soton.ac.uk

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High-Power Diode-Pumped Room-Temperature Tm:YAG and Intracavity-Pumped Ho:YAG Lasers

R.A. Hayward, W.A. Clarkson and D.C. Hanna

Optoelectronics Research Centre
University of Southampton
Highfield, Southampton, Hants, U.K.
Tel: +44 (0)703 59518
Fax: +44 (0)703 595142
email: rob@jrc.soton.ac.uk

Abstract: Efficient Tm:YAG and intracavity-pumped Ho:YAG lasers are described with respective powers of 17.5W at 2.013µm and 7.2W at 2.097µm for ~53.4W of incident diode power.

Summary

Scaling output power from 2µm solid-state lasers to meet the demands of applications such as LIDAR and mid-infrared generation via pumping of OPO's is an area which has attracted growing interest over recent years. In this paper we describe a simple strategy for achieving high power operation of a Ho:YAG laser. Singly-doped Ho:YAG is an attractive laser material for 2µm operation with much lower upconversion losses, and hence a much longer effective energy storage time (~8ms) than for Tm-sensitised Ho:YAG. Unfortunately, Ho:YAG has no absorption band in the 780nm-900nm spectral region and hence cannot be pumped directly with commercially available high-power GaAlAs and InGaAs diode lasers. One solution to this problem is to pump the Ho:YAG laser in-band, with a diode-pumped Tm laser. Recent work by Budn et al [1] has demonstrated high-power operation of Ho:YAG by direct pumping with diode-pumped Tm:YLF and Tm:YALO lasers [2]. Here we describe an alternative approach for power-scaling of Ho:YAG via intracavity pumping in a Tm:YAG laser.

A preliminary requirement for high power operation of Ho:YAG via intracavity pumping is a high-power Tm:YAG laser. There are several problems to consider when attempting to power-scale Tm:YAG. Firstly, the relatively small emission cross-section and quasi-three-level nature are demanding on the diode pump laser which must be focussed to a relatively small beam size to achieve the required pump intensity. Secondly, the high pump intensity leads to a highly aberrated thermal lens and thermally-induced birefringence, which can degrade beam quality and increase cavity loss. The low stimulated emission cross-section and quasi-three-level nature of Tm:YAG renders the performance particularly sensitive to these thermally-induced losses. To minimise beam distortion due to the aberrated thermal lens we employ a resonator design with a TEM00 beam radius, w0, which is smaller than the pump beam size w0 since the lens is more highly aberrated in the wings of the pumped region. In addition, we apply a second condition to the resonator design which is that $\frac{d\phi}{dw_0}<0$ (where $\phi$ is the thermal lens focal length) for the strongest thermal lens encountered [3]. This increases the spatial overlap of the fundamental mode with higher-order transverse modes helping to suppress their oscillation without the need of lossy apertures. A typical Tm:YAG resonator design used in our experiments is shown in Fig.1. The Tm:YAG crystal was mounted in a water-cooled heat-sink maintained at a temperature of 17°C and doped with 3% at Tm³⁺. This doping level helps to reduce upconversion losses whilst maintaining efficient "two-for-one" cross-relaxation, which is important for efficient operation and helps to minimise detrimental thermal loading. Both faces of the Tm:YAG rod were end-pumped by fibre-delivered, beam-shaped [4], 40W diode bars at 785nm, which were both focussed to beam radii of ~400µm inside the rod. The maximum combined pump power of 53.4W incident on the rod yielded a laser output power of 14.2W at 2.013µm in an unpolarised, near-diffraction-limited beam with $M^2=1.3$. Linearly-polarised operation, achieved by inserting a simple Brewster-angled glass plate, resulted in a reduced maximum power of 8.4W for 49.7W of incident pump power due to the increase cavity loss resulting from thermally-induced depolarisation. Further increase in pump power resulted in a dramatic reduction in the laser power (Fig.2), believed to be due to the combined effect of thermally-induced birefringence and increased thermal loading due to upconversion, compounded by the use of resonator which was designed to operate close to the edge of its stable regime. To reduce the effects of thermally-induced birefringence, a quarter-waveplate, aligned with its fast and slow axes parallel (or perpendicular) to the preferred plane of polarisation defined by the polariser, was inserted between the cavity end mirror.
and the Tm:YAG rod [5]. This resulted in a dramatic reduction in the depolarisation loss from >5% to <0.4% and an increase in laser power to 11.5W (fig. 2), limited only by the available pump power.

Higher output power ~17.5W (unpolarised) could be achieved, at the expense of beam quality, by using a modified cavity design (fig. 3) with a smaller TEM00 beam radius of ~200µm, which did not change significantly with varying thermal lens focal length. Using a similar cavity design to that shown in Fig. 3, and replacing the Tm:YAG rod by Tm:(Lu,Y)AG rod, doped with 3% Tm, and with 50% of the ytterbium ions replaced by lutetium, we obtained a slightly higher output power of 18W (fig. 4). This laser operates at a slightly longer wavelength (~2.020µm) than for Tm:YAG, which has higher atmospheric transmission, making it of potential interest for LIDAR.

For scaling to higher power and maintaining good beam quality, thermal loading is going to be an important factor. Inband pumping of Ho:YAG at 1.9-2µm offers a route to much lower quantum defect heating (<10%). In addition, Ho:YAG has a ~3 times larger σ/τ product than Tm:YAG and, for typical Ho⁺⁺ doping levels of ~0.5%, it has much lower upconversion losses than Tm:YAG [6]. These factors combined with its long energy storage time suggest Ho:YAG is an attractive candidate for high power CW and high-energy Q-switched operation. Intracavity pumping of Ho:YAG in a Tm:YAG laser [7] offers the advantages of a nearly uniform axial pump deposition and reduced quantum defect heat loading compared to direct inband pumping with Tm:YLF [1] or Tm:YALO [8] lasers, but at the expense of a slightly more complicated resonator design. The design used in our preliminary work (shown in Fig. 5) is based on the Tm:YAG laser resonator shown in Fig. 3. A 0.5% Ho-doped YAG rod (9mm long), mounted in a water-cooled copper heat-sink maintained at a temperature of 17°C was inserted into the Tm:YAG resonator and the output coupler replaced by one with high reflectivity at the Tm:YAG wavelength and with a transmission of ~6% at the Ho:YAG wavelength (~2.1µm). The Ho:YAG laser reached threshold for a diode power of ~10W incident on the Tm:YAG rod, and produced a maximum power of 7.2W at 2.097µm for 53.4W of incident pump power, corresponding to a slope efficiency with respect to incident diode power of 17.5%. The output beam had M² values in orthogonal planes of ~5 and ~6. This
relatively poor beam quality resulted from the use of a resonator designed for high Tm:YAG laser power rather than good beam quality, and also because the Ho:YAG laser beam experiences some beam distortion due to thermal lensing in the Tm:YAG rod. To access the full benefits of the low fractional heating in the Ho:YAG it will be necessary to decouple the Ho:YAG and Tm:YAG cavities, so that the Ho:YAG laser beam does not propagate through the Tm:YAG rod. This should allow a significant improvement in efficiency and beam quality. Thus, with the appropriate cavity design, intracavity-pumping of Ho:YAG promises to be a very attractive route to high output power in the 2μm spectral region.

References

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