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Efficient Blue Generation from
All-Solid-State Q-Switched Nd:YAG Lasers

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ABSTRACT

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This thesis describes work carried out at Southampton University that has been directed towards achieving high-power all-solid-state blue sources using two low-gain transitions of Nd:YAG. Diode-end-pumping is used to obtain efficient laser performance. The thesis attempts to tackle some of the obstacles to power scaling Q-switched low-gain lasers that use diode-end-pumping schemes.

A 1319nm Q-switched Nd:YAG laser is described that produces a 17KHz pulse train consisting of 353 watt peak power pulses delivering an average power of 780mW for doubling. Periodically poled lithium niobate (PPLN) is used to double to 659.5nm. A 54% second harmonic conversion efficiency produces 360mW of red average power. Sum frequency mixing of the red and infra-red in a second PPLN sample is achieved with a third order grating. A pulsed blue output (13.7 watts peak) at 439.7nm is achieved with good beam quality and an average power of 35mW.

A technique is described to aid power-scaling of polarised laser sources. Analysis of the quarter wave-plate technique demonstrates that the technique will be highly beneficial in reducing the depolarisation loss in low-gain solid-state lasers. The technique is applied to a 946nm laser and a 1319nm laser. Depolarisation of the 946nm source is reduced from 1.66% to 0.0006% and depolarisation of the 1319nm laser is reduced from 1.2% to 0.015%.

The quarter wave-plate technique is implemented in a high power 946nm laser that is Q-switched for low repetition rates. 0.53mJ is extracted with a 5.3KW peak pulse power at 1Khz repetition rate. The 946nm output is used to generate 473nm blue light via second harmonic generation in non-critically phase-matched LBO at 329° centigrade. An average power of 370mW is demonstrated with a conversion efficiency of 21% at 4KHz repetition rate.
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Chapter 1

Introduction and Theoretical Background

1.1 Introduction

The laser was probably the most important and exciting discovery [Maiman60] in the field of optics within the second half of the twentieth century. It has revolutionised the telecommunications industry and made a significant impact in diverse fields such as medicine, entertainment, science and military. These application areas provide a high demand for new and improved laser sources that can grant access to new wavelengths, are more compact and efficient to run and have a higher brightness than their predecessors. In the ongoing research for new sources a wide variety of laser media have been uncovered spanning from semiconductors [Hall62], [Nathan62], [Quist62] to gases [Javan61], [Patel64] to optic fibres [Desthieux93], [Percival94].

The interaction of high intensity pulses of laser light with matter uncovered the diverse field of nonlinear optics [Franken61]. One of the key benefits of nonlinear optical technology has been to provide access to new wavelengths using available laser sources via techniques such as second harmonic generation, where coherent light is generated at twice the frequency of the laser beam. One of the most successful sources to come from nonlinear optical technology is the 532nm green source, the second harmonic of the 1064nm Nd:YAG laser.

The work discussed in this thesis is based upon the solid-state laser medium neodymium doped yttrium aluminium garnet, Nd:YAG. YAG is the most common host crystal for the Nd$^{3+}$ ion. One advantage of YAG is the hardness of the garnet crystal allowing for laser operation at high intra-cavity intensities without crystal damage. Neodymium (Nd$^{3+}$) dopant substitutes the yttrium (Y$^{3+}$) ion within the crystal structure. A 1% atomic dopant concentration is commonplace for Nd:YAG laser rods. Growth of Nd:YAG is a mature technology, the crystal is cubic in structure
producing isotropic behaviour and is generally grown for laser oscillation along the [111] crystal. Light propagating through the laser rod therefore experiences a single refractive index of 1.82 [Kaminskii89].

The use of a solid-state materials as a laser host provides a great deal of flexibility allowing alterations in the dopant concentration of laser ion within the host and the use of different pump sources and heat sinking geometries. Solid-state lasers can be constructed to be compact and efficient, especially if a diode pump source is employed. Diode end-pumping of solid-state lasers can provide regions of high pump intensity enabling low gain transitions to be explored. Nd:YAG is a suitable medium for this task because it is able to withstand the substantial pump intensities required for low gain operation. The crystal is also tolerant to the high intra-cavity intensities that are present under Q-switched operation. The crystal also has a good thermal conductivity ($13 \text{Wm}^{-1}\text{K}^{-1}$) [Kaminskii89] allowing for efficient heat removal under high thermal loading conditions.
1.2 Diode-End-Pumping

For many years, flashlamps were the choice method of pumping solid-state lasers and are still in use today in numerous laser systems. Flashlamp technology in its simplest form consists of an electrical power supply to charge a capacitor, and a switch (for instance a spark plug) to dump the capacitor load through the flashlamp. The emission from a flashlamp spans a broad range of wavelengths. Although some wavelength selection may be achieved by changing the flashlamp or pulse shaping and variation of the electrical discharge intensity, the pumping process is inefficient with perhaps 1% of electrical energy successfully pumping the desired laser transition.

Advancements in diode laser technology have lead to the availability of 20 watt diode bars. A diode bar consists of a linear array of diode emitters that has an aspect ratio of $\sim 1:10000$. In the plane of the diode array, the output has an $M^2$ of $\sim 2000$ whereas orthogonal to the array the output is nearly diffraction limited. Such an output can be used to directly side-pump solid-state lasers, however side-pumping makes poor use of the available pump power because the laser mode is not matched to the pump region. For this reason, side pumping is not appropriate for pumping low gain laser transitions and therefore will not be considered here.

The diode bar output characteristics are not favourable for end-pumping of solid-state lasers. The significant difference in beam quality of the diode bar output in the two orthogonal planes implies that it is not possible for the pump to be focussed to a spot-size similar to the laser mode (circular with a radius of 100s of microns) over any reasonable length of laser rod. Reshaping the diode bar output can provide a more useful beam.

One successful beam-shaping technique uses two nearly parallel mirrors [Clarkson96] that are slightly offset from each other and angled such that the incident diode beam is effectively sliced up along the long aspect of the beam profile. The different 'slices' experience multiple reflections from the two mirrors such that the 'slices' emerge stacked on top of each other, equalising the $M^2$ of the two orthogonal planes. A key
advantage that this has over other beam-shaping techniques is that the overall brightness of the beam does not suffer significant deterioration.

A high brightness diode source allows for tighter focusing across more of the crystal length and hence a higher inversion density. Brightness [Hardman99] is defined by

\[ B = \frac{P}{\lambda^2 M_x^2 M_y^2} \]  

(1.1)

Where \( B \) is the brightness of the source (Wm\(^{-2}\)), \( P \) is the pump power (W), \( \lambda \) is the wavelength, \( M_x, M_y \) are the \( M^2 \) beam quality factors [Sasnett89] in the x and y planes respectively.

Beam-shaped diode-bar end-pumping is the most efficient method of attaining the inversion density required to produce lasing on low gain transitions because the diode pump can be focused down and co-propagated with the laser mode along the length of the laser rod to provide good laser mode – inversion density overlap.

Diode-bar end pumping does increase the severity of thermal effects within the laser system. Careful management of these thermal effects is essential for efficient laser operation. An overview of thermal effects is provided in the following section.
1.3 Thermal Effects

One method of effective heat removal from a laser rod is by mounting the rod in an actively cooled heat-sink constructed from a material with a high thermal conductivity, for example copper. An advantage of end-pumping is that during the design of the laser rod and heat-sink, the surface area in thermal contact with the heatsink to the laser rod volume can be maximised. Maximisation of the cooled surface area to rod volume can be achieved by using a long, thin diameter laser rod. This helps to reduce heat build up and hence the associated problems of thermal effects within the crystal.

A cylindrical geometry end-pumped laser rod produces a radially symmetric temperature distribution, which is advantageous, in that a radially symmetric thermal lens is present within the gain region. This thermal lens predominantly stems from the dependence of the crystal refractive index with temperature, \( dn(T)/dT=9.86 \times 10^{-6} \text{K}^{-1} \) [Kaminskii89]. Some contribution to the thermal lens is also brought about by thermally induced crystal stresses altering the crystal refractive index and also by bulging due to the expansion of the laser rod end faces.

The radial temperature profile across the laser rod face within an end-pumped system is not parabolic [Innocenzi90] and therefore the thermal lens possesses aberrations. The aberrations increase with radius from the centre of the laser rod in such a way that the effective thermal lens focal length decreases with radius. A laser beam propagating through the thermal lens experiences the diffraction loss which has a direct impact on the laser performance. Under intense thermal loading conditions, the short length of the thermal lens can cause the laser cavity to become unstable. Therefore, it is important to consider the strength of the thermal lens when designing a laser cavity.

Thermally induced stress within the laser medium not only contributes to the thermal lens but also causes birefringence within the laser crystal. Radial heat flow within the
laser crystal causes the birefringent stress planes to be set up with a polar geometry i.e. aligned radially and tangentially to the direction of the heat flow.

If the laser cavity contains no polarisation selective losses, for instance a Brewster plate, then the birefringence only effects the strength of the thermal lens by providing two different refractive index components to the thermal lens, one for the polarisation component of the laser mode that is aligned in the radial direction and one for the polarisation component aligned in the tangential direction [Forster70]. This affect is known as thermal bifocussing. Because the difference in the refractive indices is small, the effect is not usually of great concern.

For polarised laser cavities, thermally induced stress birefringence is a severe problem and, for systems with intense thermal loading, will limit the power scalability of the laser. Oscillating laser modes experience partial depolarisation when propagating through the laser rod. The amount of depolarisation is dependent upon the alignment of the incident beam polarisation in relation to the radial and tangential stress axes and the strength of the birefringence at each point on the laser rod [Koechner70]. Depolarisation loss is discussed in detail in Chapter 3.
1.4 Diode End-Pumped Solid-State Cavity Design

The open resonator scheme employed for optical systems was first suggested in 1958 [Dicke58], [Prokhorov58], [Schawlow58]. Calculations by Fox and Li [Fox61] demonstrated that steady-state solutions could indeed be obtained with an open cavity for two parallel mirrors and for two spherical mirrors separated so that their foci were coincident (confocal). Boyd and Gordon [Boyd61] explained that the confocal geometry laser cavity suffered less from misalignment and had a higher quality factor, Q, than for the plane parallel laser cavity. Q is defined as the ratio of energy stored in the resonator to power dissipated from the resonator per unit angular frequency ω₀ [Koechner96]. It was also noted that the fundamental mode experienced the least diffraction loss out of the stable modes within the confocal cavity.

Kogelnik and Li [Kogelnik66] described the application of ray transfer matrices to Gaussian beam propagation in laser cavities and presented the stability diagram for a two mirror cavity (radii of curvatures R₁, R₂) spaced by a distance d. Stable laser cavities were those within the range defined by Equation 1.2.

\[
0 \leq \left( 1 - \frac{d}{R_1} \right) \left( 1 - \frac{d}{R_2} \right) \leq 1 \tag{1.2}
\]

Stable cavities are advantageous for continuous wave or low gain systems as the high quality factor provides a low laser threshold. It is also possible to achieve good beam quality from stable cavities. One criticism of the stable cavity design is that the laser mode tends to be small compared to unstable cavity designs where the laser mode fills the gain region. This combined with the desire to add other intra-cavity optical devices, has lead to more complex cavity designs being utilised. Additional mirrors or lenses can be used to alter the internal laser mode size and external laser output characteristics to better suite the desired operating regime and cavity requirements.

When selecting an appropriate resonator design for an end-pumped laser system, one of the critical factors is the radius of the laser mode within the laser rod. This has a
direct effect on the laser threshold and the pump spot-size required (and hence the thermal loading density) within the crystal.

However, several other factors must also be considered. If the laser is to be Q switched, spot sizes at all of the optical components must be considered in relation to the intra-cavity peak intensity to avoid laser damage to coatings and delicate components. The cavity must be long enough to insert all of the required components and fit within the constraints of the pumping geometry and bench space available. The cavity length also has an influence on the pulse shape under Q switched operation. Choice of cavity also affects the stability criteria for the laser system and determines the diffraction losses of oscillating laser modes.

Performance of any cavity cannot be appreciated fully without consideration of the presence of a thermal lens within the laser medium. Symmetrical side pumping of a laser rod generates a thermal lens with a quadratic dependence on radius and therefore is a thermal lens of just one focal length. For end-pumped geometries involving a super Gaussian pump intensity profile, a thermal lens results that deviates further from a quadratic lens profile with increasing radius and therefore contains spherical aberration. It is useful to consider the whole aberrated thermal lens as a summation of thermal lenses that weaken with increasing radius. Therefore a portion of the laser mode propagating further from the central axis of the laser rod will experience a weaker focus thermal lens compared with a section of the laser mode propagating central to the laser rod radius.

For low power diode end-pumping, the laser mode is designed to fill the pump spot size to enforce TEM\textsubscript{00} laser operation. This is not the case for high power diode end-pumping however, where it is necessary that the laser mode spot-size be significantly less than the diode pump spot-size to avoid the most aberrated portion of the thermal lens.

Under high pump power conditions, the difference in spot-size between the pump and TEM\textsubscript{00} laser mode within the laser rod implies that there is an external region of the gain that is not utilised by the fundamental laser mode. Therefore higher order cavity
modes will be able to oscillate unless constrained with an aperture or by some other means. It is possible to use the weakening of the thermal lens with radius that is brought about by the radial temperature profile to suppress higher order TEM laser modes through careful choice of cavity design [Clarkson98].

The cavity components can be analysed by combining ray transfer matrices of the thermal lens, each optical component and the spacing between adjacent components to obtain a matrix expression for one round trip of the laser cavity. For a round trip matrix \( M \) where

\[
M = \begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\]  

(1.3)

The stability \( S \) of the laser cavity \( M \) is given by

\[
S = \frac{A + D}{2}
\]  

(1.4)

where stability is achieved for \( S \leq 1 \), and the laser mode TEM\(_{00}\) spot-size at the point at which the round trip matrix is started (and finished) can be calculated from Equation (1.5).

\[
w_i = \sqrt{\frac{\lambda |B|}{\pi \sqrt{1 - \left(\frac{A + D}{2}\right)^2}}}
\]  

(1.5)

Where \( w_i \) is the spot-size of a TEM\(_{00}\) Gaussian mode and \( \lambda \) is the wavelength of the resonator mode. With the aid of Equations (1.4) and (1.5), and starting the round trip matrix at the laser rod it is possible to monitor the laser TEM\(_{00}\) spot-size and stability within the laser rod as the cavity is altered.
Figure 1.1, Stability and spot-size ($w$) for a two mirror plano-concave laser, $R_c=50\text{mm}$, Cavity length=40mm verses a thin thermal lens $f$.

Figure 1.1 shows how the stability and spot-size vary with focal length for a two mirror plano-concave laser containing a thin thermal lens. It can be seen that the cavity is stable for thermal lens focal lengths as short as 40mm. The spot-size verses focal length graph demonstrates that the laser mode spot-size is very sensitive to the thermal lens focal length especially as the focal length approaches the stability edge.
1.5 Nonlinear Optical Generation

Nonlinear optical phenomena involve the interaction of high electric or magnetic fields with matter where some of these fields are in the optical frequency range. Some nonlinear optical effects were understood by 19th century physicists. For instance, the Faraday effect, Kerr effect and Pockels effect. All of these phenomena involve the presence of large electric or magnetic DC fields. It was not until the discovery of the laser that large AC fields were available in the optical frequency range.

Application of a strong (not negligible compared to the binding field) laser field on a valence electron in a material can produce oscillation of the electron dipole that is nonlinear in behaviour. This nonlinear oscillation can be expressed as a sum of harmonic components. For an applied field of \( E(t) = E_0 \sin(\omega t) \), a dipole moment of \( p(t) = eX(t) \) is obtained where

\[
X(t) = X^0 + X^{(\omega)}_0 \sin(\omega t) + X^{(2\omega)}_0 \sin(2\omega t) + X^{(3\omega)}_0 \sin(3\omega t) + ... \tag{1.6}
\]

The applied field at \( \omega \) induces the dipole to radiate at \( \omega \), 2\( \omega \), 3\( \omega \) etc. Franken [Franken61] was able to generate a few photons at 347nm (the second harmonic of 694nm) with a conversion efficiency of \( 10^{-8} \). The poor conversion efficiency was because Franken did not use phase-matching to prevent the second harmonic generated from different points in the medium from interfering destructively.

The strength of the second harmonic intensity produced as the fundamental mode propagates through the nonlinear medium can be expressed as

\[
I^{(2\omega)} = I^{(\omega)}^2 B L^2 \sin^2 \left( \frac{\Delta K L}{2} \right) \tag{1.7}
\]

for small signal fundamental intensities, where \( I^{(2\omega)} \) is the second harmonic intensity, \( I^{(\omega)} \) is the fundamental intensity, \( \Delta K \) is the difference in propagation constants \( (2K^{(\omega)} - K^{(2\omega)}) \) and \( L \) is the length of the crystal traversed. It can be seen that the second
harmonic intensity is proportional to the square of the fundamental intensity and that the second harmonic is maximised when $\Delta K=0$. The condition $\Delta K=0$ is termed the phase-matching condition.
1.5.1 Critical Phase-Matching

To achieve $\Delta K = 0$, $2K^{(2)}$ must equal $K^{(2)} = n_\omega \omega / c$, where $n_\omega$ is the refractive index experienced by the fundamental. Therefore phase-matching for second harmonic generation requires $n_\omega = n_{2\omega}$. One method of achieving this is by using a birefringent crystal for doubling. Selection of the correct propagation angle of the fundamental from the optic axis allows the refractive index of light polarised in the ordinary plane to match that of light polarised in the extraordinary plane oscillating at twice the frequency, Figure 1.1.

![Diagram](image_url)

**Figure 1.2, Type I, Critical Phase-Matching in a Negative Uniaxial Crystal**

The second harmonic is generated polarised at $90^\circ$ to the fundamental polarisation. As the name suggests, critical phase-matching is very sensitive to the phase-match angle and this limits the effectiveness of tight focussing of the fundamental to increase the conversion efficiency.
Poynting vector walk-off is also a problem with critical phase-matching. The extraordinary wave may experience walk-off from the ordinary wave because the energy of the extraordinary wave does not propagate normal to its wave front. This results in reduced conversion.
1.5.2 Non-Critical Phase-Matching

Some materials allow non-critical phase-matching or 90° phase-matching. This method has a greater angular acceptance bandwidth and does not suffer from the problem of beam walk-off associated with critical phase-matching.

![Optic Axis Diagram](image)

**Figure 1.3, Refractive Index Diagram for Non-Critical (90°) Phase-Matching**

Figure 1.3 shows that for non-critical phase-matching to take place, the ordinary (2ω) and extraordinary (ω) refractive indices equal for a phase-match angle of 90° to the optic axis. A comparison of the index ellipsoids for critical and non-critical phase-matching shows that a slight error in the phase-match angle would have a more pronounced effect for critical phase-matching than for non-critical phase-matching. Thus the angular acceptance bandwidth is greater for non-critical phase-matching, allowing for tighter focussing to be implemented to improve conversion efficiency.
Non-critical phase-matching is not possible in all materials or for all wavelengths. A nonlinear material for which 90° phase-matching is possible will only allow the 90° criterion to be met at one phase-match temperature for a particular wavelength.
1.5.3 Quasi Phase-Matching

Quasi Phase-Matching (QPM) is a relatively new engineering process that allows for nonlinear optical generation to be performed for a wide range of wavelengths at phase-match temperatures that are pre-selected by the user. QPM is designed by calculating the length of crystal at which the generated nonlinear beam starts to interfere destructively. In the engineering process [Webjorn94] the crystal field is periodically flipped at these calculated intervals so that a generated beam propagating through the crystal does not experience destructive interference, but continues to see parametric gain.

![Quasi-Phasematching (QPM)](image)

Figure 1.4, Comparison of Generated Intensity against Propagation Distance for Birefringent Phase-Matching, Quasi-Phase-Matching and No Phase-Matching [Myers98]
1.6 Overview of the Thesis

The remainder of this thesis consists of three results chapters and a summary chapter. Chapter 2 investigates blue generation by using a 1319nm Nd:YAG pump source combined with extra-cavity sum frequency generation (SFG) using two cascaded samples of periodically poled lithium niobate. Performance of the 1319nm laser and SFG results are presented.

Chapter 3 closely examines the effects of thermally induced stress birefringence in end pumped solid-state laser media. A new method of birefringence compensation is presented and theoretically compared with the uncompensated case. Two laser sources are demonstrated with and without the new compensation method. Comparison of theory with experiment and a discussion of the limits of this compensation technique are given.

Chapter 4 contains design considerations and construction of a high power pulsed 946nm laser. The laser performance is analysed and the laser used to perform second harmonic generation of 473nm blue light. Extra-cavity doubling is achieved in an LBO crystal cut for non-critical phase-matching. The blue output is characterised and possible improvements discussed.

Chapter 5 is the thesis summary for the three results chapters. A discussion of possible routes for further work is also included.
1.7 References


Chapter 2

Short Wavelength Blue Generation

2.1 Introduction

There is a considerable interest in the development of all solid-state visible sources both as an alternative to existing sources and as a route to accessing new wavelengths within the visible spectrum. As detailed in chapter 1, diode-pumped solid-state lasers possess many advantages over older technologies such as gas and dye lasers that provide visible laser light. This chapter details the design, construction and use of a 1319nm Nd:YAG laser to generate a high-power, short wavelength, pulsed blue source with the aid of nonlinear optical techniques.

A great deal of work has been directed at blue generation because of the severe lack of sources available within this region of the visible spectrum. Coherent blue light has applications in data storage, cinematic and laser displays. Blue light generation can also be used as a stepping-stone to access sub 250nm ultraviolet wavelengths through second harmonic generation.

Two types of blue laser that are currently available are the semiconductor diode laser, operating in the region of 430nm and the argon ion laser line at 488nm. Semiconductor diode research has had considerable success [Miyajima01] in producing blue sources, however, at present, these are still low power continuous wave devices. Conversely, argon ion lasers can provide hundreds of milliwatts of blue light at 488nm when lasing is prevented on the higher gain argon ion transitions. The argon ion laser suffers from several problems that make it a less attractive source, such as high electrical power consumption and a low wall-plug efficiency, expensive and frequent gas tube replacement and size of the laser head, power supply and cooling system.

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A different approach to blue light generation is available through the use of nonlinear frequency conversion which can provide access to wavelengths that are not otherwise directly generated from laser media.

Previously, a great deal of blue generation work has focussed upon the use of second harmonic generation (SHG) of the 946nm Nd:YAG laser line to produce 473nm light. One method which successfully utilised the 946nm Nd:YAG transition consisted of a single pass of the infra-red fundamental laser through a sample of periodically poled lithium niobate (PPLN) which was situated externally to the laser cavity. This technique was employed for blue light generation by V. Pruneri et al [Pruneri95] to generate 49mW of 473nm light from 3 watts of 946nm continuous wave fundamental. However, it was found from their experiments that photorefractive effects caused a significant degradation in the beam quality of the blue light generated.

Degradation in the beam quality was addressed [Ross98] by using an elevated phase matching temperature which greatly reduced the photorefractive effects within the lithium niobate. A fundamental to second harmonic conversion efficiency of 40% (450mW of 473nm) with good beam quality was demonstrated. Such a high efficiency was achieved by driving the 946nm laser at the relaxation oscillation frequency to obtain pulsed operation and thus higher peak power from the 946nm laser source. The combination of diode pumped solid-state laser technology combined with the large effective nonlinear coefficient associated with periodically poled materials, ~17pmV⁻¹ due to optimum axis selection, is therefore an efficient method of high power nonlinear generation.

This chapter presents the generation of a shorter wavelength blue light at 439.7nm using sum-frequency mixing to combine the 1319nm fundamental from an Nd:YAG source with its second harmonic at 659.5nm to generate the third harmonic at 439.7nm.
2.2 The 1319nm Laser

2.2.1 The 1319nm Transition

The 1319nm line in Nd:YAG is a four level laser transition that shares the same upper laser level as the well known 1064nm laser, Figure 2.1. However the branching ratio from the upper laser level ($^4F_{3/2}$) to the $^4I_{13/2}$ manifold which contains the lower laser level for the 1319nm transition is only 0.14 compared with 0.6 for the $^4I_{11/2}$ manifold which contains the lower laser level for the 1064nm transition [Kushida68]. The proportionally small branching ratio implies that the gain media requires a high brightness pump source to provide the required inversion density to achieve the threshold condition. The low gain nature of the laser means that suppression of the dominant 1064nm laser line is necessary. One characteristic that the 1064nm laser transition and the 1319nm transition share is the upper state lifetime, 230µs, allowing for appreciable energy storage between pulses under Q-switched operating conditions.

![Energy Level Diagram of the Nd:YAG Crystal Highlighting the 1319nm Transition](image)

Figure 2.1 Energy Level Diagram of the Nd:YAG Crystal Highlighting the 1319nm Transition
As with the familiar 1064nm Nd:YAG laser, the 1319nm laser is a four level system. Unfortunately the quantum defect heating associated with the transition is poor in comparison with 39% of the energy of each pump photon being converted to heat through non-radiative decay. This strong thermal loading within the Nd:YAG crystal must be considered when designing a laser because the refractive index of YAG increases with temperature and therefore a positive thermal lens is formed with the lens profile being dependent upon the profile of the temperature distribution within the laser rod.

The 1319nm transition is in close proximity to several other possible laser transitions that emanate from crystal field splitting within the $^4I_{13/2}$ manifold. Strong neighbouring laser transitions emit photons at 1334, 1335 and 1338nm which is too close to the required 1319nm transition to be effectively suppressed through dielectric coatings on the laser mirror surfaces. Parasitic lasing on one or more of the other transitions will therefore be present and must be suppressed by means of an intracavity component such as a solid etalon.
2.2.2 Diode End-Pumping and Thermal Considerations

Diode end-pumping is an effective method of facilitating the high pump intensity requirements of a low gain transition such as the 1319nm transition. The inconvenient spatial output characteristics of a diode bar, that is $M^2$ perpendicular to the diode array of $\sim$1 and $M^2$ parallel to the array of $\sim$2000, requires the output to be beam-shaped to provide a uniform $M^2$ in the two orthogonal planes typically with $M^2$ between 50 and 100. The beam-shaped diode pump provides a high brightness beam with directionality that allows focusing to spot-sizes in the order of hundreds of microns.

Diode-bar pump sources possess the narrow, defined wavelength associated with lasers. The peak diode wavelength can be effectively tuned by several nanometers to match the absorption peak of the laser medium. This fine-tuning of the diode wavelength is achieved by a variation in the temperature of the diode heat sink and therefore the operating temperature of the diode.

Diode end-pumping does have some disadvantages due to the nature of the thermal loading within the gain media. Unlike side pumped systems, the temperature profile that is generated in the laser media is not parabolic and therefore does not instigate a thermal lens of one focal length. In the pumped region of the laser rod, a highly aberrated thermal lens is formed which effectively increases in focal length with radius.

The strength of the pump induced thermal lens generated at the centre of the laser rod under lasing conditions can be calculated [Clarkson98].

\[
F_0 = \frac{\pi K_c w_p^2}{P_p n \frac{dn}{dT}}
\]  

(2.1)

where $F_0$ is the thermal lens on the optic axis, $K_c$ is the thermal conductivity for Nd:YAG (13Wm$^{-1}$K$^{-1}$), $w_p$ is the radius of the pump spot size, $P_p$ is the pump power incident on the laser rod, $\gamma$ is the portion of pump photon energy that is converted to
heat due to quantum defect heating (39%), $\eta_{abs}$ is the proportion of the pump power that is absorbed in the laser rod and $\frac{dn}{dT}$ is the change in the refractive index of the crystal with temperature ($9.86 \times 10^{-6}K^{-1}$). Figure 2.2 demonstrates the thermal lens focal lengths that can be expected according to equation (2.1) for a 1319nm Nd:YAG continuous wave laser that is end-pumped by a 14 watt diode-bar.

Graph of Thermal Lens Focal Length (mm) against Spot Size (µm) for a 1319nm Continuous Wave Nd:YAG Laser

![Graph of Thermal Lens Focal Length against Spot Size](image)

Figure 2.2, Dependence of the Thermal Lens Focal Length on the Pump Spot-Size for a 1319nm CW Nd:YAG Laser

Under nonlasing or Q switched conditions the thermal lens focal length will become shorter as more heat is deposited within the laser medium via interionic upconversion. For high repetition rate Q switching the increase of thermal loading due to upconversion should be small because the upper laser level is frequently depopulated therefore reducing the probability of energy transfer between adjacent laser ions. Interionic upconversion is discussed further in Chapter 4.
Smaller pump spot-sizes not only lead to a stronger thermal lens, the more pronounced temperature profile causes more stress to be present within the crystal structure which not only adds to the strength of the thermal lens [Koechner96b], but also causes thermally induced stress birefringence to be present that will cause a depolarisation loss under polarised operating conditions, see Chapter 3.

A 400μm radius pump spot-size was selected for this experiment. This spot size was found to provide a good inversion density without hindering laser performance due to thermal effects. This radius gives a thermal lens focal length of 125mm under continuous wave operation for 14 watts of pump power.
2.2.3 Laser Design and Construction

A cylindrical geometry 10mm 1% doped Nd:YAG rod was used as the laser medium. The two ends of the rod were anti-reflection coated for 1.32μm to avoid lasing off the rod end faces. The dielectric coating was also specified to be high transmission for both the 809nm pump wavelength and the 1064nm Nd:YAG laser transition. A water-cooled copper heat sink was used to house the laser rod. The heat sink was kept at a temperature of 14° centigrade, the laser rod was in good thermal contact with the heat sink.

A 20-watt Opto Power Corporation beam-shaped diode bar was used as a pump source. The diode was temperature tuned to the 809nm absorption peak by minimising the transmitted power through the gain medium. The pump was focussed into the Nd:YAG rod to a spot size of 400μm radius by two crossed cylindrical lenses.

A three-mirror folded arm cavity was constructed around the laser rod. The cavity consisted of a plane input coupler, plane output coupler and a 50mm radius of curvature concave turning mirror. All optical components were coated for high transmission at 1064nm to prevent lasing on the dominant Nd:YAG line. The input coupler optical coating was also specified to be high transmission at 809nm, Figure 2.2.

![Diagram of the Laser Cavity for the Continuous Wave 1319nm Laser, the angle formed between the two arms of the laser cavity was much smaller than depicted to minimise astigmatism](image)

Figure 2.2, Diagram of the Laser Cavity for the Continuous Wave 1319nm Laser, the angle formed between the two arms of the laser cavity was much smaller than depicted to minimise astigmatism
To minimise the effects of the thermal distortion to the laser mode, the $TEM_{00}$ mode was mode-matched with the pump beam such that the waist of the laser mode was $\sim 75\%$ of the waist of the pump laser within the laser rod. Although this mode matching should allow for a less distorted laser beam, an optically pumped portion of the laser rod is left that has undepleted gain, this gain region can lase as higher order cavity modes.

Higher order mode suppression was achieved by utilising the non-parabolic profile of the laser rod thermal lens to force the higher order and fundamental laser modes to compete for the gain inside the laser rod [Clarkson98]. Cavity lengths of 102mm and 28mm were selected to provide suitable laser mode spot-size within the laser rod and the required focussing characteristics that prevented higher order modes from lasing, Figure 2.3.

![Graph](image)

**Figure 2.3, A Graph of $TEM_{00}$ Mode Radius within the Laser Rod with respect to Thermal Lens Focal Length**
It can be seen from Figure 2.3 that the laser mode spot-size obtained for 125mm focal length is less than 75% of the pump radius. This is because the laser is to operate under Q switched conditions and therefore will have a stronger thermal lens. Also the addition of the Q switch to the long arm of the laser cavity causes an increase in the optical path length which has the effect of increasing the laser mode spot-size within the laser rod.

The above cavity without the Q switch or an etalon to suppress parasitic lasing produced a continuous wave output power of 1.72 watts with an $M^2$ of 1.35. Analysis of the spectral output was carried out using a spectrometer. It was found that the laser was simultaneously oscillating on the 1319nm and 1338nm transitions.

To suppress the 1338nm laser transition a 100μm solid etalon was inserted in the laser cavity to act as a wavelength selective loss. The laser was Q-switched with a lead molybdate acousto-optic modulator aligned at Brewster’s angle inside the laser cavity. Lead molybdate has a refractive index of 2.2, therefore Brewster’s angle was calculated to be $65.5^\circ$ (2.2).

\[
\theta_{\text{Brewster}} = \tan^{-1}\frac{n_{\text{Q-switch}}}{n_{\text{air}}} \tag{2.2}
\]

The laser was operated at a pulse repetition rate of 17kHz to produce sufficient peak power as to provide high conversion efficiency without causing damage to the PPLN samples. Q-switched pulses of energy 60μJ and 170ns duration (FWHM) were produced corresponding to a peak power of 353W in a linearly polarised fundamental transverse mode (beam quality factor, $M^2 < 1.2$). After collimation and focusing, an average power of 780mW (275W peak) was available for harmonic generation.
2.3 SHG and SFG

2.3.1 Periodically Poled Lithium Niobate

Lithium niobate is a well known crystal for use in nonlinear optics. The effective nonlinear coefficient for the material can be greatly enhanced through periodically poling the material using the electric field poling technique [Webjorn94]. Phase-matching in such a periodic structure to achieve frequency conversion (up via harmonic generation or down via parametric generation/oscillation) is termed quasi-phase-matching (QPM).

PPLN is a very attractive material for nonlinear frequency conversion because it allows the manufacturer to maximise the nonlinearity ($d_{\text{eff}} \sim 17 \text{pm V}^{-1}$) by selecting the crystal axis with the highest nonlinear coefficient. Periodic poling of lithium niobate, and other related ferroelectric materials, is now a mature technology that allows crystals to be tailored, through careful choice of the domain-inversion period, to provide phase-matching and operation at specific wavelengths for various applications. The temperature dependence of the refractive index of lithium niobate allows the phase-matching condition to be further controlled, for instance to optimise harmonic generation, or to tune signal and idler wavelengths generated in parametric down-conversion configurations. Additionally, elevated operating temperatures (typically $\sim 140^\circ \text{C}$) reduce detrimental photorefractive effects. Careful grating design ensures operation at the desired temperature.

Use of the $d_{33}$ nonlinear optical coefficient in the frequency conversion experiments means that both the fundamental and second harmonic are polarised parallel to the z-axis of the z-cut PPLN samples. Long lengths of poled material can be effectively utilised because QPM does not suffer beam walk-off, therefore the spatial overlap is maximised. In addition, the angular and temperature acceptance bandwidths are large compared with critical phase-matching. Therefore, significant conversion efficiencies can be realised on a single pass using modest extra-cavity fundamental intensities.
The two crystal samples that were used in the following experiment were poled by G W Ross and polished by P Britton.

Second harmonic generation (SHG) of 659.5nm light from the 1319nm fundamental was achieved using PPLN of period 12.34\(\mu\)m, a thickness of 0.5mm and length 20mm. The grating period was chosen to allow first-order QPM SHG at an elevated temperature of 140°C. This elevated temperature was chosen in order to suppress photorefractive effects.

To generate the third harmonic of 1319nm by SFG at 439.7nm, a second PPLN sample was used. This PPLN sample had a period of 11.62\(\mu\)m, thickness 0.3mm and length 25mm. First order QPM for the SFG process would require lithium niobate periods that were sub 4\(\mu\)m. This is currently difficult to achieve over lengths of more than a few mm with good uniformity through samples of 0.3mm and thicker. A third order grating was therefore fabricated. Better control at these larger periods permitted a higher fidelity and optimisation of a 50:50 mark-to-space domain inversion ratio both to maximise the third-order conversion efficiency to the blue and to minimise photorefractive effects. The period was designed for third-order QPM SFG at 140°C.

Neither of the PPLN samples were anti-reflection coated and thus the experiment was hindered by a 16% reflection loss per surface. To prevent optical feedback from the PPLN surfaces disrupting the laser performance, the PPLN samples were cut and polished with a 1° wedge angle between the entrance and exit faces.
2.3.2 Nonlinear Generation

659.5nm red light can be used as a pump source for Cr:LiSAF lasers and provides a high peak power solid-state alternative to the HeNe laser. 659.5nm is also at twice the wavelength of the 330nm absorption peak within germanosilicate glass. Under the correct conditions, this peak can used to optically induce a refractive index change within the pumped region of the glass. Pumping the 330nm-absorption peak has advantages over the more commonly used 242nm-absorption peak because the absorption length of 330nm light in photosensitive glass is much greater than at 242nm. This allows for a greater penetration of the index change into the volume of the glass [Dianov95].

The 1.32μm neodymium transition has previously been explored by several groups as a route to red generation. G. J. Hall and A Ferguson [Hall94] recorded 18mW of single frequency red second harmonic by doubling a 1319nm Nd:YAG ring laser using LBO in a secondary cavity, Figure 2.4. Lincoln and Ferguson investigated intra-cavity doubling of a modelocked Nd:YLF laser and achieved 300mW of 659nm output from an LBO crystal [Lincoln94].

![Figure 2.4, Schematic of Nd:YAG Ring Laser and Pumping Arrangement [Hall94]](image)

Morrison [Morrison95] constructed a Q switched Nd:YLF laser that was operated at 100Hz repetition rate. The laser output was passed through a crystal of non-critically
phase-matched LBO producing pulsed red light of 0.85mJ, 64ns pulses corresponding to ~85mW of average power with peak powers of ~1300 watts.

In 1999, Inoue et al. [Inoue99] built a high-power system consisting of two Nd:YAG laser rods each pumped with a 180 watt side-pumping module, Figure 2.5. Intra-cavity doubling with a KTP crystal produced 6.1 watts of 659.5nm continuous wave output with an $M^2$ of 5.6.

![Figure 2.5, Schematic of Nd:YAG Laser and Laser Module [Inoue99]](image)

In the experiment described below, the generation of 659.5nm red light by SHG of 1319nm is required to pump a second PPLN crystal for sum frequency generation. For best SFG results, one third of the fundamental power is required to remain unconverted in the SHG process. Also the second harmonic and the fundamental beams should be of high brightness (low $M^2$, high average powers and peak pulse powers) and be mixed on a one for one photon basis. The 659.5nm red photons have twice the energy of the 1319nm fundamental photons and therefore twice the measured average power of red light to fundamental radiation is required. Equation (2.3) equates the energy of a photon $E$, to the photon wavelength $\lambda$, where $h$ is Planck's constant $6.63\times10^{-34}$ Joule seconds and $c$ is the speed of light in a vacuum $3\times10^8$ meters seconds$^{-1}$.  

35
\[ E = \frac{hc}{\lambda} \]  

(2.3)

The photon energy for 659.5nm red light is \(3 \times 10^{-19}\) Joules (1.9eV) compared with \(1.5 \times 10^{-19}\) Joules (0.94eV) for the 1319nm red photon energy. The blue photons should have an energy equal to the sum of the red and infrared photons, \(4.5 \times 10^{-19}\) Joules which, from (2.3), equates to \(\sim 439.7\)nm. Figure 2.4 shows the experimental setup for the SFG experiment.

![1319nm Laser Diagram](image)

**Figure 2.4, Experimental Setup for Sum Frequency Generation**

Two insulated PPLN ovens kept the PPLN samples at the correct phase-match temperature. Each oven was temperature stabilised with an electronic feedback. The collimated fundamental laser output was focussed to a spot size of 42\(\mu\)m inside the first PPLN sample using a 150mm focal length lens. An average internal fundamental power of 670mW resulted in the generation of 360mW (141W peak) of second harmonic red at 659.5nm. This corresponds to a conversion efficiency of 54%.

Figure 2.5 shows how the conversion efficiency depends upon the fundamental power. The output red beam had a circular profile with \(M^2 = 1.1\), indicating successful suppression of photorefractive effects and no optical damage at these operating power levels.
The generated second harmonic and the remaining unconverted fundamental were then refocussed into a second uncoated PPLN sample to achieve sum frequency generation of 439.7nm blue light, the third harmonic of the Nd:YAG source. Average internal powers of 174mW at 1319nm and 246mW at 659.5nm generated 35mW (13.7W peak) of blue light in a single-pass with a conversion efficiency of 8%. The blue output had a circular spatial profile with $M^2 = 1.1$. Figure 2.6 demonstrates the dependence of the blue output on the fundamental input power squared.
Graph of Blue Output Power (mW) against 1319nm Power Squared (W^2)

Figure 2.6, Third Harmonic Output Power against Fundamental Power Squared
2.4 Summary

The results obtained demonstrate the ability to generate a significant amount of short wavelength blue light from PPLN using sum frequency generation in a cascaded extra-cavity approach. The results highlight the high single-pass nonlinear conversion efficiencies that can be realised for low gain lasers when combining Q-switched diode end-pumped solid-state technology with PPLN. Elevated phase-match temperatures for the PPLN samples have allowed photorefractive effects to be avoided for both of the generated wavelengths.

It should be possible to improve the system so that a higher blue output is achieved. One issue with the 1319nm laser was that a significant portion of the circulating laser intensity within the cavity was lost through depolarisation of the laser beam within the laser crystal. This depolarisation was caused by thermally induced stress birefringence being present due to the radial temperature gradient. The depolarised component of the beam was ejected from the cavity at the Brewster angled Q-switch. Compensation for the stress birefringence would have increased the laser output power. Further discussion on depolarisation loss can be found in Chapter 3. Any increase of the diode pump input to produce significant power increases to the 1319nm laser without degradation in the laser beam quality would require some form of compensation for the stronger thermal lens that would be generated.

None of the PPLN surfaces were antireflection coated and therefore a loss of 16% was experienced for each of the four surfaces of the PPLN samples. Considerable improvements in the blue power generated could be observed if antireflection coatings are used. Antireflection coatings would remove the need for wedged PPLN sample end faces. The wedged surfaces of the PPLN samples proved to cause slight beam walk-off between the fundamental and the second harmonic due to the wavelength dependence of the refractive index of PPLN.

A telescopic refocussing arrangement between the two PPLN samples that used lenses of different focal lengths would enable the spot-size within the second PPLN sample
to be reduced to account for the reduction in beam intensity. Further improvements in PPLN of other periodically poled technology may lead to the creation of high quality gratings of smaller periods. This may in future allow sum frequency generation of 439.7nm to be achieved from a first order grating.
2.5 References


Chapter 3

Thermally Induced Stress Birefringence and the Quarter Wave-Plate Method

3.1 Overview

Thermal loading of laser media is an unavoidable by-product of all laser systems. A portion of the pump energy is absorbed by the laser medium and will not be used to generate laser photons. Instead, this energy is converted to heat and causes an increase in the temperature of the laser medium. In solid-state laser materials, there are several consequences of this heating that impinge on the laser performance. For instance, a thermal lens is generated due to the temperature dependence of the refractive index of the solid-state material. This thermal lens affects the stability characteristics of the laser cavity and can cause diffraction losses to the laser mode because of aberrations in the thermal lens profile.

This Chapter deals solely with effects caused by stresses generated within the laser crystal when optically pumped and the consequences that these stresses have on solid-state lasers with cylindrical rod geometry.

An introduction to thermally induced stress is followed by existing methods of stress birefringence compensation and the theoretical background of thermally induced stress birefringence. An effective technique to reduce depolarisation loss caused by stress birefringence, the quarter wave-plate technique, is presented and the theoretical benefits are compared to the practical results that have been obtained using lasers of different wavelengths. Finally, the Chapter concludes with a discussion into the benefits and limitations of the quarter wave-plate technique.
3.2 Thermally Induced Stress

Figure 3.1 denotes the pumping geometry for a longitudinally pumped cylindrical geometry Nd:YAG laser rod. The rod is mounted in a metal heat sink, usually copper, brass or aluminium. For high power laser systems it is common to actively cool the heat sink to provide a constant heat sink temperature. The laser rod, of radius $R_b$, is end-pumped by a focussed laser beam with a $1/e^2$ Intensity pump spot size of $w_p$.

![Figure 3.1, Laser Rod and Heat Sink Geometry for End-Pumping](image)

Heat deposited in a pumped Nd:YAG cylindrical laser rod flows outwards towards the crystal heat sink. A temperature gradient is therefore present between the centre of the crystal and the heat sink, where the temperature of the rod must equal the temperature of the heat sink under efficient cooling conditions. The radial temperature gradient implies that the centre of the crystal is hotter than the radial extremes, therefore the radial thermal expansion of the crystal is self contained causing stresses to occur.

Analysis of the stress in cylindrical rod geometries has been based upon equations of Timoshenko and Goodier, [Timoshenko51] from which the radial $\sigma_r$, tangential $\sigma_\phi$ and axial $\sigma_z$ stresses within a cylindrical, uniformly-pumped isotropic rod at a point radius $r$ from the centre of the rod are shown [Forster70] to be

44
\[ \sigma_r(r) = QS(r^2 - R_e^2) \]  
\[ \sigma_\phi(r) = QS(3r^2 - R_e^2) \]  
\[ \sigma_z(r) = 2QS(r^2 - R_e^2) \]  

A positive number represents tensile and negative represents compressive stress. Q is the heat flow per unit volume and S is given by [Koechner96a]

\[ S = \frac{\alpha E}{16K(1-\nu)} \]  

The pump power required to cause fracture can be calculated from (3.2), (3.3) and (3.4a) using \( \sigma_{\text{max}} \) as the tensile strength.

\[ P_p = \frac{8\pi K(1-\nu) L \sigma_{\text{max}}}{\alpha E \gamma \eta_{\text{abs}}} \]  

\( \alpha \) is the thermal coefficient of expansion, E is Young’s modulus, \( P_p \) the pump power, \( \gamma \) the quantum defect heating, \( \eta_{\text{abs}} \) the proportion of pump absorbed in the rod, K is the thermal conductivity, \( \nu \) is Poisson’s ratio and L the length of the laser rod.

Fracturing of the laser material is the most severe effect of thermal loading in that the crystal suffers fatal damage. Fracture occurs when the stress induced by the thermal loading within the laser host exceeds that manageable by the material. YAG is able to withstand greater compressive stress than tensile stress and therefore fracture tends to occur at the radial extremities of the laser rod. The fracture limit is different for each material and in the case of YAG, the subject of this thesis, the fracture limit is relatively high. The level of thermally induced stress that a material can tolerate before fracture is indicated by the thermal shock parameter, Figure 3.2.
<table>
<thead>
<tr>
<th>Material</th>
<th>Glass</th>
<th>GSGG</th>
<th>YAG</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Shock Parameter</td>
<td>R</td>
<td>1</td>
<td>6.5</td>
<td>7.9</td>
</tr>
</tbody>
</table>

Figure 3.2, Table of Thermal Shock Parameter for Different Laser Hosts [Koechner96a]

For the above case of a uniformly pumped laser rod, Koechner states the stress fracture limit in the form

\[ \frac{P}{L} = 8\pi R \]  \hspace{1cm} (3.5)

where \( P = P_{\text{abs}} \gamma \), and \( R \) is the thermal shock parameter given by

\[ R = \frac{K(1-\nu)}{\alpha E} \sigma_{\text{max}} \]  \hspace{1cm} (3.6)

and \( \sigma_{\text{max}} \) is the maximum surface stress of the material. Numerical modelling of stress within a cylindrical laser rod has been conducted for end-pumped systems [Cousins95] for different pump spot-size to laser rod radius and examines fracture as a function of laser rod aspect ratio. Chen has published on the importance of neodymium concentration when considering thermal fracture especially in materials such as Nd:YVO₄ that have comparatively short absorption length for equivalent Nd dopant concentrations and a low tensile stress [Chen99].

Chen and Cousins both advocate the absorption of the pump power over longer crystal length by decreasing the dopant concentration or pumping from both ends of the laser rod. These strategies produce more uniformity in the stress across the rod axis with a lower peak stress at the pumped surface(s).

Stress within the laser rod is known to contribute to the thermal lens generated under optical pumping. This contribution is because the refractive index possesses stress dependence given by Equation 3.7, [Tidwell92].
\[
\frac{\Delta n_{\text{Stress}}}{\Delta T} = n^3 \alpha C_{r,\phi}
\]  

(3.7)

The relative contribution that Equation 3.7 has on the total focal length of the thermal lens for Nd:YAG is roughly 20% [Koechner96b]. \(n\) is the refractive index of the laser rod, \(\alpha\) the thermal expansion coefficient and \(C_r\) and \(C_\phi\) are the photoelastic coefficients for radial and tangential stresses. The two photoelastic coefficients cause two slightly different focal lengths to be present. A light ray propagating through the laser rod, incident at a particular point on the rod face is subject to either one or both of the refractive indices depending upon the components of the electric field polarisation in the radial and tangential coordinate axes. The presence of these two focal lengths is known as bifocussing and could affect the beam quality of the laser mode.

Another thermally induced effect within solid-state laser systems is stress birefringence. The remainder of the chapter will investigate the influence of stress birefringence on laser performance and detail a technique for significantly improving the performance of low-gain solid-state systems by greatly reducing the depolarisation loss without restricting the cavity design or greatly hindering the overall performance of the laser system.

Much research has been carried out attempting to understand thermally induced stress and the effects of birefringence and bifocussing in the laser medium. In August of 1970, Forster and Osterink [Forster70] published a paper analysing thermal lensing and bifocussing within Nd:YAG and observed stress induced birefringence using a He:Ne probe. This paper was followed a month later by an in-depth analysis of stress birefringence, [Koechner70], including calculation of the depolarisation loss for a top-hat laser profile propagating through a radially-cooled flashlamp-pumped (parabolic thermal profile) Nd:YAG laser rod. In Solid-State Laser Engineering [Koechner96c] Koechner states the equation for depolarisation loss for the case where the laser mode fills only half of the laser rod and has a Gaussian beam profile.
Various compensation schemes to reduce the effects of stress birefringence and bifocussing have been suggested and implemented. The thrust of compensation techniques has been towards forcing a ray that is exposed to thermally induced stress within an optical system to experience the exact opposite of that stress within the same cavity round trip thus undoing any birefringence or bifocussing that may have occurred. One approach is to position a 45° Faraday rotator in close proximity to the laser rod and an end mirror, Figure 3.2 [Jackel94], [Lee96]. After passing the laser rod once the laser mode double passes the Faraday rotator incurring a 90° polarisation rotation such that electric field components that experienced the radial refractive index on the first pass experience the tangential refractive index on the second pass and visa versa.

The Faraday rotator method has the disadvantage that the cavity must have a second arm routed through the polarising component as the plane of polarisation of the laser mode is rotated through 90° on the double pass of the Faraday rotator. Some of the materials that exhibit the Faraday effect tend to be of poor optical quality and thus are an extra loss to the laser cavity. This loss can be detrimental for low gain transitions. Long lengths of material and high magnetic field strengths are required to obtain a 45° rotation of the polarisation azimuth tend to be large and therefore can be impractical. One restriction to cavity design is due to the 90° rotation of the polarisation of the laser mode within the cavity. A four-pass cavity design is one method of managing this rotation.

![Figure 3.3, Schematic of four-pass Nd:glass amplifier, PBS stands for polarising beam splitter and FR faraday rotator [Lee96]](image)

An alternative to using the above configuration is to use two identical laser rods with identical pumping geometries. In theory the stresses present in each of the laser rods
should be identical. Compensation is possible by rotating the polarisation of the laser mode between the two laser rods by 90° usually by using a quartz rotator [Scott71], [Tidwell92].

With the quartz rotator setup, Figure 3.4, a second arm is not required to provide a four-pass arrangement despite the plane of polarisation of the laser mode undergoing rotation on passing the quartz rotator. This is because the polarisation is rotated in the opposite direction upon the second pass of the rotator, before the polarising component is reached. Use of two laser rods places restrictions on the cavity design especially for end pumping where at least one 45° turning mirror would be required as an input coupler.

In practice, to get good quality compensation with two rods, re-imaging optics are required because each laser rod possesses a thermal lens that displaces the ray path so that a propagating ray does not experience the exact opposite stress in the second laser rod [Lu96].

![Figure 3.4, Schematic diagram of birefringence-compensated laser [Scott71]](image)

Several variations on the above two approaches to compensation have been demonstrated. J. Richards [Richards87] replaced the Faraday mirror with a Porro prism and a quartz rotator. Also in an eight-pass amplifier [Kiriyama97] uses the principal of the two rods and a quartz rotator but passes the laser beam under amplification back through the same laser slab after passing the quartz rotator, Figure3.5.
Figure 3.5, Schematic of the laser-diode pumped eight-pass slab amplifier geometry,

[Kiriyama97]
3.3 Thermally Induced Stress Birefringence

Thermally induced stress birefringence becomes manifest when a polarising component is inserted within a laser cavity. Thermally induced stress birefringence does not affect lasers where the laser medium already possesses strong linear birefringence, for example Nd:YLF. However materials that exhibit isotropic behaviour, such as Nd:YAG cut in the [111] direction, do suffer. Stress birefringence is such a severe problem because a polarised output is a common requirement for a laser system, for instance if the laser output is to be applied in nonlinear techniques or is required to be Q-switched.

In the previous chapter, one significant cause of decreased power output for the 1319nm Nd:YAG pump laser was highlighted as being depolarisation loss i.e. a loss created by a portion of the circulating cavity beam becoming depolarised by the laser rod and hence ejected from the laser cavity by the polarising acousto-optic modulator. Depolarisation of the laser mode within the laser rod and hence the large loss of output power was due to thermally induced stress birefringence.

Localised heating within a laser medium causes a temperature gradient between the centre of the pumped region and the heat sink. For a laser rod the heat sink is established on the outer radius of the cylinder whilst the rod is most intensely pumped in the centre. Thus radial temperature gradients are present during laser operation. Such thermal variations cause mechanical stress within the crystal. The stress axes run parallel and perpendicular to the heat flow and therefore are in a polar geometry about the centre of the laser rod.

When thermally induced stress birefringence is present, the radial and tangential stresses present at each point throughout the laser crystal possess different refractive indices. For X polarised light travelling through the laser rod along the Z (optic) axis and incident at a point P, Figure 3.6, on the surface of the rod, the light will generally experience two refractive indices, \( n_r \) and \( n_\theta \) in amounts dependant upon the point of incidence P. On propagation through the laser rod, the component of light that
experienced refractive index $n_r$ will be phase shifted relative to the component experiencing $n_q$. The light will therefore emerge from the rod with an elliptical polarisation. To obtain the total depolarising effect of the laser rod all points on the rod must be considered.

![Figure 3.6, Cross-Section of the Laser Rod Including Polarised Laser Field $E_x$ at Point P and the Radial and Tangential Components of $E_x$](image)

From Figure 3.6 it is possible to see two regions where $X$ polarised light incident at point P will be unaffected by the stress birefringence. Light incident at a point on or near the X plane will just experience refractive index $n_r$ and therefore no phase shift will occur. Similarly, light incident at a point on or near the Y plane will only experience $n_q$ and therefore will not emerge elliptically polarised. We can therefore expect that the largest depolarisation will occur at points in the planes at 45° to the X, Y planes as light incident will experience the two refractive indices $n_r$ and $n_q$ equally.

It is possible to view the depolarisation effects of a laser rod using a polarised probe beam passing through a pumped laser rod that sits between two crossed polarisers that have their axes aligned to the probe so as to prevent transmission of the probe beam at
the second polariser. Light can only pass the second polariser if a part of the beam has suffered depolarisation by the laser rod.

The areas of depolarisation shown in white are known as isogyres, Figure 3.7. The greatest depolarisation occurs in the planes at 45° to the planes of the two polarisers and the plane of polarisation of the probe laser.

Figure 3.7, Thermal Stress in a Flashlamp Pumped Nd : LaSOAP Crystal

[Koechner96d]

The amount of stress birefringence that the ray, Figure 3.6, entering point P on the laser rod face is subjected to on a single pass through the crystal can be quantified [Koechner70]. The setup can be considered as though the laser rod was between two polarisers with co-aligned transmission axes, [Borne97] Figure 3.8.

Figure 3.8, Laser Rod between Two Parallel-Aligned Polarisers, Arrows
Consideration of the individual matrices for these components produces an expression for the transmission through the system for a particular input ray, Equation 3.8.

\[
\begin{bmatrix}
E_x' \\
E_y'
\end{bmatrix} =
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
\cos\phi & \sin\phi \\
-\sin\phi & \cos\phi
\end{bmatrix}
\begin{bmatrix}
e^{i\delta} & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
\cos\phi & -\sin\phi \\
\sin\phi & \cos\phi
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix}
\]

\( (3.8) \)

Where \( E_x \) and \( E_y \) are the X and Y components for the electric field of the input ray, \( \phi \) is the angle formed by \( \text{POX} \), Figure 3.6. \( \delta \) is the phase difference that an electric field propagating through the laser rod in the tangential stress plane acquires relative to the electric field propagating in the radial stress plane on exiting the rod. As detailed in Figure 3.8, the transmitted electric field after the second polariser is X plane-polarised. For the case of no stress birefringence, hence \( \delta = 0 \), \( E_x' = E_x \).

Considering just the laser rod with a linearly polarised input beam, Equation 3.9 gives the amplitudes for both the transmitted, \( E_{x*} \), and the rejected, \( E_{y*} \), electric field components at the second polariser.

\[
\begin{bmatrix}
E_{x*} \\
E_{y*}
\end{bmatrix} =
\begin{bmatrix}
\cos\phi & \sin\phi \\
-\sin\phi & \cos\phi
\end{bmatrix}
\begin{bmatrix}
e^{i\delta} & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
\cos\phi & -\sin\phi \\
\sin\phi & \cos\phi
\end{bmatrix}
\begin{bmatrix}
E_x \\
0
\end{bmatrix}
\]

\( (3.9) \)

An expression can therefore be obtained, Equation 3.10, for the electric field loss component of the system for a general propagated ray.

\[
E_{y*} = \sin(2\phi)e^{i\frac{\delta}{2}}\sin\left(\frac{\delta}{2}\right)E_x
\]

\( (3.10) \)

Equation 3.10 is multiplied by its complex conjugate to ascertain the intensity of the loss. The result is given in Equation 3.11.
\[ L_d(r, \phi) = \frac{I_\star}{I_x} = \sin^2(2\phi)\sin^2\left(\frac{\delta}{2}\right) \]  \hspace{1cm} (3.11)

where \( L_d \) is the depolarised intensity of the input ray due to stress birefringence, it is straightforward to obtain the polarised, and therefore transmitted, intensity, Equation 3.12.

\[ \frac{I_\star}{I_x} = 1 - \sin^2(2\phi)\sin^2\left(\frac{\delta}{2}\right) \]  \hspace{1cm} (3.12)

\( \delta \) is for a single pass only therefore it is necessary to multiply this by 2 for a standing wave laser cavity, \( \delta \) can be expressed in terms of \( r \), the radial distance of the ray from the centre of the laser rod, \( \lambda \) the wavelength of the light, \( l \) the length of the rod, \( \Delta n \) the difference in refractive index between the tangential and radial stress planes, Equation 3.13 assumes that the temperature profile is parabolic in the region of interest.

\[ \delta = \frac{2\pi}{\lambda} l \Delta n r^2 \]  \hspace{1cm} (3.13)

To obtain the depolarisation loss for a laser beam passing through the laser rod it is assumed that the laser mode is largely unaffected and does not change size when propagating the laser rod. It is necessary to integrate Equation 3.11 weighted by the laser beam intensity distribution with respect to the radius of the rod and the angle \( \phi \).

\[ L_d(r, \phi) = \frac{\int_{\phi=0}^{2\pi} \int_{r=0}^{\infty} \sin^2(2\phi)\sin^2\left(\frac{2\pi}{\lambda} l \Delta n r^2\right) I_0 e^{-\frac{r^2}{w^2}} rd\phi}{\int_{\phi=0}^{2\pi} \int_{r=0}^{\infty} r I_0 e^{-\frac{r^2}{w^2}} rd\phi} \]  \hspace{1cm} (3.14)

and substituting Equations 3.15a&b for the differences in refractive index for the radial and tangential planes and the heat flow per unit volume.

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\[ \Delta n = n' \alpha \frac{Q}{K_e} C_B, \quad Q = \frac{P_P \eta_{\text{abs}}}{\pi w_p^2 l} \]  

(3.15a&b)

Gives an expression for the total depolarisation loss for the beam

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

(3.16)

where

\[ A = \frac{K_e \Delta w_p^2}{P_P \eta_{\text{abs}} n^3 \alpha C_B w_i^2} \]  

(3.17)

Therefore the amount of depolarisation loss has a squared dependence upon the ratio of the pump area to laser mode area but is not dependent upon the length of the crystal. Also the depolarisation loss is inversely proportional to the wavelength of light squared and proportional to the pump power squared for \( |A| \gg 4 \).

As an example take a 946nm laser with 14 watts of pump power focussed to \( w_p = 240 \times 10^{-6} \text{m} \) with a laser spot-size of \( 180 \times 10^{-6} \text{m} \), absorption efficiency \( \eta_{\text{abs}} \) of 0.8, \( \gamma = 0.145 \) quantum defect heating, refractive index \( n = 1.82 \), \( C_B \) the photoelastic coefficient of birefringence = -0.0099 [Koechner96a] and \( K_e = 13 \text{ w m}^{-1} \) thermal conductivity [Kaminski89].

For the above values, \( A \) equals -31.4, thus \( L_d = 0.1\% \).
3.4 The Quarter Wave-Plate Technique

The Quarter Wave-Plate Technique describes an effective new tool for greatly reducing the depolarisation loss for a cavity by using only one low loss component. A quarter wave-plate is inserted between the laser rod and the input-coupling mirror with the three components in close proximity. The quarter wave-plate is aligned with axes parallel and perpendicular to the polarisation of the oscillating laser cavity mode as defined by the cavity polariser (Brewster plate or Q-switch). There will therefore be no effect on the laser mode from the quarter wave-plate for the portion of the beam that is not affected by stress birefringence.

It has been shown earlier in the chapter that the greatest depolarisation loss is exhibited in the planes at 45° to the polarisation of the laser mode. After one pass of the laser rod, the beam in this plane will be depolarised by an amount depending upon the section of the laser rod traversed. In the 45° plane, the laser beam experiences the radial and tangential stress planes equally. The beam passes the quarter wave-plate, is reflected off of the input coupler and passes the quarter wave-plate a second time rotating the depolarised component electric field vector by 90°. Thus on double passing the laser rod the depolarised component of the beam experiences the opposite birefringence to the first pass, compensating the depolarisation.

For radial planes other than the 45° planes, some compensation is present though not perfect as the strengths of the electric field vectors that experience the radial and tangential stress axes are different. The least amount of compensation is achieved along the planes at 22.5° and 67.5° to the polarisation of the laser mode.

It is possible to calculate the depolarisation loss that will be experienced by analysing the matrices for the components within the laser cavity. On a double pass of the laser rod, the beam passes:

Laser Rod → Quarter Wave-Plate → Mirror → Quarter Wave-Plate → Laser Rod
Equation 3.18 gives the matrices for the beam through the system until just before the final polariser in order to determine what proportions of the beam is transmitted and what is rejected.

\[
\begin{bmatrix}
E' _x \\
E' _y 
\end{bmatrix} =
\begin{bmatrix}
\cos \phi & \sin \phi \\
-\sin \phi & \cos \phi
\end{bmatrix}
\begin{bmatrix}
e^{i \delta} & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
\cos \phi & -\sin \phi \\
\sin \phi & \cos \phi
\end{bmatrix}
\begin{bmatrix}
e^{i \pi} & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix}
\]

(3.18)

The double pass of the quarter wave-plate has been expressed as a half wave-plate. Multiplying the matrices leads to an expression for the component of the electric field vector that would be rejected by the system, Equation 3.19.

\[
E'_y = -\sin(4\phi)\sin^2\left(\frac{\delta}{2}\right)e^{i \delta} E_x
\]

(3.19)

The intensity for the rejected component of the ray is obtained by multiplying by the complex conjugate.

\[
L_d(r, \phi) = \sin^2(4\phi)\sin^4\left(\frac{\delta}{2}\right)
\]

(3.20)

The loss for the compensated system is the normalised integral of Equation 3.21, weighted by the laser beam intensity distribution.

\[
L_d(r, \phi) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \sin^2(4\phi)\sin^4\left(\frac{\delta}{2}\right) I_0 e^{-2\pi r^2} rdrd\phi}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I_0 e^{-2\pi r^2} rdrd\phi}
\]

(3.21)

substituting Equations 3.13 and 3.15a&b and integrating yields
\[ L_d = \frac{3}{4A^4 + 20A^2 + 16} \]  

(3.22)

where \( A \) is given by Equation 3.17.

For the 946nm laser example above, \( L_d = 7.7 \times 10^{-5} \% \) which is an improvement of three orders of magnitude. It is interesting to note that there is an \( A^4 \) term which greatly reduces the depolarisation loss for \( |A| > 1 \). However, as the pump power increases, \( |A| \) decreases and as \( |A| \) approaches 1 the \( A^4 \) term becomes less dominant in the equation. As \( A \) tends to 0 the depolarisation loss tends to 19\% with the quarter wave-plate as opposed to 25\% without.

The pump power for the example at which \( A = -1 \) is 440 watts at which point the quarter wave-plate still provides some compensation (\( L_d = 7.5\% \) with QWP, 20\% without). This demonstrates the quarter wave-plate technique as an essential tool in the power scaling of low gain diode-end-pumped Nd:YAG lasers that are required to provide polarised output and is a potential solution for stress birefringence for higher gain lasers, for instance lasers operating on the 1064nm line. As expected, the technique has been shown to work well for pump powers associated with diode pumped solid-state lasers but to be unable to substantially compensate very high pump power systems e.g. [Fluck99].
3.5 High-Efficiency Polarised 946nm Nd:YAG Laser

The 946nm laser was selected as a test bed for the quarter wave-plate method. The 946nm laser is quasi-three-level, is a low gain transition, and therefore requires a high pump intensity to achieve threshold. The pumping requirements make the laser susceptible to thermal effects including that of thermally induced stress birefringence whilst the low gain, quasi-three level nature of the transition require any birefringence compensation components to be low loss.

A 20 watt beam-shaped [Clarkson97] diode bar, temperature tuned to the 809nm Nd:YAG absorption peak, was focused tightly using a pair of cylindrical lenses to give spot sizes at focus of 142μm in the bench plane (x plane) and 131μm in the y plane. The beam quality of the pump source was measured as $M_x = 72, M_y = 64$ at full power. The available output power at the focus is displayed in Figure 3.8.

![Graph of Output Power (watts) vs Current (amps) for a Focussed Beam-Shaped Diode Bar Pump Source](image)

Figure 3.9, Output of a 20W Beam-shaped Diode Bar
It can be seen that the diode bar has a threshold of 5 amps and a linear slope efficiency of 56%WA⁻¹.

A 3mm 1.1% neodymium doped laser rod was found to give the best output power performance of 2.06 watts form a plane-plane cavity with the laser rod heat-sink cooled to a temperature of 10°C. The pump light that was transmitted by the laser rod was measured to be 33% of the incident power. The confocal parameter for the pump beam focus inside the YAG rod was calculated using Equation 3.23.

\[ z_c = \frac{2\pi w_0^2}{M^2 n \lambda} \]  \hspace{1cm} (3.23)

Equation 3.23 gives a value for \( z_c \) of 1.16mm with \( \lambda \) as 809\times10⁻⁹m and \( n \) as 1.82.

To design the laser cavity, a calculation for the thermal lens focal length at the centre of the laser rod for maximum pump power was made using Equation 3.24 [Clarkson98].

\[ F_{r=0} = \frac{\pi K_c w_p^2}{P_p \gamma \eta_{abs} \frac{dn}{dT}} \]  \hspace{1cm} (3.24)

Where \( K_c \) is the thermal conductivity (13w m⁻¹ K⁻¹), \( w_p \) is the pump spot size, \( P_p \) is the pump power incident on the laser rod (13.6w), \( \gamma \) is the proportion of absorbed pump power converted to heat (14.5%), \( \eta_{abs} \) is the proportion of pump power absorbed by the laser rod (67%) and \( \frac{dn}{dT} \) is the change in refractive index with temperature (7.3\times10⁻⁶ K⁻¹). A thermal lens focal length of 7.16\times10⁻² meters was obtained.

Cavity design was carried out using the Maple mathematics package to find a stable solution to the round trip matrix that would also promote TEM₀₀ mode operation by forcing higher order cavity modes to compete with the TEM₀₀ mode for the gain in the centre of the laser rod [Clarkson98]. The cavity was designed to support a laser mode spot size at the laser rod of \( \sim110\mu m \) with a thermal lens focal length of \( \sim72mm \).
The chosen laser design was a three mirror folded arm cavity with a plane input coupler, plane output coupler and curved (50mm radius of curvature) high reflector, Figure 3.10. Arm lengths of ~65mm for the long arm containing the laser rod and polariser and ~30mm for the folded arm were used. The mounted laser rod was positioned in close proximity to the input coupler, leaving just enough room for the quarter wave-plate to be lowered in and out of the laser beam path. The output coupling that was used for the laser was 6.8%.

![Diagram of laser setup](image)

**Figure 3.10, 946nm Cavity Setup with Quarter Wave-Plate and Brewster Plate**

The laser was optimised at full power without polariser or quarter wave-plate to provide good beam quality ($M^2 \sim 1.2$, measured with a Coherent Modemaster) with high output power (3.42 watts for 13.6 watts incident). Figure 3.11 is a graph of 946nm unpolarised output power verses pump input power. A slope efficiency of 33.7% with a threshold of 3.52 watts was obtained with little sign of roll off at higher powers.
Alignment of the polarisation axes of the quarter wave-plate was performed outside of the laser cavity. Polarisation of the laser output was first achieved by inserting the Brewster plate into the laser cavity and optimising the plate angle to minimise the depolarisation loss and maximise the laser output power.

A Glan-Foucault polariser was placed in the polarised laser beam to provide total extinction of the laser output. The polariser was then rotated through $90^\circ$ to maximise the laser throughput and a second polariser was placed in the beam (further from the laser than the first) and aligned for maximum beam extinction. Now that the two crossed polarisers were setup in alignment to the laser beam polarisation, the quarter wave-plate fast and slow axes could be aligned to the laser polarisation.
The wave-plate was held on a rotating mount and put between the polarisers. The mount was rotated to minimise the laser throughput. The high quality of the extinction ratio of the polarisers \((1 \times 10^6)\) allowed the throughput to be minimised visually with the aid of an infrared viewer. The Brewster plate was then removed from the cavity.

The aligned quarter wave-plate was added to the cavity to determine the change in laser performance. A maximum output power of 3.22 watts was achieved with a beam quality of \(\sim 1.2M^2\). The laser threshold was measured to be at 3.45 watts giving a slope efficiency of 31.5%. The slight performance loss was due to the reflection of a small amount of the incident pump power off of the quarter wave-plate (1.5% per surface) and the component cavity insertion loss measured as .025% for both surfaces.

With the quarter wave-plate removed and the Brewster plate added to polarise the cavity, the performance of the laser was severely impacted. A maximum 946nm output power of 2.09 watts was achieved using 13.1 watts incident, however, further increase in the pump power caused a decrease in the output power. At maximum output power the effective output coupling, Equation 3.25, of the depolarisation loss was calculated as 1.66% compared with an output coupler of 6.8%.

\[
T_{\text{eff}} = \frac{2L_{\text{Brewster}}T_{\text{oc}}}{P_{\text{out}}} \tag{3.25}
\]

\(T_{\text{eff}}\) is the effective output coupling, \(L_{\text{Brewster}}\) is the depolarisation loss from one face of the Brewster plate, \(T_{\text{oc}}\) is the transmission of the output coupler and \(P_{\text{out}}\) is the polarised output from the laser. The polarisation extinction of the output beam was analysed using a Glan-Foucault polariser as 15:1. A laser threshold of 3.72 watts and beam quality at maximum pump power of 1.44M² were measured.

A marked improvement in output power was measured with the quarter wave-plate and the Brewster plate in the cavity. A maximum output power of 2.9 watts was recorded which appeared to only be limited by the amount of pump power available Figure 3.12. The output power was stable and the beam quality was good \((<1.2M^2)\), the laser threshold was 3.54 watts.
Output Power vs Incident Pump Power for Polarsed 946nm Laser with and without Quarter Wave-Plate

Figure 3.12, Performance Comparison of Polarised 946nm Laser with and without A Quarter Wave-Plate

The effective output coupling of the Brewster Plate was calculated to be less than 0.0006% compared with the 6.8% output coupler implying that the depolarisation loss was negligible in this case when using quarter wave-plate compensation. The polarisation extinction ratio of the output beam was measured as greater than 50:1.

The quarter wave-plate technique has been practically demonstrated in a 946nm diode end-pumped laser cavity. A reduction in the depolarisation loss from 1.6% to less than 0.0006%, a three orders of magnitude reduction, was measured achieving an output power of 2.9 watts with beam quality $<1.2M^2$. 
Theoretical analysis of this 946nm setup gives a value for $A$ of 31 and therefore predicts uncompensated depolarisation loss, Equation 3.16, to be 0.1% and the compensated depolarisation loss, Equation 3.22, to be 0.00008%. Both predictions are roughly an order of magnitude too low although the improvement from uncompensated to compensated performance for both theory and experiment is by the same order of magnitude.
3.6 Wavelength Dependence of the Quarter Wave-Plate Method

3.6.1 Quarter Wave-Plate Method at 1.3\(\mu\)m

A 1.319\(\mu\)m laser was constructed to test the applicability of the quarter wave-plate method to lasers operating at longer wavelengths. Equation 3.17 implies that the longer wavelength should reduce the depolarisation loss, however this factor should be more than offset by the increase in the quantum defect heating.

The laser cavity that was used for the experiment was designed to operate at high power under a situation where the laser rod was subject to significant thermal effects including that of stress birefringence. Calculation of the on-axis thermal lens using Equation 3.24 gave a maximum thermal lens focal length of 29mm. This is a significantly shorter thermal lens focal length than for the 946nm experiment because the amount of pump energy that is lost due to quantum defect heating is nearly 39%.

A four mirror cavity Figure 3.13 was used that restricted the TEM\(_{00}\) laser mode (60\(\mu\)m). The TEM\(_{00}\) mode size was significantly smaller than the pump focus spot-size (156\(\mu\)m) and therefore encouraged multimode operation (M\(^2\)=5) allowing a stable, high output power despite the severe thermal lens.

![Figure 3.13, 1319nm Laser Cavity with Brewster Plate and Quarter Wave-Plate](image)

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A quarter wave-plate at 1.32μm was used for the stress birefringence compensation. The wave-plate was anti-reflection coated at 1.32μm and specified as high transmission at 0.81μm. However, on measuring the transmission at 0.81μm, the wave-plate was found to have a single-pass transmission loss of ~9%, Figure 3.14 causing a decrease in the available pump power.

![Diode Power Measured Before and After 1.3μm Quarter Wave-Plate](image)

Figure 3.14, Graph Demonstrating the Pump Transmission Loss Through the 1319nm Quarter Wave-Plate

A 10mm 1% doped Nd:YAG cylindrical laser rod was mounted in a copper heat sink. The heat sink was maintained at a temperature of 14°C by a Neslab water-cooled system. The quarter wave-plate was mounted between the laser rod and the input coupler such that it could be easily lowered into the path of the laser beam.

The unpolarised laser cavity produced a maximum output power of 3.23 watts for 13.6 watts of pump power, with a low threshold of 1.3 watts pumping. The slope was
not linear with poor slope efficiency near threshold and a slight roll off at maximum pump power, Figure 3.14. The average slope efficiency across the lasing range was 26%.

Output Power Verses Input Power for 1.3\(\mu\)m Unpolarised Laser

![Graph showing output power versus input power for a 1.3\(\mu\)m unpolarised laser.]

Figure 3.14, 1.3\(\mu\)m Unpolarised Laser Performance versus Diode Pump Power

The poor slope efficiency near threshold can be attributed to the small ratio of the TEM\(_{00}\) laser mode size to the pump spot-size. The TEM\(_{00}\) mode has the most efficient overlap with the pump and is distant from aberration in the wings of the pump. However, the size of the TEM\(_{00}\) mode restricts it from taking all of the gain. All of the gain in the pumped region is not utilised until higher order modes begin to lase, Figure 3.15.
Graph of Laser Beam Quality ($M^2$) versus Pump Power (watts)

![Graph of Laser Beam Quality versus Pump Power](image)

Figure 3.15, Laser Beam Quality versus Pump Power

Addition of the polariser substantially reduced the output at maximum pump power to 1.8 watts. The maximum output power was 2.26 watts achieved with 11.6 watts of diode power with an $M^2$ of 4 suggesting that the birefringence loss was bias towards the higher order modes. Using the 3% output coupling of the laser, the birefringence loss effective output coupling was calculated to be 1.2%, Equation 3.25.

The quarter wave-plate was added to the laser. A maximum output power of 3.12 watts was achieved with a beam quality of $5.2M^2$. The depolarisation loss was calculated to be 0.015%, an improvement of two orders of magnitude.

$A$ is calculated, Equation 3.17, to be $-7.2$ which corresponds to an uncompensated depolarisation loss of 1.8% and a compensated depolarisation loss of 0.025% which is in good agreement with the practical results obtained. Figure 3.16 shows the 1.3μm polarised output with and without compensation.
Graph of Polarised 1.3μm Laser with and without Quarter Wave-Plate Birefringence Compensation

![Graph](image)

Figure 3.16, Performance of Compensated (Solid Line) and Uncompensated (Dashed Line) 1.3μm Laser
3.7 Conclusions and Further Work

Analysis of thermally induced stress birefringence for both uncompensated and quarter wave-plate compensated cases has been presented. Two sets of experiments have demonstrated that the quarter wave-plate technique is a viable, low loss solution to the problem of depolarisation loss in low-gain solid-state YAG lasers. As has been discussed the quarter wave-plate technique is of limited use for high gain, high power systems where an alternative method of compensation would be more appropriate, Figure 3.17.

![Isogryes](image)

Figure 3.17, Isogryes For a) Faraday Rotator b) Quarter Wave-Plate Technique c) Quarter Wave-Plate Aligned at 45° to Polarisation Axis d) No Compensation For Side Pumped 1064nm Nd:YAG Laser Dissipating 50 Watts of Heat, A=0.6. [Fluck99]

The quarter wave-plate method was also tested within a single laser rod ring laser. A half wave-plate was used in place of the quarter wave-plate to provide adequate rotation of the depolarised portion of the laser mode. This did not prove a successful compensation scheme due to the large round trip distance traversed between successive passes of the laser rod. A possible solution would be to use two laser rods with equal pump inputs and position the half wave-plate between the two rods in a similar manner to Figure 3.4.

Power scaling of low gain solid-state YAG lasers can be undertaken without the restriction of stress birefringence. For the 1319nm laser, the horrendous thermal lensing and therefore high aberration loss create a power-scaling barrier that can be
reached with one 20W diode bar. The 946nm laser is a more efficient source and therefore it should be possible to scale polarised 946nm output to higher powers.
3.8 References


Chapter 4

High Power Blue Generation

4.1 Introduction

The 946nm Nd:YAG laser is of considerable interest to researchers as it provides a route to obtaining blue light via second harmonic generation. Unfortunately power scaling of the 946nm laser has been much more problematic compared with the far better known and widely used 1046nm Nd:YAG laser. Koechner's Solid-State Laser Engineering [Koechner96] refers to early work on the 946nm transition that produced lasing by cooling the laser rod [Wallace71]. Low gain neodymium transitions have become increasingly viable with the application of diode lasers as pump sources. The advantage of greatly increased brightness and directionality with diode lasers compared to flashlamp sources has enabled high conversion efficiencies and multi-watt average powers from the 946nm laser.

Despite the progression of laser diode technology, the 946nm transition still poses difficulties for the laser scientist. Not only does the transition have a low gain cross-section, the lower laser level shares the same manifold as the ground state and therefore is subject to reabsorption loss. The combination of a low gain cross-section and reabsorption loss demand tight, high brightness focussing which, although quite possible using beam-shaped diode-bars, encourages the severe thermal problems associated with end-pumping of laser media.

The 946nm line has a high quantum efficiency and therefore under continuous wave operation the aberrated thermal lens can be managed with the aid of efficient cooling techniques and cavity design [Clarkson96]. However, under Q-switched operation, heat generation can increase significantly due to interionic upconversion from the upper laser level. This extra heat loading and hence stronger thermal lensing makes the design of a stable cavity a difficult task.
Second harmonic generation of 532nm from the 1064nm Nd:YAG laser transition is a successful, commercial reality. 532nm green sources are available in multi-watt continuous wave and Q switched models that use diode bar technology. The commercial success of the 1064nm laser can be attributed to the high gain and four level nature of the transition. Progress in second harmonic generation of blue light from the 946nm laser line has not been as rapid despite a strong demand for blue laser sources.

One of the routes to blue generation that has been explored is to use periodically poled materials in a single-pass extra-cavity arrangement. Clarkson et al [Clarkson96] achieved 49mW from a 6mm periodically poled lithium niobate (PPLN) crystal pumped by a continuous wave 946nm laser. The laser was pumped by a 20 watt diode bar. The result was superseded by Ross et al [Ross97] where the 946nm laser was driven at its relaxation oscillation frequency by oscillating the position of the output coupler and hence the cavity length with a piezoelectric mount. Higher peak powers obtained from the relaxation oscillations and a longer (15mm) PPLN crystal produced 450mW of 473nm blue light with good beam quality.

An alternative route to blue light generation from a 946nm pump source has been achieved via intra-cavity doubling. Kellner et al [Kellner97] compared the performance of three nonlinear crystals LiB$_3$O$_5$ (LBO), LiIO$_3$ and β-BaB$_2$O$_4$ (BBO) in the second arm of a three mirror 946nm laser cavity pumped by a 40 watt diode source. The 4mm BBO crystal produced the greatest blue output power (550mW).

Pierrou et al [Pierrou99] used periodically poled KTiOPO$_4$ (PPKTP) as an intra-cavity doubler in a four mirror cavity pumped by 40 watts of diode power. 740mW of blue output was achieved from a 9mm long crystal.

Czeranowsky et al [Czeranowsky99] used a crystal of LBO in a four mirror cavity and achieved 1.3 watts of blue output for 22.7 watts of diode pump power with the aid of quarter wave-plate birefringence compensation, [Clarkson98a].
Greater output powers have been obtained from intra-cavity doubling methods due to the high intra-cavity fundamental intensities. However all the authors of the above intra-cavity work have commented upon significant output power fluctuations and hypothesise that the fluctuations are caused by mode instabilities of the fundamental. Extra-cavity doubling using PPLN is limited by the low damage threshold (~100MWcm\(^{-2}\)) of the nonlinear crystal and the manufacturing difficulties with extending the length, depth of penetration and quality of the periodically poled samples.

This chapter details an alternative route to generating blue light. A Q-switched 946nm source that is capable of operating at high peak powers is used to pump a non-critically phase-matched LBO crystal. The technical difficulties that arise with the construction of the Q-switched source are detailed and the experimental results presented.
4.2 Diode Bar End-Pumping

4.2.1 Efficient Diode-Bar End-Pumping

Power scaling of diode laser technology has been the vehicle that has directly enabled the power scaling of diode end-pumped solid-state lasers. The fragile nature of the diode laser has led power scaling to be achieved by combining a strip of low power diodes manufactured on the same wafer in close proximity and that are electrically powered from the same source. Some ingenious beam-shaping techniques have been employed to reshape the output of diode-bars into a more symmetric beam with $M^2$ of similar values for orthogonal planes. As discussed in Chapter 1, this work makes use of the two mirror beam-shaping technique [Clarkson96a].

Generally, for end-pumping schemes, the pump beam requires collimating after the diode source and refocussing before the laser to deliver the pump light to the solid-state gain medium. One method used a collimating lens after the beam-shaped diode bar and either one spherical or two cylindrical focusing lenses before the gain medium to generate the required spot-size [Sipes85]. Pump reflecting mirrors are used between the collimating and focusing lenses to direct the collimated beam to the laser head, Figure 4.1.

![Figure 4.1, Free Space Diode Pumping Scheme](image)
With a laser system that is pumped by such a setup, it is often difficult to determine the cause of any degradation in laser power or beam quality. The source of the performance loss can lie in one of three areas:

1. The beamshaped diode bar pump source
2. The optics for collection, direction and focussing the pump radiation
3. The laser cavity

Reoptimisation of the laser system in this case can be time consuming. Analysis of the laser alignment is made easier if the light from the diode bar is coupled into a double clad optic fibre. Provided that the measured pump power that is emitted from the fibre does not decrease, any decrease in performance from the laser system is due to either poor laser cavity alignment or a reduction in the overlap of the focussed pump image with the laser mode in the laser rod.

A decrease in the fibre output power is due either to the diode bar optics or due to the fibre input coupling of the diode pump radiation which can easily be reoptimised without interfering with the laser cavity, Figure 4.2.

![Diagram](image)

Figure 4.2, Fibre Coupled Diode Pumping Scheme

The fibre end provides a point source that can be reimaged within the laser medium. Use of an optical fibre as a point source for a solid-state laser has advantages other than diagnostic.
Radiation traversing through the fibre loses any spatial definition that may be caused by the spatially periodic layout of the diode emitters on the diode array and therefore the likelihood of ‘hot-spots’ within the laser medium is greatly reduced. Another advantage is that the circular symmetry of the fibre output allows focussing to be achieved with a spherical lens rather than cylindrical lenses in each plane.

Multiple reflections within the fibre also cause the spatial profile of the pump beam to alter at the exit face compared to the spatial profile of the pump focussed at the fibre input coupling. At the fibre input, the spatial profile is of a low order super-Gaussian with a narrow peak and much of the power dispersed in the ‘wings’. At the fibre output, the spatial profile of the pump radiation is confined to within the fibre exit aperture and is therefore more rounded and closer to a flat-top profile, a high order super-Gaussian, Figure 4.3.

A pump beam with a flat-top profile is desirable because the thermal lens that is produced is roughly half that for a Gaussian profile for the same pump power [Clarkson98b]. Investigation into the dependence of spherical aberration on the super-Gaussian order of the pump beam was conducted by S. B. Sutton and G. F. Albrecht [Sutton93]. They concluded that the higher the order the larger the portion of the laser mode that was not influenced by thermal aberrations. The profile of the super-Gaussian order is given by

$$I = I_0 \exp\left(\frac{-2r^m}{w_p^m}\right)$$

(4.1)

where $I_0$ is the pump intensity at the centre of the laser rod, $r$ is the distance from the centre of the rod, $w_p$ is the pump spot-size and $m$ is the super-Gaussian order where a value of 2 corresponds to a Gaussian profile and $\infty$ corresponds to a flat-top profile.
A simple experiment was conducted to determine whether all of the pump light was being efficiently utilised within the gain medium. Pump light exiting an Opto Power 250μm fibre with a 0.22 NA was collimated and refocussed using two 50mm focal length lenses placed 100mm apart. A variable aperture was positioned centrally between the collimating and focussing lenses and central about the pump axis, Figure 4.4.

The pump light was focussed into a Nd:YAG laser rod that was coated for 946nm operation (anti-reflection @946nm, high transmission @1046nm and 809nm) and placed within a half confocal resonator which was optimised for maximum output power. The aperture was then closed slightly and the laser reoptimised. This process was repeated to find the aperture diameter that corresponded to maximum laser output power.
With the aperture fully open, 10.4 watts of diode pump power gave 1.17 watts of 946nm output measured after an 810nm pump filter. Maximum 946nm power of 2.2 watts was obtained with the aperture reduced to a diameter of 16.5mm, which corresponded to 8 watts of diode pump power.

Not only was a portion of the pump light failing to contribute to useful gain within the laser, that portion of the pump light was still contributing to thermal loading within the laser and thus degrading the laser performance. Calculation of the numerical aperture for the pump beam that achieved best laser performance gives

\[ NA = \frac{D}{2F} = 0.165 \]  \hspace{1cm} (4.2)

This is substantially less than the NA of the fibre. In the design of lens systems, spherical aberration tends to become a concern when the NA of a beam exceeds ~0.1. To determine whether spherical aberration was preventing the use of all of the pump light, the experiment was repeated using proprietary Gradient lenses manufactured by Lightpath.

Gradient lenses are manufactured from a block of glass made by vapour axial deposition, VAD, such that the refractive index of the glass changes to maintain a parabolic optical density across the lens and therefore prevent spherical aberration.
The Gradium lenses that were used in the experiment produced a maximum laser performance for 0.24 NA, which corresponded to a reduction in apertured diode pump power of 1.3% compared with a 23% reduction with standard lenses.

The findings highlight the degradation in pump beam quality and hence laser pumping efficiency when standard optics are used for high numerical aperture pump beams. Measurement of the pump beam quality using a Beamscope did not reveal the degradation.

Pump power loss due to spherical aberration was made apparent through fibre coupling of diode bars due to the NA of the fibres used (0.22NA). However, high NA conditions exist within some of the diode beam-shaping optics and also are common when a free-space propagated diode beam is tightly focussed into laser media. Such tight focussing is generally a requirement when pumping low gain or quasi-three level lasers.
4.2.2 Optical Pumping with Multiple Diode Bars

An ideal laser that does not suffer from thermal or damage limitations is only limited by the amount of pump power available. Initially, pump power is required so that the laser achieves the threshold condition, at threshold the gain in the laser medium is equal to the cavity losses. On further increase of the pump power, an ideal laser would increase output power linearly in accordance with the slope efficiency.

The 946nm laser is very different from this ideal scenario due to the tight focussing requirements, and hence high thermal loading, of this low gain quasi-three-level transition. However, to appreciate fully the mechanics of the 946nm system and to achieve optimum results it is desirable to have sufficient pump power available.

To increase the pump power, it is necessary to use either a diode bar with a higher output power or multiple diode bars. At the time that these experiments were carried out, the highest diode bar power available at 809nm was 20 watts from an Opto Power Corporation OPC-A020-mmm-CS. To achieve higher pumping powers, it was necessary to use two of these sources.

Polarisation coupling was attempted using two identical, beam-shaped and collimated, diode bars. The polarisation of one of the diodes was rotated through 90° in relation to the other diode using a half wave plate with the fast and slow axes aligned at 45° to the diode beam polarisation. One of the diode beams was magnified with a telescope so that both beams had the same spot-size at the point of recombination. The two beams were combined using a polarising beam splitter. The beams were co-aligned to overlap at the polarising beam splitter and at their focus within the laser medium, Figure 4.5.

Free space propagation of the diode beams between the diode lasers and the 946nm laser was used to preserve the degree of polarisation. Unfortunately, the extinction ratios for the diode bars were found to be poor after beam-shaping. When considering the losses of the extra components used to polarisation couple the two bars, there was
no significant improvement in total available pump power compared with the pump power from a single diode bar.

Figure 4.5, Free Space Polarisation Coupling Scheme

An alternative dual pumping scheme was utilised by pumping the laser medium from both ends. This method has several advantages over polarisation coupling. The polarisation of the diode beams is not important for this technique and therefore fibre can be used to propagate the beams, Figure 4.6.

Figure 4.6, Dual Pumping Scheme with Fibre Coupled Diode Bars
Use of optic fibre coupling brings the benefits of improved pump profile, ease of alignment and symmetry of the output. In this dual pumping arrangement there are fewer components in the setup and therefore less pump power is lost en route to the laser head. Pumping from both ends also provides a more even distribution of gain throughout the laser medium rather than concentrating the bulk of the inversion density (and heat loading) at one end.

Care has to be taken that the majority of each pump beam is absorbed within the laser rod to prevent damage to the diode bars. Any pump light transmitted by the laser rod is likely to be collected by the focussing optics for the opposite diode bar and refocussed onto the diode bar facet.
4.3 High-Power 946nm Laser Design

4.3.1 The 946nm Laser Transition

The 946nm transition has a high quantum efficiency and therefore low quantum defect heating. Only 14.5% of the photon energy is lost in non-radiative decay between the pump wavelength at 809nm and the ground state. However, this low gain transition has a stimulated emission cross-section of $4 \times 10^{-20} \text{cm}^2$ [Fan87], an order of magnitude lower than the 1064nm transition ($2.8 \times 10^{-19} \text{cm}^2$).

The high quantum efficiency is because the 946nm transition is between the lowest level of the $^4F_{3/2}$ upper laser manifold and the highest level of the $^4I_{9/2}$ manifold. The $^4I_{9/2}$ manifold includes the ground state laser level. Therefore photons created by spontaneous or stimulated emission at the 946nm wavelength that traverse the laser medium experience some reabsorption back into the gain medium due to the finite population (0.74%) [Fan87] of the lower laser level. Photon reabsorption is a loss to the laser system, and therefore has the effect of increasing the pumping threshold at which lasing occurs.

![Energy Level Diagram of the 946nm Transition in Nd:YAG](Image)

Figure 4.7, Energy Level Diagram of the 946nm Transition in Nd:YAG
The population of the lower laser level under thermal equilibrium conditions is given by the Boltzmann distribution

$$N_1 = f_1 N_0 = \frac{g_1 N_0 e^{-\frac{\Delta E_1}{kT}}}{\sum_i g_i e^{-\frac{\Delta E_i}{kT}}} \quad (4.3)$$

where $N_1$ is the population in the lower laser level, $N_0$ is the total population of the ground state manifold, $f_1$ is the fraction of the total ground state manifold population within the lower laser level, $g_1$ is the degeneracy of the lower laser level $\Delta E_1$ is the energy difference between the lower laser level and the ground state, $k$ is the Boltzmann constant, $T$ is the temperature, $i$ is an integer variable representing each level within the ground state manifold, $g_i$ is the degeneracy of each level, $\Delta E_i$ is the energy difference between the ground state level and each energy level within the ground state manifold.

Fan and Byer [Fan87] calculated the laser rate equations for a quasi-three-level system exhibiting reabsorption loss. Assuming that ground state depletion is negligible, the laser rate equation for the upper laser level is

$$\frac{dN_2(r,z)}{dt} = f_2 R_p(r,z) - \frac{N_2(r,z) - N_2^0}{\tau} - f_2 c \sigma \left[ N_2(r,z) - N_1(r,z) \right] \Phi \phi_0(r,z) = 0 \quad (4.4)$$

where $N_2$ is the population in the upper laser level, $f_2$ is the fraction of the total $^4F_{3/2}$ population residing in the upper laser level, $r$ is the radial co-ordinate to the laser optical axis, $z$ is the co-ordinate parallel to the laser optical axis, $r_p(r,z)$ is the normalised pump spatial distribution, $N_2^0$ is the population of $N_2$ at thermal equilibrium, $\tau$ is the lifetime of the upper state manifold, $\Phi$ is the cavity photon number, $\phi_0(r,z)$ is the normalised spatial photon distribution, $\sigma$ is the gain cross-section, $c$ the speed of light in a vacuum and $n$ the refractive index of the laser medium and for the lower laser level

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\[
\frac{dN_1(r,z)}{dt} = -f_1 R_p(r,z) - \frac{N_1(r,z) - N_0}{\tau} + \frac{f_1 c \sigma [N_2(r,z) - N_1(r,z)]}{n} \Phi \phi_0(r,z) = 0 \tag{4.5}
\]

Using the above two equations Fan and Byer presented an equation for the population inversion density of a quasi-three-level laser

\[
\frac{d\Delta N(r,z)}{dt} = (f_1 + f_2) R_p(r,z) - \frac{\Delta N(r,z) - \Delta N^0}{\tau} - \frac{(f_1 + f_2) c \sigma \Delta N(r,z)}{n} \Phi \phi_0(r,z) = 0 \tag{4.6}
\]

Fan and Byer also developed an expression for the required absorbed pump power to obtain threshold condition.

\[
P_{th} = \frac{\pi h \nu_p}{4 f \eta_p \sigma \tau} \left( w_i^2 + w_p^2 \right) \left( L + T + 2 f_1 N_0 \sigma l \right) \tag{4.7}
\]

where \( L \) is the round-trip cavity loss, \( T \) the transmission of the output coupler, \( 2 f_1 N_0 \sigma l \) the reabsorption loss (where \( l \) is the length of the laser rod, \( \sigma \) is the emission cross-section and \( \eta_0 \) the ratio of excited ions generated per pump photon) and

\[
P_{th'} = P_{th} \left( 1 - \exp(-\alpha l) \right) \tag{4.8}
\]

where \( \alpha \) is the absorption coefficient of the pump in the gain medium. A useful equation to calculate the optimum length of the laser medium to promote the lowest threshold was also given.

\[
\alpha \exp(-\alpha l) \left( \frac{2 \sigma f_1 N_0}{\alpha} + L + T + 2 \sigma f_1 N_0 l \right) - 2 \sigma f_1 N_0 = 0 \tag{4.9}
\]

However, the Fan and Byer calculations for laser performance above threshold relied on the specific condition that the laser and pump modes were perfectly matched. Risk [Risk88] made more generalised calculations based on the rate equations of Fan and
Byer and consideration of the change of laser intensity on traversing the laser medium. The Risk paper reaffirmed the threshold equation for quasi-three-level systems because the reabsorption loss term is not dependent upon relative spot-sizes of the pump and laser modes. Equations for the slope efficiency that depended upon the ratio of laser mode to pump mode spot-size and on the reabsorption loss were also presented. The slope efficiency for a quasi-three-level system is given by

\[
\frac{dP_{\text{out}}}{dP_p} = \frac{T}{(L + T)} \frac{\nu_L}{\nu_p} \eta_a \frac{dS}{dF}
\]  

(4.10)

where \(P_{\text{out}}\) is the laser output, \(P_p\) the incident pump power, \(\eta_a\) is the proportion of pump absorbed, \(\nu_p\) and \(\nu_L\) are the pump and laser frequencies, \(T\) is the output coupling and \(L\) the cavity losses excluding output coupling and reabsorption. For conditions just above threshold \(dS/dF\) is given by

\[
\frac{dS}{dF} \mid_{S \to 0} = \left(1 + a^2 \right) \frac{1}{\left(1 + a^2 \right)^2} \frac{1}{1 + \frac{B}{2(1 + a^2)}}
\]  

(4.11)

\[
a = \frac{w_p}{w_L}
\]  

(4.12)

\[
B = \frac{2N_1 \sigma l}{(L + T)}
\]  

(4.13)

the slope efficiency tends to improve with increasing pump power for lasers exhibiting reabsorption loss because the loss becomes saturated by the cavity photon density. Risk demonstrated that the ideal ratio for the pump and laser modes was 1 only for lasers that experience no reabsorption loss. When reabsorption loss is present, it is more efficient to have the laser mode smaller than the pump mode to avoid the high regions of loss in the wings of the pump beam.
4.3.2 Thermal Lensing Under Lasing and Non-Lasing Conditions

One advantage of the 946nm transition is the small quantum defect heating (14.5%) thus reducing the heat per photon that is deposited within the laser rod. It is useful to consider the thermal lens that is present due to quantum defect heating at the centre of the laser rod where lensing is the strongest [Clarkson98b].

\[
    f(0) = \frac{\pi K_c w_p^2}{P_p \eta_{abs} \frac{dn}{dT}}
\]  

(4.14)

Where \( K_c \) the thermal conductivity is 13Wm\(^{-1}\)K\(^{-1}\), \( \gamma \) is the quantum defect heating, \( \eta_{abs} \) is the proportion of pump power absorbed and \( \frac{dn}{dT} \) is the sensitivity of the crystal refractive index to temperature 9.86\( \times 10^{-6} \)K\(^{-1}\). For the 946nm laser in this Chapter \( w_p \), the pump spot-size is 150\( \mu \)m and \( P_p \) the pump power is 17W. Continuous wave operation gives a thermal lens for this laser of 40mm at the centre of the laser rod using Equation (4.14).

The thermal lens that is present within the laser rod under non-lasing conditions is stronger than the thermal lens under continuous wave 946nm operation. One of the reasons for the increase in lens strength is that the quantum defect heating increases because photon emission is not dominated by stimulated emission at 946nm. For the non-lasing scenario, calculation of the quantum defect requires consideration of the branching ratio for fluorescence between the upper laser level and the lower laser level and the quantum defect for each transition. It is also necessary to consider non-radiative decay processes by multi-phonon relaxation between the excited state and the ground state.

For Nd:YAG, the quantum defect heating under non-lasing conditions is over 29% [Pollnau98]. For the case of the pumped Nd:YAG crystal described above, the thermal lens focal length is decreased to 20mm. Operation of the 946nm laser in the Q switched regime will incur a thermal lens between the continuous wave thermal lens

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(40mm) and the non-lasing thermal lens (20mm) depending upon the Q switch repetition rate.

Another effect that can have a significant influence on the thermal lens focal length is that of interionic upconversion. Interionic upconversion is a mechanism by which a laser ion that is in an excited state can be influenced by an adjacent excited laser ion such that energy from one ion is transferred to the other, thereby promoting one ion to a higher excitation state and reducing the other to a lower excitation state.

Upconversion is most significant under non-lasing, or Q-switched, conditions because a high inversion density is present. A high inversion density means that the probability of two adjacent laser ions both being in an excited state is much greater. The continuous photon population in the laser cavity during CW operation prevents upconversion processes increasing once threshold is reached. Q switching of the laser, especially at low repetition rates, temporarily removes the circulating cavity photon population and therefore allows the inversion density and the probability of upconversion to increase.

One effect that the upconversion process has on the characteristics of the laser medium is to reduce the average upper laser level lifetime. This reduction has an impact on the energy storage capability of the media and therefore reduces the energy extraction possible from a Q switched pulse.

Another side effect of upconversion has is to increase the heat deposited within the laser media. Heat generation comes from multi-phonon decay of the upconverted ion back to a lower energy level. The deposited heat manifests itself by adding to the thermal lens already present due to quantum defect heating within the crystal.

Upconversion in Q-switched, end-pumped, laser systems poses several problems from a design perspective. It is generally simpler to construct a continuous wave laser and then look to Q-switch the cavity rather than to build a Q-switched laser from scratch. However the behaviour of the laser cavity mode in terms of the stability, beam quality and TEM₉₀ mode size is generally highly sensitive to the thermal lens, which will be
different for the two situations. In fact, adjustment of the Q-switch repetition rate will also have a significant effect by altering the strength of the thermal lens from the continuous wave regime (at high repetition rates) towards the non-lasing regime (at low repetition rates). It is therefore probable that the perfect CW cavity design is far from the perfect Q-switched design.

The aberrated nature of the thermal lens is also further enhanced through upconversion due to the extra heat loading. Thus diffraction losses in the 'wings' of the thermal lens are more extreme, further increasing the cavity losses.

Work at Southampton University that investigated upconversion in diode-end-pumped Nd:YLF [Hardman99] led to the development of an equation to determine the ratio of thermal lens powers with and without upconversion under non-lasing conditions.

\[
\Gamma_{\text{Upcon}} = \frac{1}{\rho} \left( 1 - \frac{2(1 - \rho)}{\beta} \left[ 2\left(\sqrt{1 + \beta} - 1\right) + \ln \left( \frac{4}{\beta} \left( \sqrt{1 + \beta} - 1 \right) \right) \right] \right)
\]  

(4.15)

where \( \Gamma_{\text{Upcon}} \) is the ratio of thermal lens powers for laser media with and without upconversion, \( \rho \) is the fraction of absorbed pump power converted to heat ignoring upconversion (0.29 under non-lasing conditions), and \( \beta \) is given by

\[
\beta = \frac{8WP_p \alpha_p \tau^2}{\pi w_p^2 h v_p}
\]

(4.16)

With \( W \) as the upconversion parameter \((5 \times 10^{23} \text{ m}^3 \text{ s}^{-1}) [\text{Guy98}] \) for Nd:YAG, \( P_p \) as the pump power, \( \alpha_p \) the pump absorption coefficient \((410 \text{ m}^{-1})\), \( \tau \) the fluorescence lifetime \((230 \mu\text{s})\), \( w_p \) the pump spot-size \((150 \mu\text{m})\), \( h \) is Planck's constant and \( v_p \) the pump frequency. Applied to the 946nm laser with 150\( \mu \text{m} \) pump spot-size, a value of 1.87 is calculated for \( \Gamma \) implying that the thermal lens focal length under non-lasing conditions could be as short as 10.5mm.

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4.3.3 The 946nm Pump Source

Two 20 watt beam-shaped fibre coupled diode bars were used to optically pump a 7mm long, 2mm diameter 1% doped Nd:YAG laser rod from both ends. A maximum of 17 watts of pump power was available at the laser rod. The reduction in pump power was due to optics that were not anti-reflection coated for the pump wavelength.

The Nd:YAG laser rod was multi-layer dielectric coated on both faces to be high transmission for the pump and the 1064nm laser line, and anti-reflection coated for the 946nm wavelength. A copper heat sink housed the laser rod. A laser rod heat-sink temperature of 13°C was maintained using water cooling from a Neslab refrigeration unit.

A four mirror cavity consisting of a plane input coupler, plane output coupler, one convex mirror and one concave mirror was setup with a fused silica acousto-optic modulator positioned in the final arm of the cavity. The acousto-optic modulator was mounted such that the resonator mode was translated vertically on passing through the glass to offset the Q switch astigmatism with that of the tilted laser cavity mirrors and hence reduce the astigmatism of the laser output.

![Diagram](image)

*Figure 4.8, 946nm Nd:YAG Laser and LBO Frequency Doubler*
Without the AO modulator or the quarter wave-plate in the cavity, the laser produced a maximum output power of 4.6 watts. Addition of the AO modulator (with no RF applied) had a detrimental effect, Figure 4.9, reducing the output power to .037 watts for 17 watts of pump.

![Graph showing laser output power vs. incident pump power](image)

**Figure 4.9, CW Polarised Laser Performance with (linear slope) and without (roll-off) the Quarter Wave-Plate**

The quarter wave-plate was inserted between the input coupler and the laser rod and a polarised output of 3.5 watts with beam quality of $M_x^2=2.2$, $M_y^2=1.2$ was measured. The slope of the laser did not suffer from roll off at high power. The polarised laser had slope efficiency of 22.6% with a threshold of 1.5 watts. The 1.5 watt threshold was close to that calculated using Equation (4.7) which gave a 1.7 watt threshold.

On Q switching the 946nm source, a maximum pulse energy (0.53mJ FWHM pulse length 85ns) was obtained for a pulse repetition frequency of 1KHz, Figure 4.10. Maximum peak pulse power (1.7KW FWHM pulse length 87ns) was obtained at a repetition rate of 2KHz. Deterioration of the peak pulse power below 2KHz could be due to thermal roll off as the TEM$_{00}$ spot-size increases towards that of the pump spot-size and therefore experiences greater diffraction loss from the aberrated portion of...
the thermal lens. This theory is supported by the pulse to pulse stability of the beam that was observed with a fast silicon photodiode.

On reduction of the Q-switch repetition rate, the pulse stability was found to stabilise below 10KHz. This stability region suggests that the laser mode was, at this point, confined to the same gain region within the laser rod by its increased size. At higher repetition rates, the smaller laser mode size would allow some displacement in the laser optic axis from pulse to pulse to harness a higher gain region that was not depleted by the previous pulse. Of course, at 4 KHz and below, depleted regions would cease to become a factor as the time between pulses exceeds the upper level fluorescence lifetime of 230μs.

Graph of 946nm Pulse Energy verses 1/Repetition Rate

![Graph of 946nm Pulse Energy verses 1/Repetition Rate](image)

*Figure 4.10, 946nm Pulse Energy against 1/Repetition Rate*
4.4 473nm Blue Generation

The 946nm output was focussed into a 15mm long crystal of LBO which was Brewster cut for type I non-critical phase-matching. The LBO crystal was housed within a brass oven with two 50 watt induction heaters powered by a temperature regulated mains supply. A thyristor was wired between the supply and the induction heaters to temper the maximum power throughput and thus smooth temperature fluctuations within the oven. The oven was insulated in a macor ceramic box to reduce the exposure of the LBO to thermal gradients.

Type I non-critical phase-matching with LBO is the preferred method for second harmonic generation of the 1064nm line due to the large angular and temperature acceptance bandwidths and the maximised $d_{\text{eff}}$ nonlinear coefficient due to the 90° phase matching. Non-critical phase-matching of the 946nm wavelength requires a much higher temperature than for the 1064nm line. The required temperature can be calculated [Kato94].

![Temperature Bandwidth for SHG of 946nm Light in Noncritically Phase-Matched LBO](image)

Figure 4.11, Temperature Phase-Match Bandwidth of SHG from a 946nm Laser in LBO
\[ T_{pm} = \left(-1.8933\lambda^4 + 8.8866\lambda^3 - 13.0198\lambda^2 + 5.4015\lambda\right) \times 10^3 \text{ (°C)} \quad (0.95 \leq \lambda \leq 1.3) \quad (4.17) \]

Equation (4.17) gives a phase-match temperature of 329°C, which is higher than the optimum measured oven temperature of 306.5°C, Figure 4.11. This temperature discrepancy is likely to be due to the separation of the crystal and the thermocouple within the oven. A Q-switch repetition rate of 20KHz was used to obtain the graph of the temperature phase-match bandwidth.

Figure 4.12 shows the dependence of blue peak power with fundamental peak power. The roll off in blue peak power suggests a degradation in the beam quality of the fundamental as the laser approached its thermal stability limit at the lowest repetition rates.

Graph of Second Harmonic (473nm) Peak Power Against Fundamental (946nm) Peak Power

![Graph of Second Harmonic Peak Power](image)

Figure 4.12, Blue Peak Power Against Fundamental Peak Power

A maximum blue peak power of 1.7KW was achieved at 2KHz repetition rate.
Figure 4.13 shows the second harmonic pulse energy as a function of $1/\text{repetition rate}$. The slight roll off indicates a decline in the doubling efficiency that could be due to a deterioration in beam quality. A pulse energy of 0.12mJ was obtained at 2KHz repetition rate.

Figure 4.13, Second Harmonic Pulse Energy verses $1/\text{Q-Switch Repetition Rate}$
Figure 4.14 shows the average blue power achieved with respect to 1/ repetition rate. As would be expected, the most blue was obtained at a repetition rate of 4KHz which corresponds to a time between pulses of 250μs, close to the 230μs upper laser level lifetime. The maximum blue average output power was 370mW, corresponding to a conversion efficiency of 21%. 
4.5 Conclusions

A high power 946nm Q-switched laser has been demonstrated using two fibre coupled diode pump sources. Birefringence loss has been successfully minimised by the quarter wave-plate method to provide 3.5 watts of polarised output. The four mirror laser cavity has been shown to be capable of handling the range of strong thermal lenses that are present under Q-switching of low gain end-pumped systems.

Q-switching has been demonstrated from 50KHz to 1KHz providing a maximum peak pulse power of 5KW in an 85ns pulse. A maximum pulse energy of 0.53mJ was obtained at 1KHz repetition rate. Slight degradation in laser performance at 1KHz suggested that the laser was operating near the cavity stability limit defined by the thermal lens within the laser rod. Optimum operation of this laser was between 10KHz and 2KHz. Between these repetition rates the pulse to pulse fluctuations were minimal.

High energy (0.12mJ) blue pulses have successfully been generated using a crystal of LBO cut for 90° phase-matching in a single pass extra-cavity geometry. A specially constructed oven enabled the high phase-match temperature of 329°C (306.5°C measured) to be reached. Maximum blue power of 365mW was recorded in a 4KHz pulse train equating to a conversion efficiency of 21%. A maximum blue peak-power of 1.7KW was obtained at a 2KHz repetition rate.

These experimental results highlight the strength of the 4-mirror cavity design in strong thermal lensing conditions. The highest peak power to date has been achieved from a 946nm laser operating at low repetition rates.

Scalability of the 946nm laser requires measures that would allow the cavity to cope with the increased heat loading from higher pump powers. One method that may enable scalability would be to use a laser rod with a reduced neodymium dopant concentration. Reduction in the neodymium concentration would serve to reduce the
amount of interionic upconversion and hence the strength of the thermal lens especially at lower repetition rates.

Improved performance from the 946nm laser might be gleaned from using a single higher power diode bar now that this technology has become available. Pumping the laser rod from both ends requires that virtually all of the pump light is absorbed within the laser crystal to avoid focussing the output of one pump back onto the other diode facet which could cause damage.

The length of crystal required to absorb the enough of the pump is greater than the optimum length as given by Equation (4.9). The optimum length is brought about through a trade-off between pump absorption efficiency and reabsorption loss. Figure 4.15 demonstrates the ideal crystal length (the minima of the graph) as being 4.5mm, some 2.5mm shorter than the length of laser rod used in this experiment.

Graph of Differential of Threshold Power with Rod Length Squared verses Rod Length

![Graph of Differential of Threshold Power with Rod Length Squared verses Rod Length](image)

Figure 4.15, Optimum Rod Length For Minimising Threshold of a 946nm Laser
The double pass reabsorption loss that is associated with the extra 2.5mm of laser rod can be calculated from the reabsorption loss term in Equation (4.7). The reabsorption loss for the extra 2.5mm of laser rod has an effective output coupling of 2.2% and would have had a significant influence on the laser threshold.

Perhaps a better alternative to reducing the laser rod length might be to lower the dopant concentration of neodymium ions from 1% to 0.7%. This would achieve similar results to decreasing the laser rod length in terms of reducing the threshold but also has the added advantage of reducing the heat deposition due to upconversion and hence the thermal lens. A reduction in the thermal lens should reduce thermal lens aberrations and increase cavity stability at low repetition rates.

Power scaling of low gain lasers is limited by the lens aberrations brought about by the strong non-parabolic thermal gradient associated with end-pumped systems. True power scaling of low gain end-pumped systems can only be realised once a practical solution to the losses caused by the aberrated thermal lens is found.
4.6 References


Chapter 5

Summary and Further Work

5.1 Summary of Results

5.1.1 Introduction

The experimental content of this thesis examines the viability of using diode end-pumped solid state Nd:YAG lasers as a pump source for the nonlinear generation of blue light. The Thesis centres on two low gain transitions of Nd:YAG, one transition emitting radiation at 1319\text{nm} and the other at 946\text{nm}. This Chapter is broken down into a summary for blue generation from each laser source. Within each summary, the advantages and disadvantages of using the transition are considered, the section describes what has been demonstrated and what steps may be taken to further increase the blue output from these two systems.

A separate section contains a discussion of the quarter wave-plate method. The section highlights the need for a low-loss birefringence compensation technique and examines the results obtained from experimental work on two polarised Nd:YAG laser sources, one at 946\text{nm} and the other at 1319\text{nm}. A discussion of the limitations of the quarter wave-plate technique and a comparison of theoretical analysis with the experimental results of the lasers is presented.
5.1.2 Generation of 439.7nm Blue Light

439.7nm light has successfully been generated from a Nd:YAG laser oscillating on the 1319nm low gain transition using sum frequency generation in periodically poled lithium niobate. An exciting aspect of this result is that the wavelength of the blue light is significantly shorter than the 488nm wavelength of the Ar\textsuperscript{3+} laser line to be considered a very different blue source. In fact, the generated blue light is closer to the 455nm blue region that is optimum for laser projection and other RGB display applications, than the Ar\textsuperscript{3+} and doubled 946nm (473nm) output.

The 1319nm laser transition has a stimulated emission cross-section of 9.5\times10^{-20}\text{cm}^2 [Kaminskii90], which is somewhat smaller than the dominant 1064nm transition (2.8\times10^{-19}\text{cm}^2). Lasing of the 1319nm line has been demonstrated using diode-end-pumping which has the advantage of creating a large inversion density that can be efficiently mode-matched with the laser mode. Parasitic lasing on the 1064nm laser line was prevented by specifying the multi-layer mirror coatings high transmission at that wavelength. Lasing on the 1338nm laser line was prevented by introducing an etalon as a wavelength selective loss within the cavity.

Diode-end-pumping of cylindrical, edge-cooled, laser rods generates a non-parabolic thermal lens that becomes progressively weaker and more aberrated with increasing radius. The profile of the generated thermal lens was used to suppress lasing on higher order modes by designing a cavity for which the laser mode spot-size reduced, within the laser rod, with increasing focal length [Clarkson9]. A beam quality of \textit{M}^2 < 1.2 was achieved. The thermal lens focal length within the laser rod was calculated as 125mm for continuous wave operation.

The source was successfully Q-switched with a rhomboid lead-molybdate acousto-optic modulator. At a repetition rate of 17KHz gave peak powers of 353 watts with a pulse energy of 60\muJ. An average power of 780mW was available for nonlinear generation.
Second harmonic generation of 659.5nm red light was achieved in a single pass through periodically poled lithium niobate. An elevated phase-match temperature was used to avoid photorefractive effects. A maximum conversion efficiency of 54% was obtained producing an average red power of 360mW with peak powers of 141 watts. Beam quality of less than 1.2 M² was measured.

Blue light (439.7nm) was produced by sum frequency mixing of the red (659.5nm) and infra-red (1319nm) light within a second PPLN sample. Manufacture of sub-300μm periods over any significant length of lithium niobate produces poor quality gratings. For this reason, a third order grating was used. An average blue power of 35mW was obtained with peak powers of 13.7 watts. An elevated phase-match temperature was found to avoid photorefractive effects. A beam quality of < 1.1 M² was measured.

Use of the quarter wave-plate method would minimise the depolarisation loss for the 1319nm laser. Increasing the pump power may lead to some increase in the laser output power. However, it is expected that the output would become limited by the severe thermal effects that the 1319nm laser is subject to because of the poor quantum efficiency.

Another power limitation in this experiment is caused by the damage threshold of PPLN (100MWcm⁻²). If there is an improvement in the laser performance, an increase in the Q-switch repetition rate or an increase in the spot-size of the fundamental within the PPLN sample might be required to reduce the pulse peak intensity.

Reduction in the pulse intensity would alter the SHG conversion efficiency. The optimum SHG conversion efficiency for this experiment is 67% so that there is a 'one for one' photon ratio of red and 1319nm light available for sum frequency generation.

An improvement in grating fabrication technology that lead to the development of good quality, sub 4μm gratings would substantially improve the blue conversion efficiency. The refractive index of PPLN is high and therefore anti-reflection coatings

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would be a beneficial addition. This would reduce the reflection loss per surface for PPLN from 16%.

The PPLN samples used in this experiment were slightly wedged to avoid back reflections into the laser cavity. A large reduction in the reflection loss would mean that the PPLN samples could have both entrance and exit surfaces polished perpendicular to the grating. Parallel end-faces would eliminate beam walk off due to the \( \lambda \) dependent refraction of the red and infrared beams and the air-PPLN interfaces.

Generation of blue light via sum frequency generation for the 1319nm laser provides a new wavelength blue source. Improvements in laser and PPLN technology should allow for average blue powers greater than 100mW. However, this approach to blue generation is not suitable for obtaining high peak power sources due to the damage limitations of the nonlinear medium.
5.1.3 Generation of 473nm Blue Light

473nm blue light has successfully been generated from a 946nm Nd:YAG laser via second harmonic generation. The 946nm laser, although possessing a high quantum efficiency (85.5%), suffers from reabsorption loss due to the lower laser level residing in the ground state manifold. Reabsorption loss increases the threshold pump power required to achieve lasing. For this reason, and because the 946nm laser transition is low gain transition, the pump has to be tightly focussed within the rod.

Pump light from each beam-shaped diode bar was coupled into a double-clad optical fibre for delivery to the laser head. An experiment to examine the ‘usefulness’ of the fibre output was conducted using a variable aperture placed in a collimated portion of the beam. It was found that a significant portion of the light from the fibre contributed to the thermal loading of the laser rod but not to the laser output power. This degradation in the pump beam was not evident when the beam quality of the pump light was measured at the laser rod. Exchanging all lenses in the system for Gradium lenses (which have an optical path length that is parabolic with radius) dramatically improved the quality of the beam.

For the blue generation experiment, fibre-coupled diode end-pumping was used to pump the laser rod from both end. A continuous wave maximum 946nm average power of 4.6 watts with a pump threshold of 2 watts was achieved for 17 watts of diode pump power using a 4 mirror laser cavity.

A fused silica acousto-optic modulator was used to obtain the fundamental peak powers required for doubling in LBO. Unlike nonlinear generation in PPLN, LBO has a high damage threshold (1GWcm\(^{-2}\)) although the effective nonlinearity of LBO (1.2pmV\(^{-1}\)) is less than PPLN (17pmV\(^{-1}\)) and therefore higher fundamental peak powers are required to achieve good conversion efficiency.

Q-switching of the 946nm laser drastically increased the thermal loading due to ionic upconversion processes occurring between adjacent Nd\(^{3+}\) laser ions. The thermal
lens under nonlasing conditions was predicted as short as 10.5mm. The laser cavity was designed to accommodate thermal lens focal lengths down to near this prediction.

Q-switching was demonstrated from 50KHz to 1KHz with a maximum peak power of 5.3KW being measured at 1KHz repetition rate. A maximum pulse energy of 0.53mJ was extracted also at 1KHz repetition rate. The stability and the beam quality of the laser was found to improve as the repetition rate decreased which, it is believed, was due to the TEM$_{00}$ laser mode spot-size increasing within the laser rod to fill the gain region. Some signs of instability and thermal roll-off were observed at 1KHz.

Doubling to the blue was achieved using LBO in a single pass extra-cavity configuration. Non-critical phase-matching was used because the effective nonlinear coefficient is maximised, the phase-matching condition has a higher temperature and angular acceptance bandwidth than for critical phase-matching and Poynting vector walk-off is avoided. A calculated temperature of 329°C was required to achieve doubling of 946nm via non-critical phase-matching. A brass oven containing the crystal was insulated with Macor ceramic and electrically heated. A 15mm Brewster cut LBO crystal was used.

A maximum of 370mW average power of blue light was recorded at a fundamental repetition rate of 4KHz, which corresponded to a conversion efficiency of 21%. A peak blue pulse power of 1.7KW was recorded with a repetition rate of 2KHz, maximum pulse energy of 0.12mJ was extracted at 2KHz repetition rate.

An additional arm was added to the laser cavity and the LBO was inserted. Under continuous wave operation, a blue output power of roughly 1 watt was measured, however the output power was extremely unstable so no further characterisation was performed.

One route to increase the blue output generated might be to increase the diode pump power available and thus increase the pump intensity within the laser rod. This would have an adverse effect of increasing the thermal loading especially for low repetition rate Q-switching. To prevent an increase in thermal loading under Q switched
conditions, the dopant concentration of the laser rod could be reduced. This would have the effect of reducing thermal loading due to inter-ionic upconversion. If the rod was to still be pumped from both ends, a longer length laser rod could be used to ensure that the same percentage of pump power absorbed is realised over the length of the crystal.

One disadvantage of pumping from both ends is that care must be taken not to couple pump light from one fibre-coupled diode bar into the other. Any back-coupled light would be imaged onto the diode bar facet where damage may occur to the diode emitters.

To prevent damage to the diode-bar, it has been ensured that most of the diode pump is absorbed over the length of the laser rod. The laser rod is therefore not of optimum length when reabsorption losses are considered. A 7mm laser rod was used in the experiment but theory, Equation (4.9), shows that the rod length should be shorter, 4.5mm.

A solution to this problem would be to use a higher output power diode-bar and pump a 4.5 mm laser rod just from one end. This would enable the optimisation of the laser crystal length, minimising reabsorption loss and therefore reducing the laser threshold. An alternative to using a shorter rod would be to use a 7mm rod with a lower dopant concentration (0.7%). This would have the added advantage of reducing upconversion and hence thermal loading at low Q switch repetition rates.

Some problems were caused by running the LBO oven at such a high temperature. 329°C was close to the maximum temperature limit for the heaters and some deposit, near the heater housing, on the brass oven became apparent over time. This deposit also lead to a deterioration in the surface quality of the LBO to the point where the crystal would eventually have to be repolished. A redesigned oven would benefit from either using heaters rated at a higher temperature or enclosing the LBO inside glass windows to prevent the crystal surfaces encountering any out-gassing.
A redesign of the oven should also better insulate the mount from the oven. Despite the oven being encased in Macor ceramic, heat was conducted through the mount into the optical bench. This, combined with convection heating from the oven, refrigeration units for the diode-bar and laser rod lead to thermal drift of the laser and a variation in laboratory temperature of 10°C. Without an efficient laboratory heat extraction system, it is likely that further power-scaling of pump sources would exacerbate this drift.
5.1.4 Birefringence Compensation using the Quarter Wave-Plate Method

Birefringence compensation has been demonstrated for two wavelengths of Nd:YAG, 946nm and 1319nm. Both of these transitions are low gain. The 946nm laser also suffers from reabsorption loss and therefore requires a high pump density to achieve threshold. The 1319nm laser has a poor quantum efficiency and therefore has severe heat loading problems, even under continuous wave operation. Both of these lasers therefore tend to suffer from stress birefringence due to the high thermal loading density. These two lasers are also highly susceptible to any cavity loss whether it is depolarisation loss or insertion loss caused by intra-cavity components used to compensate for depolarisation loss.

Other birefringence compensation schemes, although offering theoretically 100% compensation, tend to either use high insertion loss components (Faraday rotator method [Jackel94]) or set-ups that require two identically pumped laser rods, a quartz rotator and reimaging optics. Such compensation schemes are better suited to high gain systems.

An analytical comparison of a new compensation scheme, the quarter wave-plate method, and the case for no compensation has been presented for end-pumped, cylindrical geometry, laser rods. The assumption is made that the difference in the radial and tangential refractive indices due to stress has a parabolic dependence with radius i.e. the pump has a flat-top profile. This assumption breaks down for Gaussian pump profiles as the laser mode spot-size increases with respect to the pump spot-size.

Both cases (with polarisation compensation and without) are dependent upon a common term A, where A is equal to

\[ A = \frac{K_c \lambda w_p^2}{P_p \eta_{abs} n_2^3 \alpha C_B w_l^2} \]  

(5.1)
A can be seen to be dependent upon the ratio of the pump ($w_p$) to laser mode ($w_l$) area. Also the wavelength of the laser mode ($\lambda$) offsets the quantum defect heating of the transition ($\gamma$) somewhat. However, $A$ is not dependent upon the crystal geometry. For the case of no birefringence compensation, the depolarisation loss is given by

$$L_d = \frac{1}{4 + A^2} \quad (5.2)$$

Using the quarter wave-plate method, the depolarisation loss is given by

$$L_d = \frac{3}{4A^4 + 20A^2 + 16} \quad (5.3)$$

It is interesting to note that for large $A$, Equation (5.3) is governed by the $A^4$ term. However, as $A$ approaches 1, the $A^2$ term becomes more influential. Figure 5.1 is a theoretical calculation of the depolarisation loss verses pump power for a 1319nm laser.

![Figure 5.1, Graph of Depolarisation Loss with Pump Power for 1319nm Laser](image-url)
The graph is for the case of laser mode size equalling the pump mode size (worst case scenario). One can see that the quarter wave-plate method is effective for moderate pump powers but, with this setup, pump powers in excess of 100 watts induce significant depolarisation loss. Further power-scaling of the technique can be achieved by reducing the laser mode spot-size relative to the pump spot-size. If the laser mode is 75% of the pump spot-size, a 3 fold \((1/0.75^4)\) increase in pump power would be required to give the same depolarisation loss.

![Depolarisation Loss vs Pump Power Graph](image)

**Figure 5.2, Graph of Depolarisation Loss against Pump Power with and without Birefringence Compensation**

Figure 5.2 shows the significant improvement in reduction of the depolarisation loss at low to moderate pump power levels for the above 1319nm case.

Experiments to ascertain the performance of the quarter wave-plate method were carried out for both the 946nm and 1319nm laser transitions. A 946nm Nd:YAG laser was constructed using a three mirror folded arm resonator. A pump power of 13.1 watts was incident on the laser rod giving a thermal lens of 72mm. Polarisation of the cavity incurred a depolarisation loss of 1.66% compared to an output coupler of 6.8%. Addition of the quarter wave-plate to the cavity decreased the depolarisation loss to
0.0006%. Thus the depolarisation loss was negligible with quarter wave-plate compensation.

A four mirror 1319nm laser was also constructed with much more severe thermal lensing (29mm focal length) than for the 946nm case. When the laser was polarised, the laser performance was severely degraded. A depolarisation loss of 1.2% was calculated compared to an output coupler of 3%. On addition of the quarter wave-plate, the depolarisation loss was reduced to 0.015%, again showing significant improvement in laser performance.

The experimental results for the depolarisation loss for the 946nm laser are an order of magnitude higher than those predicted by theory for the compensated and uncompensated cases. However the improvement in the depolarisation loss between the compensated and uncompensated cases is in agreement. For the 1319nm laser, theory and experiment agree to within a factor of 2, and similarly, the predicted improvement and the actual improvement when compensation is used in good agreement.
5.2 Future Work

A discussion of possible improvements to the blue generation experiments has already been presented. The main long-term limitations for these laser sources and for blue generation using these sources are the problems caused by the severe thermal lensing within the laser rod.

Thermal problems are brought about by heat loading from the diode pump source due to quantum defect heating and upconversion (especially under Q-switched conditions) within the laser medium. End-pumping configurations, where the pump light is concentrated around the centre of the laser rod in a super-Gaussian beam profile, lead to a non-parabolic radial thermal profile across the rod.

The thermal restrictions for the power-scaling of diode end-pumped solid-state lasers are due to two main reasons:

1. Increasing strength of the thermal lens with pump power
2. Increasing aberrations of the thermal lens profile with pump power

As the strength of the thermal lens increases, the thermal lens becomes shorter and cavity design becomes more complex. Use of a convex input coupler to compensate for some or the all of the thermal lens can help with cavity design although the defocussing power of the input coupler must be considered when focussing the pump into the laser rod. Convex input couplers tend to give lasers a higher threshold because the thermal lens is small at lower pump powers and therefore the curvature of the input coupler overcompensates and acts as a loss to the cavity. This technique is best used when the laser will only be operational at one power level and, if the laser is Q-switched, one repetition rate.

Whether or not the strong thermal lens is compensated by a defocussing component within the cavity, the thermal lens within the laser rod still acts as an aberration loss. Deviation of the thermal lens from the ideal parabolic lens profile increases with laser
rod radius. Therefore, it is common in high pump power diode-end-pumped systems, to design the laser cavity to produce a TEM$_{00}$ spot-size that is smaller than the diode pump spot-size.

It has been demonstrated [Clarkson98] that the progressive weakening of the thermal lens focal length with laser rod radius (the lens aberration) can be used to restrict oscillation of other, higher order, laser modes within the cavity. Even when utilising this technique, the lens aberrations still limit laser performance. This is because the TEM$_{00}$ mode does not fill the pumped volume of the laser rod.

The TEM$_{00}$ laser mode of a low power diode-pumped solid-state laser typically fills the whole of the gain region. This not only gives the laser mode full access to the gain, it ensures good beam quality as there is no gain region left for higher-order modes. For high pump power systems, the gain in the extremities of the laser rod pumped region is wasted and may further contribute to thermal loading within the crystal via upconversion because there is no lasing present to deplete the gain.

For high power end-pumped systems, compensation for the aberrated component of the thermal lens is necessary to make use of the full gain region. High gain systems are able to make use of nonlinear optical techniques to correct for thermal lensing.

A common technique involves creating a phase conjugate mirror using stimulated Brillouin scattering, SBS. Deformation of the phase profile of the laser mode from the first pass of the laser rod thermal lens to be undone upon phase conjugate reflection back through the thermal lens. The efficiency of the mirror reflectivity is dependent upon the peak intensity of the laser and so SBS is only applicable to high gain pulsed systems [Eichler94]. Another thermal lens compensation technique uses the nonlinear process of four wave mixing to produce a phase conjugate mirror [Mailis99]. This phase conjugate mirror forms part of the laser cavity and compensates for any aberration that the laser mode suffers from the round trip.

These nonlinear techniques are not suitable for systems operating on low gain transitions such as the 946nm and 1319nm lasers. Use of intra-cavity compensation
components has been suggested instead of using nonlinear optics to compensate for the aberrated thermal lens. Some work has been done using a deformable cavity mirror to correct the phase of the laser mode [Zeng98]. Diamond turned aspheric optics have also been used as phase correcting elements. For instance, J. Kasinski et al [Kasinski97] used two CaF$_2$ aspheric lenses to reshape the output of a 1064nm Nd:YAG laser before amplification. Aspheric optics have been used intra-cavity to correct for thermal lensing. Tidwell et al used a CaF$_2$ asphere in a two rod 1064nm Nd:YAG laser. The asphere was found to have a single pass loss of 0.5% due to scatter from its surface.

Such aspheric solutions are not ideal for low gain end-pumped systems, Tidwell’s laser had a 1.5mm pump beam radius and therefore the laser mode was an order of magnitude larger to that in a 946nm laser. This increase in laser mode makes the construction of an asphere an easier task. Also a 1% round-trip insertion loss for the component is rather high.

An alternative method for correction of thermal lens aberrations could make use of the photosensitivity of some glasses. Under high intensity laser irradiation at the correct wavelength, it is possible to generate a refractive index change in glass. Germanosilicate glass is the most commonly used glass that demonstrates this effect. Photosensitivity has also been demonstrated in a variety of other non-silicate glasses, calcogenides, lead germanate, fluoroaluminates.

Optical fibre that consists of a fused silica core and a germanosilicate cladding can be periodically irradiated with 244nm ultraviolet radiation (frequency doubled 488nm argon ion laser) to form a grating structure within the fibre cladding. Typically the refractive index change is of the order of $1 \times 10^{-3}$. These fibre Bragg gratings can be designed to operate as band pass filters in telecommunications applications or high reflectivity mirrors for fibre lasers.

Unfortunately, the irradiation of germanosilicate glass described above does not penetrate far into the glass (tens of microns) because of the strong UV absorption. In fact, a tapering of the refractive index change is seen across the fibre.
To create a component that could significantly alter the phase front of a laser mode, a refractive index change is required through a depth of the glass. For light at a wavelength of 1μm with a component refractive index change of $1 \times 10^{-3}$, a component thickness of 1mm would allow a variation in the component optical thickness significant enough to provide a $2\pi$ phase change to the laser mode.

**Ge 242nm Absorption Peak**

![Graph showing the 242nm Absorption Peak in Germanosilicate Glass Responsible for Photosensitive Refractive Index Changes]

To obtain a millimetre thick refractive index change a different approach to UV irradiation must be considered. T. Monro [Monro99] produced a 1 centimetre long waveguide in a sample of germanosilicate glass deposited on a substrate. This was achieved by focussing an argon ion laser, operating solely on the 488nm laser line, down to a 5μm spot-size on the polished end-face of the germanosilicate substrate. The sample was irradiated for 10 hours. A refractive index change, which began at the surface, propagated through the germanosilicate layer by self-confinement of the 488nm beam. The refractive index change was brought about by 2-photon absorption.
This occurs when two 488nm photons are in proximity of a 242nm absorption site at the same time. Both photons are absorbed by the site and an index change is generated.

Writing refractive index changes using UV radiation is virtually instantaneous, however the 2 photon process is much slower. It is the much reduced likelihood of absorption within the glass that allows the refractive index change (waveguide) to propagate into the glass. A ten hour write time (a millimetre an hour) to alter the refractive index in a 10μm diameter cylinder is not suitable for creating a complex phase compensator. Two-photon absorption is dependent upon the peak intensity of the blue light and not the average intensity. Therefore it should be possible to reduce the write time by using a pulsed system. An alternative to the 488nm blue light, the photon equivalent of 242nm UV radiation, would be 473nm light, the second harmonic of 946nm Nd:YAG. This would correspond to absorption at 236.5nm, which is situated on the 242nm absorption peak.

T. Monroe used a thin layer of germanosilicate glass deposited on a substrate because it is difficult to make a bulk sample. Both germanium oxide and silicon dioxide are glass formers, that is, melting of either of the compounds and then casting will form a glass. When the two compounds are heated together, (silicon dioxide is usually the greater molar amount with perhaps 10% germanium oxide) on casting it is difficult to form a high quality glass due to defects within the structure.

To improve the quality of germanosilicate glass, glass makers add glass modifiers to the melt. Unfortunately, glass modifiers work by reducing the defects within the glass. It is these germanium oxygen deficient centres (GODC) or defects that produce the absorption peak at 242nm. It is the GODC absorption peak to which the photosensitivity is attributed.

An alternative to a bulk cast sample can be obtained from a fibre preform. One method of making fibre preforms is to use a technique called metal-organo chemical vapour deposition, MOCVD. This process works by taking the chlorides of the chemicals required and passing the mix, in gas form, down a fused silica tube. The
tube is heated by a moving burner to about 2000°C and the chemicals are burned in oxygen. Some of the oxide deposits on the tube whilst the rest is removed as soot. MOCVD builds up thin layers of glass. Once enough layers are present, the tube is heated at \( \sim 2200°C \) with a reduced gas flow causing the tube to collapse.

The above method was used by the Author to produce a core of germanosilicate glass. The glass appeared to be of good optical quality. When a cross-section of the glass was cut, however, the core shattered away from the fused silica wall due to the stress of the interface.

As an alternative, a square section fused silica preform tube was used. A 1mm thick deposit was put down. The tube was not collapsed so that the square shape was retained. Before cutting the preform, hot wax was poured inside to dampen the vibrations from the saw. Sections were successfully cut and polished to give rectangular samples of 1mm thick germanosilicate glass on fused silica substrates.

Other methods of optical fibre preform can be used to produce high quality geramosilicate glass. Vapour axial deposition VAD is a common preform technique, which has the advantage of forming a large core diameter. VAD samples are a common choice for scientists studying the photosensitivity of glass.

A detailed study of these glasses is required to determine whether significant index changes of any depth can be written using 2 photon absorption. An alternative writing approach that should also be investigated is that of using 330nm light (from an argon ion laser or the fourth harmonic of 1319nm Nd:YAG). Figure 5.3 does not make any absorption peak at 330nm clear. This is because the peak is three orders of magnitude smaller than the 242nm peak. However, it has been shown that this peak does allow for significant photosensitive refractive index changes when irradiated. Irradiation time is longer than for the 242nm peak, but this has the advantage that the 330nm write beam has a much longer absorption length.

The ability to combat some or all of the effects of thermal lensing would allow successful utilisation of both the 946nm and 1319nm Nd:YAG transitions to develop
modest power visible sources using nonlinear optical techniques. This would be a significant step forward to providing an effective all-solid-state alternative to argon ion sources. 473nm from a doubled 946nm laser would be a suitable replacement for the 488nm laser line. The 473nm light could be further doubled to replace the FRED Ar$^{3+}$ line at 244nm that is frequently used for optical fibre grating manufacture. As mentioned above, quadrupled 1319nm light at 329.8nm would provide a good replacement for the 337nm Ar$^{3+}$ laser line and of course the green argon line already has a 532nm diode pumped Nd:YAG alternative that is commercially available.
5.3 References


Appendix A : List of Publications

Journal Publications


Conference Publications


