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UMI
QUASI-FOUR-LEVEL LASER DESIGN AND ANALYSIS OF Nd:YAG
OPERATING AT THE 946 NM TRANSITION

by

Elka Ertur Koehler

A Dissertation Submitted to the Faculty of the
COMMITTEE ON OPTICAL SCIENCES (GRADUATE)
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2000
As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Elka Ertur Koehler entitled Quasi-Four-Level Laser Design and Analysis of Nd:YAG Operating at the 946nm Transition and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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ABSTRACT

Nd:YAG, well known for its operation at 1064nm, has a weaker transition at 946nm, whose lower level is thermally populated. This dissertation describes the design and development of a diode pumped, room temperature, quasi-four-level laser operating at the 946nm transition of Nd:YAG. The design addresses two primary issues in obtaining an efficient, high energy oscillator at 946nm. These are the ground state reabsorption losses due to the thermally occupied lower laser level, and the population inversion losses incurred at the much stronger 1064nm transition. With 55 mJ in the normal mode, and 25 mJ in the q-switched mode, the output energies obtained are the highest energies per pulse reported to date for a diode pumped, 946nm Nd:YAG laser.

A quasi-four-level laser theory is developed and used to optimize oscillator parameters affected by the thermally occupied lower laser level. The laser material length and the folded V shaped cavity are selected to maximize the gain per round trip in the cavity. The availability of stacked and microlensed diode array bars, along with an efficient pump coupling technique, allows the use of an end pumped configuration which provides the high pump density required to reach threshold in quasi-four-level lasers.

The oscillator design was further refined to eliminate possible parasitic lasing paths and minimize amplified spontaneous emission losses at the 1064nm transition. A large diameter laser disk with a Samarium doped cladding, which absorbs the 1064nm radiation, reduces the number of 1064nm ASE paths which deplete the inversion density in the pumped volume. The cladding significantly improves the storage efficiency, and hence the q-switched efficiency, of the oscillator.
Although the oscillator was developed specifically for remote sensing of atmospheric water vapor, other applications can also benefit from the development of an efficient 946nm laser source. When frequency doubled, this wavelength allows access to the blue, which is highly desirable for high density data storage, displays, biological applications, and underwater communications.
INTRODUCTION

1.1 Objective

Laser remote sensing has proven to be a powerful technique for measuring important atmospheric variables such as water vapor, ozone, greenhouse gases, chemicals, biological agents, wind speed, clouds and aerosols. Compared to passive sensors, lidar systems can provide atmospheric profiles in greater detail, and measurements can be better localized. Consequently, there has been considerable interest in developing efficient and reliable laser systems for long term operation in space. Satellite-based remote sensing of these various parameters is useful for analyzing industrial and military activities world wide, and for monitoring atmospheric chemistry and dynamics. This information is also necessary for weather forecasts, and for predicting the effects of global changes.

One specific active remote sensing technique is Differential Atmospheric Absorption Lidar (DIAL) which provides range resolved molecular content, such as water vapor, in the atmosphere. In a DIAL system the transmitter of the remote sensor probes the atmosphere with two narrow linewidth laser pulses at slightly different wavelengths, one of which must be tuned to the absorption line of the targeted molecule. Since the wavelengths are closely spaced, the aerosol backscatter is equivalent for both pulses. Consequently, by comparing the returned signal power from both the on and off line pulses, the molecular concentration of the target constituent can be mapped as a function of range [Browell, E. et al., 1979].
NASA Langley Research Center (LaRC) has been a leader in developing DIAL technology for aircraft and spacecraft applications. Specifically, the Lidar In-space Technology Experiment (LITE) was a three-wavelength, space based, back scatter lidar developed by NASA LaRC to fly on the Space Shuttle. The transmitter consisted of a flashlamp pumped, frequency doubled and tripled 1 Joule Nd:YAG laser. LITE flew on Discovery in September 1994 as part of the STS-64 mission. The goals of the LITE mission were to validate key lidar technologies for spaceborne applications, to explore the applications of space lidar, and to gain operational experience which will benefit the development of future systems on free-flying satellite platforms. The LITE instrument collected over 40 GBytes of data, which provided the first highly detailed global view of the vertical structure of cloud and aerosol from the Earth’s surface through the middle stratosphere [Grant, B. et al., 1997].

In addition to LITE, LaRC also fully engineered Lidar Atmospheric Sensing Experiment (LASE), the first modular, tunable, autonomous DIAL system for the remote measurement of water vapor, aerosols and clouds across the troposphere. It was completely designed, built and environmentally tested at LaRC. LASE was designed to fly aboard a NASA/Ames ER-2 aircraft (a modified U-2 spy plane) and operate at altitudes from 58,000 to 70,000 feet. LASE has been validated with results showing an accuracy better than the initial requirement for vertical profiles of water vapor in the troposphere. No other instrument in the world can provide the spatial coverage and accuracy of LASE. The high quality, low maintenance design has allowed the instrument
to also be flown on other aircraft including the NASA P-3 and DC-8 [Browell, E. V. et al., 1997].

Although the LASE transmitter, a Titanium Sapphire oscillator pumped by a frequency doubled, flashlamp pumped Nd:YAG oscillator, was quite successful in airborne DIAL applications, a more efficient and reliable system is necessary for space borne applications. The work presented here on the development of a 946nm laser is a step towards the next generation DIAL system for tropospheric water vapor measurements from both airplanes and satellites. With the existence of relatively strong atmospheric water absorption lines in the 946nm region [Giver, L.P. et al., 1982], a diode pumped Nd:YAG system operating on the \(^2\text{F}_{3/2} \rightarrow \^4\text{I}_{9/2}\) transition promises to be a suitable candidate for Differential Absorption Lidar (DIAL) measurements to be taken from high altitudes. With good mechanical, thermal, and optical properties, Nd:YAG is a mature, well-developed material that is readily available for use.

There are numerous advantages to developing a 946nm Nd:YAG transmitter. In addition to targeting the relatively strong water lines, Nd:YAG at 946nm offers the advantages of simplicity, reliability, and efficiency of a diode pumped system for space based lidar applications. Since the efficiency, size, weight, and lifetime of available laser technology restricts the practical implementation of satellite-based lidar systems, directly diode pumped 946nm technology offers a rare opportunity to address all of these major difficulties. It provides the required wavelength in a single step process, without additional processes such as frequency doubling or frequency conversion that further reduce the system efficiency. Figure 1-1 illustrates the reduced number of processes
required to achieve the desired wavelength in the directly pumped Nd:YAG transmitter. Furthermore, by employing well-developed diode arrays at 808nm instead of flashlamps, 946nm operation in Nd:YAG provides a compact, reliable, and efficient transmitter for space applications. As a matter of fact, the 946nm laser utilizes the same diode arrays used for commercial pumping of Nd:YAG operating at 1064nm.

The lifetimes and efficiencies of diode pumped solid state systems are substantially higher than comparable flashlamp pumped systems. With an average
lifetime of $10^7$ shots [Koechner, W., 1999]. Flashlamp pumped systems are not suitable for long term space applications. Furthermore, due to their wide spectral output, flashlamps yield much lower pumping and consequently overall system efficiencies. High electrical to optical system efficiency is a critical requirement given the limited resources associated with space borne applications. The excess pump energy from the flashlamps also induces heating of the laser material, necessitating the use of rather large undesirable water cooling systems in an environment limited by size and weight. As a matter of fact, it is this reduction in waste heat by diode pumping that allows room temperature operation of the 946nm transition in Nd:YAG. Furthermore, as seen in section 2.1, diode pumping also allows the use of shorter rods necessary for the efficient operation of quasi-four-level lasers.

The development of a diode pumped Nd:YAG laser operating at the 946nm transition also provides a direct growth path to the application of other Nd doped garnets. Though not as efficient as other lines, 946nm does overlap weaker H$_2$O absorption lines, making limited DIAL measurements possible under certain conditions. Since the exact laser emission wavelength depends on the host material, stronger water vapor absorption lines in the vicinity of 946nm can be targeted by selecting an appropriate garnet. Changing the composition of the host material shifts the energy levels of the $^4F_{3/2}$-$^4I_{9/2}$ transition, allowing other wavelengths to be generated. Spectroscopic studies on various Nd doped garnets have so far successfully indicated that the emission line at 946nm can be tuned by changing the composition of the host material [Zokai, M. et al., 1979]. By systematically changing the Ga composition in the host $Y_3Ga_xAl_{15-x}O_{12}$, Barnes and
Walsh have demonstrated the tunability of Nd doped YGAG from 939nm to 945nm [Walsh, B. M. et al., 1998]. Since the fundamental laser dynamics of the quasi-four level Nd transition at 946nm remains consistent with various hosts, the design and development of a Nd:YAG laser at 946nm can directly be applied to the next generation Nd garnet materials which are currently under study. This prototype will serve as a baseline in the development of optimum 940nm laser parameters and architecture for maximum efficiency.

In addition to having to meet the restrictions inherent to satellite based systems, lasers for DIAL systems must also meet other stringent system performance requirements. For accurate measurements, the laser must have single axial and transverse mode with a narrow linewidth output that can be tuned on and off the targeted absorption line. The required narrow linewidth can be achieved by injection seeding the oscillator with a microchip laser built from a matching laser material, while the tunability to the off line can be achieved by lasing on the slope of the gain curve instead of on the peak. Although output energies on the order of 500mJ at a repetition rate of 20 Hz are necessary for space borne applications, the goal of this program was to demonstrate the feasibility and efficiency of a diode pumped 946nm transmitter for an aircraft based DIAL demonstration. The Q-switched energy requirements for an aircraft demonstration then drop to 25mJ at a repetition rate of 20Hz. Due to the availability of only one pump diode array stack, limited system potential has been demonstrated for a possible aircraft application. A system concept to show energy scalability for space applications will be
presented in Chapter 5. Table 1.1 summarizes the requirements for both aircraft and space based DIAL systems.

<table>
<thead>
<tr>
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<th>Space Water Vapor DIAL</th>
<th>Aircraft Water Vapor DIAL</th>
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<tbody>
<tr>
<td>Wavelength</td>
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<td>25 mJ</td>
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<tr>
<td>Linewidth</td>
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<td>≤ 1 pm</td>
</tr>
<tr>
<td>Stability</td>
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<td>~ 0.25 pm</td>
</tr>
<tr>
<td>Pulse Length</td>
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<td>&gt; 15 nsec</td>
</tr>
<tr>
<td>Spectral Purity</td>
<td>&gt; 99.5 %</td>
<td>&gt; 99.5 %</td>
</tr>
<tr>
<td>Divergence</td>
<td>0.1 mrad</td>
<td>0.1-2.0 mrad</td>
</tr>
</tbody>
</table>

Table 1-1 Laser transmitter requirements for water vapor DIAL.

1.2 History of related work

The drive to produce blue sources by frequency doubling the 946nm output in Nd:YAG has been the primary force in the development of this technology for years. The second harmonic at 473nm is highly desirable for numerous applications such as optical data storage and displays, biomedical and communication technologies, shallow water laser bathymetry (depth measurement), and satellite to submarine optical communications [Rankin, M. B.. 1983]. Recently, there even has been some interest in frequency quadrupling 946nm to obtain a UV source at 237nm for use in basic scientific research [Hollemann, G. et al.. 1993].
Earliest work on the 946nm line of Nd:YAG was published by R.W. Wallace and S. E. Harris in 1969 who demonstrated intracavity frequency doubling of 946nm at -40 C. This was achieved by flashlamp pumping a 75mm long Nd:YAG rod, cooled by nitrogen gas bubbled through liquid nitrogen [Wallace, R. W. et al., 1969]. Since then, N. Barnes and B. Walsh have been able to model and demonstrate flashlamp pumped room temperature operation of 946nm laser with a 0.9% slope efficiency using a Nd:YAG rod with diffusion bonded undoped ends [Barnes, N. P. et al., 1997].

In 1987, T.Y. Fan and R. Byer modeled and demonstrated continuous wave (cw) operation of a dye laser pumped, quasi-four-level 946nm laser with 17mW of output power at a 16% slope efficiency [Fan, T. Y. et al., 1987]. A comparable model on quasi-four-level operation of Nd:YAG was also developed by Risk [Risk, W. P., 1988] who demonstrated a cw diode pumped, room temperature, 946nm laser with 42mW of output power at 16% slope efficiency in terms of incident pump power [Risk, W. P. et al., 1987].

Similar quasi-four-level laser theories have been developed by other researchers who use different thermally occupied ground state laser materials for their analysis and demonstrations. For example, Raymond Beach validated his quasi-four-level laser model using Yb:YAG whose terminal laser level is thermally populated at 612 cm\(^{-1}\) [Beach, R., 1996], while Krupke investigated the very same concept of ground state depleted lasers in Nd:Y\(_2\)SiO\(_5\) whose lower Stark level lies 355 cm\(^{-1}\) above the ground state [Krupke, W. F., 1989]. B. Walsh and N. Barnes investigated the spectroscopy and lasing characteristics of numerous combinations of Nd doped Y\(_3\)Ga\(_x\)Al\(_{15-x}\)O\(_{12}\) materials strictly for applications using the 946nm transition [Walsh, B. et al., 1998]. By systematically changing the Ga
concentration in the garnet, they were able to demonstrate and predict the tunability of the 946nm line in various hosts. This technique is especially useful for DIAL applications where numerous water vapor absorption lines in the vicinity of 946nm can be targeted.

Stringent demands on the diode pump size and beam quality, stipulated by the need to saturate the ground state reabsorption losses, has historically limited the 946nm operation of Nd:YAG to low power systems. Yves Lutz demonstrated the energy scalability by pumping Nd:YAG with a much better behaved beam from a titanium doped sapphire laser compared to that of a diode array. A maximum output energy of 83.5 mJ at 3 Hz with a slope efficiency of 32.3% was reported [Lutz, Y. et al., 1998].

With the advancement of the diode technology, the efficiencies and output powers of diode pumped 946nm systems have progressively been improving. Following Hollmann’s 200 mW [Hollemann, G. et al., 1995] and Frietag’s 800 mW single frequency nonplanar ring laser [Freitag, I. Et al., 1995], Clarkson and Hanna obtained 3 Watts of output power with 33% slope efficiency [Clarkson, W. A. et al., 1996]. Recently, Hanson reported 10mj output energy with a slope efficiency of 13% in a highly multimode output. Using an intracavity negative lens to increase cavity mode size, 6.5 mJ in a TEM_{60} beam was also demonstrated with this system. Passive Q-switching of the same oscillator with a Cr:YAG slab resulted in 4 distinct output pulses per pump pulse, and electro-optic Q-switching yielded 3mJ of output [Hanson, F. et al., 1998].

As we have seen, a bulk of the previously reported work on the 946 nm transition in Nd:YAG consists mostly of cw and low energy systems. However, many applications
including DIAL require pulsed operation with high output energies per pulse. The results reported in this publication far exceed those of most recently reported diode pumped, pulsed 946nm laser work. The system described in this publication provides 55 mJ of output with 25% slope efficiency with respect to incident pump energy in a TEM$_{00}$ beam. Furthermore, although the slope efficiency for the Q-switched mode drops to 11%, the 25mJ of output is also the highest Q-switched energy per pulse reported to date.

### 1.3 System description

Before proceeding to discussions of design optimization details, the final oscillator configuration will be described in this section.

![Figure 1-2 946nm laser oscillator configuration.](image)

The laser material is a 4mm long, 10mm diameter, 1% doped Nd:YAG disk fabricated with a 2 degree wedge for reasons that will be explained in section 2.2. A Samarium doped cladding surrounds the Nd:YAG disk with an index matching fluid.
between the disk and the clad to ensure good optical contact. Section 2.2 also discusses
the need for the Sm doped cladding.

The resonator is folded into a V shape to take advantage of the available gain by
quadrupling the passes through the pump volume per round trip. The resonator employs a
flat output coupler and a concave end mirror which support a relatively large TEM$_{00}$
mode in the cavity to meet the energy and beam quality specifications. The large mode
volume defined by the resonator mirrors drives the pump size requirements.

To meet the pump density requirements associated with the 946nm transition,
which will be discussed in chapter 2, the Nd:YAG crystal is end pumped with a 30 bar
stack of 100 watt, pulsed, GaAlAs bars emitting at 808 nm. The highly diverging and
large emitting area of the diode array stack is first microlensed to reduce the fast axis
divergence, and then focused with a long, tapered fused silica lens guide, also known as a
lens duct. The coupling scheme and efficiency are presented in chapter 3.

In order to analyze the dynamics of this transition with minimal temperature
fluctuations, all data was taken at a low pulse repetition rate of 1 Hz. The pump pulse
length is 160 microseconds, while the opening of the Q-switch is optimized at 161
microseconds. A fused silica double Brewster's angle acousto-optic Q-switch is used to
minimize the insertion losses.

With an 82.5% reflective output coupler, 10m highly reflecting end mirror, and a
4mm long, 10mm diameter 1% Nd:YAG disk, 55mJ of output energy at 25% slope
efficiency with respect to incident pump energy is demonstrated in the normal mode.
This is the highest reported energy to date for a diode pumped, room temperature 946nm
oscillator with a TEM\textsubscript{00} output. Q-switched operation at 1 Hz yields 25mJ of output energy with 11\% slope efficiency.

1.4 Overview

The spectroscopic properties of Nd:YAG which shape and mold the oscillator design will be the focus of chapter 2. A quasi-four-level laser model based on previously reported theories [Fan. T. Y., 1987] and spectroscopic properties of Nd:YAG [Walsh. B. et al. 1998] is developed in this chapter. Specifically, the reasons for selecting this particular rod geometry, resonator configuration, and pumping scheme are discussed. Energy storage issues observed in small signal gain measurements lead to the discussion and quantitative analysis of the 1064nm loss mechanisms in various laser rod geometries.

In chapter 3, the entire pump module output, including the diode array stack and the lens duct, is theoretically and experimentally characterized. In cases where accurate measurements are difficult to obtain, pump beam parameters necessary as input for the laser model are deduced using a ray trace model.

In chapter 4, the theoretical model is applied to the oscillator design developed in chapter 2. The model predictions are verified with experimental data. The output coupler, end mirror curvature, and pump diameter are optimized for maximum energy output in a TEM\textsubscript{00} mode. Normal mode cavity losses and efficiency factors are extrapolated from experimental data. The measured data shows good agreement with the theoretical model.
Chapter 5 gives a brief review of the work presented and provides suggestions for improving the efficiency in the next generation oscillator. It also includes a conceptual design to demonstrate energy scalability.
2 OSCILLATOR DESIGN

This chapter presents the laser material issues and the system requirements that give rise to the oscillator design. The dominating factors that drive the design parameters such as the rod size and geometry, pumping scheme, and resonator configuration are as follows.

- Thermally populated lower laser level
- The much stronger 1064nm transition in Nd:YAG
- High energy requirement
- Single TEM$_{00}$ mode requirement

Using an extension of previously reported theories [Fan, T. Y., 1987], a quasi-four-level laser model that takes these parameters into account is developed and used to optimize the laser performance. Specifically, section 2.1 investigates the effect of the lower level thermal population on the pump geometry and the rod length. The Nd:YAG rod length is optimized, and verified experimentally with small signal gain measurements. Section 2.2 explores various design options in search of the optimum laser rod geometry that minimizes inversion losses caused by the much stronger 1064nm transition. Small signal gain and fluorescence measurements are taken to further evaluate variations on the rod parameters such as diameter, wedge, doping concentration, and Samarium (Sm) doped claddings. Section 2.3 describes the resonator parameters that are selected in order to meet the system requirements of good beam quality and high energy. Pump beam requirements defined by the mode volume in the cavity are also presented.
2.1 Lower level thermal population effects

Figure 2-1 shows the energy level structure of the Nd$^{3+}$ ion in a YAG host [Fan, T. Y. 1987]. Although both the 1064nm and the 946nm transitions originate from the $^4F_{3/2}$ manifold, the 946nm transition in Nd:YAG terminates at the highest Stark level of the $^4I_{9/2}$ ground state. At only 857 cm$^{-1}$ above the ground state, the lower laser level of the 946nm transition is thermally populated at room temperature following Boltzmann’s distribution. This lower level thermal population poses several issues that must be addressed in designing an efficient oscillator at 946nm.

![Nd:YAG energy level diagram](image)

Figure 2-1 Nd:YAG energy level diagram.
2.1.1 High pump density requirement

In order to overcome the reduction in inversion density caused by the thermal occupation of the lower laser level, higher pump densities are necessary to reach the lasing threshold at the 946nm transition. Assuming rapid thermalization of the manifolds, the fractional lower and upper level thermal population distributions of the 946nm transition are given by the following Boltzmann distribution.

\[
F_n(T) = \frac{\exp(-E_n/kT)}{\sum_{i=1}^{m} \exp(-E_i/kT)}
\]

Accordingly, using the energy level values for Nd:YAG from Figure 2-1, at room temperature (300K), 0.7557% of the lower manifold population occupies the terminal laser level, while 61.2% of the upper laser manifold population resides in the metastable laser level. Due to this significant lower level population, the four level laser theory of the 1064nm transition in Nd:YAG no longer applies to the 946nm laser transition, and the lower level population must be considered in the laser rate equations. When the laser material is optically pumped, the following rate equations describe the respective population densities of the upper and lower laser levels (See Appendix for derivation from manifold rate equations).

\[
\frac{dN_2(r, z)}{dt} = F_2 \cdot R \cdot r_p(r, z) - \frac{N_2(r, z)}{\tau} - N_2(r, z) \cdot (F_1 + F_2) \cdot \sigma \cdot c \cdot \Phi \cdot \frac{l_0(r, z)}{n} + N_{10} \cdot Z_2 \cdot \sigma \cdot c \cdot \Phi \cdot \frac{l_0(r, z)}{n}
\]

\[
\frac{dN_1(r, z)}{dt} = -F_1 \cdot R \cdot r_p(r, z) + \frac{N_{10} - N_1(r, z)}{\tau} - N_1(r, z) \cdot (F_1 + F_2) \cdot \sigma \cdot c \cdot \Phi \cdot \frac{l_0(r, z)}{n} + N_{10} \cdot F_2 \cdot \sigma \cdot c \cdot \Phi \cdot \frac{l_0(r, z)}{n}
\]
The following table lists the variables used in the rate equations with their respective values and definitions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_2(r,z)$</td>
<td></td>
<td>Upper level population density</td>
</tr>
<tr>
<td>$N_1(r,z)$</td>
<td></td>
<td>Lower level population density</td>
</tr>
<tr>
<td>$F_1$</td>
<td>0.007557</td>
<td>Boltzmann lower level distribution of the 946nm transition at 300K</td>
</tr>
<tr>
<td>$F_2$</td>
<td>0.621</td>
<td>Boltzmann upper level distribution of the 946nm transition at 300K</td>
</tr>
<tr>
<td>$N$</td>
<td>$1.38 \times 10^{-26}$ m$^{-3}$</td>
<td>Dopant density for 1% Nd</td>
</tr>
<tr>
<td>$N_{10}$</td>
<td>$F_1 N$</td>
<td>Unpumped lower level population density</td>
</tr>
<tr>
<td>$\phi$</td>
<td></td>
<td>Intracavity photon number</td>
</tr>
<tr>
<td>$R$</td>
<td></td>
<td>Number of ions transferred to the pump band per unit time</td>
</tr>
<tr>
<td>$w_p$</td>
<td>~1mm or ~1.25mm</td>
<td>Pump radius determined by the lens duct exit aperture size</td>
</tr>
<tr>
<td>$w_0$</td>
<td>0.97mm</td>
<td>TEM$_{00}$ mode radius determined by the Gaussian propagation equations</td>
</tr>
<tr>
<td>$L$</td>
<td>4mm</td>
<td>Nd:YAG disk length</td>
</tr>
<tr>
<td>$H$</td>
<td>5mm</td>
<td>Nd:YAG laser disk radius</td>
</tr>
<tr>
<td>$\tau$</td>
<td>230 $\mu$sec</td>
<td>Upper level fluorescence lifetime of Nd in YAG</td>
</tr>
<tr>
<td>$\tau_l$</td>
<td>~nsec</td>
<td>Lower level fluorescence lifetime and is assumed to be very fast</td>
</tr>
<tr>
<td>$l_p$</td>
<td>160 $\mu$sec</td>
<td>Pump pulse width</td>
</tr>
<tr>
<td>$\sigma_a$</td>
<td>$2.9 \times 10^{-24}$ m$^2$</td>
<td>Absorption cross section at 808nm</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$6.13 \times 10^{-24}$ m$^2$</td>
<td>Emission cross section of the 946nm transition [Barnes]</td>
</tr>
<tr>
<td>$\sigma_{1064}$</td>
<td>$6.5 \times 10^{-23}$ m$^2$</td>
<td>Emission cross section of the 1064nm transition [Koechner]</td>
</tr>
</tbody>
</table>

Table 2-1 Laser parameter descriptions and values.
The pump rate $R$ at which the Nd ions are excited increases the upper level population density, whereas spontaneous and stimulated emissions deplete the upper level population density. The spontaneous emission decays at a rate inversely proportional to the upper level lifetime, while the stimulated emission reduces the upper level population density at a rate proportional to both the emission cross section and the intracavity photon number $\phi$.

The upper and lower population densities in the crystal vary across the coordinate along the axis of the laser ($z$), and along the transverse radial coordinate ($r$). The radial pump distribution is approximated by a uniform intensity distribution, while the transverse pump distribution drops exponentially along the laser axis due to absorption. The pump profile in the laser crystal will further be described in Chapter 3. and following calculations assume a normalized distribution given by

$$r_p(z) = \frac{N \cdot \sigma_a}{\pi \cdot w_p^2 \cdot (1 - \exp(-N \cdot \sigma_a \cdot L))} \cdot \exp(-N \cdot \sigma_a \cdot z)$$  \hspace{1cm} 2.4$$

The normalized spatial distribution of the laser mode volume assumes a circular Gaussian beam without diffraction effects given by

$$l_o(r, z) = \frac{2}{\pi \cdot w_o^2 \cdot L} \cdot \exp\left(-\frac{2 \cdot r^2}{w_o^2}\right)$$  \hspace{1cm} 2.5$$

The laser output beam profile, which follows a TEM$_{00}$ intensity distribution, will be presented in chapter 4.
In steady state, we can solve the rate equations for the inversion density.

\[ \Delta N(r,z) = N_2(r,z) - N_1(r,z). \]

\[ \Delta N(r,z) = \frac{(F_1 + F_2) \cdot R \cdot \tau \cdot r_\tau(r,z) - N_{io}}{(F_1 + F_2) \cdot \frac{(c \cdot \tau \cdot \sigma \cdot \Phi \cdot I_o(r,z))}{n} + 1}. \]

As seen in equation 2.6, because of the thermally populated lower laser level (N_{io}), a relatively high pump density is necessary to achieve inversion. As long as the number of ions excited by the pump rate R is below the thermally occupied lower level population, inversion will not be achieved.

In order to predict the pump energy required to reach laser threshold, we first evaluate the round trip gain and losses in the cavity. Assuming at threshold the intracavity photon number \(\Phi\) is zero, the small signal gain coefficient \(g_o(r,z)\) can be calculated by averaging over the cavity mode and integrating over the diameter of the laser crystal (H).

\[ g_o(r,z) = \iint_{a=0}^{L} \left[ (F_1 + F_2) \cdot R \cdot \tau \cdot r_\tau(r,z) - N_{io} \right] \cdot \sigma \cdot 2 \cdot \pi \cdot r \cdot I_o(r,z) dr \cdot dz \]

At threshold, the round trip gain equals \(4g_oL\) due to the unconventional \(V\) shaped resonator. This configuration allows the gain to build within the relatively short pump volume via quadruple passes per round trip. Although the rod is only 4mm long, folding the cavity at the rod effectively doubles the gain per single pass. Since the pump beam exiting the lens duct is diverging, this configuration exploits the tightest area of the pump beam by placing the short laser rod at the vertex of the acute angle formed by the \(V\)
shaped resonator. The angle is kept at a small angle of 4 degrees to minimize deviation from the nominal coating reflectivities designed for zero degree of incidence angles on the rod.

Meanwhile, the round trip cavity losses at 946nm are given by

$$\delta = -\ln(R_1) - 2\ln(R_3) - \ln(R_2) - 4\ln(1 - R_{\text{disk}}) + 4aL$$  \hspace{1cm} (2.8)$$

where the variables are illustrated in Figure 2-2, and their values listed in Table 2-2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>99.5%</td>
<td>End Mirror</td>
</tr>
<tr>
<td>$R_2$</td>
<td>70%-98%</td>
<td>Output Coupler</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.2m$^{-1}$</td>
<td>Material losses @ 946nm</td>
</tr>
<tr>
<td>$R_{\text{disk}}$</td>
<td>0.05%</td>
<td>Nd:YAG surface facing output coupler</td>
</tr>
<tr>
<td>$R_3$</td>
<td>99.5%</td>
<td>Nd:YAG surface facing lens duct</td>
</tr>
</tbody>
</table>

Table 2-2 Cavity loss parameters and values at 946nm

Figure 2-2 Loss mechanisms in the resonator.
Since the V shaped resonator supports four passes per round trip, the losses must take into account two reflections from the surface of the disk facing the lens duct ($R_3$), in addition to the reflections from the output coupler ($R_2$), and the highly reflecting end mirror ($R_1$). The four-pass material scatter and absorption losses at 946nm, and reflection losses at the disk surface facing the output coupler ($R_{disk}$) per round trip also contribute to the total system losses.

At threshold, the gain in the inverted material must equal the losses in the cavity.

$$4 \cdot L \cdot \int_{0}^{L_H} \int_{0}^{H} (F_1 + F_2) \cdot R_{th} \cdot \tau \cdot r_p(r,z) - N_{th} \cdot \sigma \cdot I_0(r,z) \cdot \frac{2 \cdot \pi \cdot r}{dr \cdot dz} = \delta$$

This threshold condition can be solved to obtain the pump rate, $R_{th}$, from which the threshold pump energy can be calculated.

$$R_{th} = \frac{\delta + L_{re}}{4 \cdot L \cdot \sigma \cdot \tau \cdot (F_1 + F_2) \int_{0}^{L_H} \int_{0}^{H} r_p(r,z) \cdot I_0(r,z) \cdot \frac{2 \cdot \pi \cdot r}{dr \cdot dz}}$$

where $L_{re}$ is the reabsorption losses in the threshold region given by

$$L_{re} = 4 \cdot L \int_{0}^{L_H} \int_{0}^{H} F_1 \cdot N \cdot \sigma \cdot I_0(r,z) \cdot \frac{2 \cdot \pi \cdot r}{dr \cdot dz}$$

The number of photons excited during the pump pulse after all energy transfer losses are taken into account directly correlates to the pump energy required to reach threshold. These energy transfer processes, which reduce the effective number of ions transferred to the upper level, include the absorption efficiency $\eta_a$, quantum efficiency $\eta_q = 0.95$, storage efficiency $\eta_s$, photon efficiency $\eta_p$, and beam overlap efficiency $\eta_b$.

The absorption efficiency, $\eta_a$, provides the fraction of the pump energy absorbed in the laser crystal and is approximated by
where \( T_p = 95\% \) is the transmission of the AR coated surface of the Nd:YAG disk facing the pump beam at the pump wavelength of 808nm.

The beam overlap efficiency, \( \eta_b \), gives the spatial overlap of the pump and the cavity mode volumes, and assuming collinear propagation is calculated using the following integral [Koechner].

\[
\eta_b = \frac{\int \int r(r,z) \cdot l_o(r,z) \cdot 2 \cdot \pi \cdot r \cdot dr \cdot dz}{\int \int (l_o(r,z))^2 \cdot 2 \cdot \pi \cdot r \cdot dr \cdot dz}
\]

As seen in equation 2.13, the mode and pump volumes must be matched for high beam overlap efficiency. The pump area not only needs to match the mode diameter but also needs to sustain a depth of focus on the order of the rod length.

The photon efficiency, \( \eta_p \), which represents the ratio of the laser photon energy to the pump photon energy, is given by

\[
\eta_p = \frac{\lambda}{\lambda_p}.
\]

The storage efficiency, \( \eta_s \), is the ratio of the energy extracted from the upper level during the pump pulse to the total energy deposited, and is calculated using

\[
\eta_s = \frac{1 - \exp(-t_p / \tau)}{t_p / \tau}
\]

Hence, when the laser material is pumped, the effective number of excited ions which contribute to the lasing threshold is reduced by the total efficiency factor
Given the pump rate at threshold \( R_{\text{th}} \), the pump energy to reach threshold is

\[
E_{\text{th}} = h \cdot v \cdot \tau_p \frac{R_{\text{th}}}{\eta}
\]  

2.16

As seen in equation 2.16, the gain from the number of ions excited by the pump rate must not only exceed the round trip cavity losses \( \delta \), but also the ground state absorption losses at laser wavelength \( (L_{\text{re}}) \) in order to reach the threshold condition for lasing. Fortunately, with the availability of high power diode arrays that can be stacked and microlensed to provide bright and intense beams, the relatively high pump densities required for efficient operation of quasi-four-level lasers are now feasible. Provided that the output from the diode array stack can be focused efficiently and uniformly, an end pumped configuration using these stacks is the optimum geometry in achieving the levels of inversion densities necessary to reach threshold in quasi-four-level laser materials. End pumping not only improves the pump and mode beam overlap efficiency, but also reduces the wasted pump volume in which ASE and parasitic lasing can rob the population inversion. Hence, within mechanical, thermal, and cost constraints, a diode pump module consisting of thirty, 100Watt bars stacked with 800 micron bar to bar spacing is used as the pump source.

The laser output energy and slope efficiency as a function of incident pump energy can be derived using the saturated gain equation. The factor of 4 in the denominator accounts for the four beams from the quadruple passes per round trip saturating the same pump volume.
\[ g = \Delta N\sigma = \frac{g_o}{1 + \frac{4 \cdot I}{I_s}} \]  

Of these variables, \( g_o \) is given in equation 2.7, and the saturation intensity \( I_s \) is

\[ I_s = \frac{h \cdot v}{(F_1 + F_2) \cdot \sigma \cdot \tau} \]  

Solving for \( I \) in equation 2.17 gives the intracavity beam intensity from which the output energy can be derived using

\[ E_{out} = \frac{I \cdot (1 - R_2) \cdot t_p}{\pi \cdot w_p^2} \]  

After making the necessary substitutions, laser output energy can be calculated using

\[ E_{out} = \sigma_s \cdot (E_p - E_{th}) \]  

where the slope efficiency, \( \sigma_s \), is defined by

\[ \sigma_s = \eta_c \cdot \eta \]  

and \( \eta_c \) is the coupling efficiency given by

\[ \eta_c = \frac{1 - R_2}{-3 \cdot \ln(R_1) - \ln(R_2) - 4 \cdot \ln(1 - R_{disk}) + 4 \cdot \alpha \cdot L} \]  

The theoretical output energy as a function of incident pump energy will be validated with experimental data in chapter 4.
2.1.2 Rod length constraint

In addition to requiring high pump densities, the lower level thermal population also limits the rod length due to reabsorption losses at the laser wavelength. Although pump absorption efficiency $\eta_a$ increases with the rod length, so does the reabsorption losses $L_{re}$ caused by the lower level thermal population. Figure 2-3 a, which is obtained using equation 2.12, illustrates the increased fraction of absorbed pump radiation in longer rods, while Figure 2-3 b) charts the rising reabsorption losses in longer rods for low intracavity energies where $\Phi$ is assumed to be zero. This assumption is made to account for the highest possible losses in the gain medium. As seen in equation 2.23, the reabsorption losses peak at low intracavity circulating energies because as the pump density rises the increased numbers of intracavity photons saturate the reabsorption losses [Fan]. As seen in Figure 2-3 c), the small signal gain in the threshold region, which takes both the absorption efficiency and the reabsorption losses into account using equation 2.7, indicates an optimum rod length in the vicinity of 5mm for a 2mm pump spot and 4mm for a 2.5mm pump spot.

\[
L_{re} = 4 \cdot L \int_0^H \int_0^L \frac{F_1 \cdot N \cdot \sigma}{(c \cdot \tau \cdot \sigma \cdot \Phi \cdot I_o(r,z))} \cdot I_o(r,z) \cdot 2 \cdot \pi \cdot r \cdot dr \cdot dz
\]

2.23
Figure 2-3  a) Absorption efficiency ($\eta_a$), b) ground state reabsorption losses ($L_{re}$), c) small signal gain ($4g_aL$) for various rod lengths.
Next we evaluate the pump energy required to reach threshold for a range of rod lengths. The threshold pump energy as a function of rod length can be calculated by solving equation 2.9 for $R_{th}(L)$ and substituting it in

$$E_{th}(L) = h \cdot v \cdot t_p \frac{R_{th}(L)}{\eta(L)}$$

2.24

where $\eta(L) = \eta_a(L)\eta_q \eta_p \eta_s \eta_b$, and $\eta_a(L) = (1 - \exp(-N \sigma_a L)) T_p$.

The graph of incident threshold pump energy as a function of the rod length in Figure 2-4 indicates an optimum solution in the vicinity of 4mm long rod length for both a 2mm and a 2.5mm pump spot diameter. As expected the threshold pump energy for the 2.5mm pump diameter is higher than that for a 2mm pump spot. All calculations assume quadruple passes per round trip cavity configuration.

![Graph showing theoretical predictions of optimum rod length for minimum threshold energy in 2mm and 2.5mm pump spot diameters.](image)
As mentioned previously, the quadruple pass per round trip is selected to maximize the gain in a given pump volume. Since the reabsorption losses impose an upper limit on the rod length, the four pass per round trip geometry maximizes the gain in a selected rod length. After modifying the gain equation to \( 2g_0 L \) and the losses to \(-\ln(R_2)-\ln(R_1)-2\ln(1-R_{\text{disk}})+2\alpha L\) in the model for a double pass geometry, the threshold pump energy can be viewed as a function of rod length for both a double pass and a four pass oscillator in Figure 2-5. The double pass oscillator is optimized at a rod length of approximately 5mm, and it still requires 58mJ of energy to reach threshold. Furthermore, this assumes a constant pump diameter across the rod length, which is not the case. Conversely, the four-pass pump geometry requires only 37mJ of pump energy to reach the threshold in a 4mm long rod.

![Figure 2-5](image.png)

Figure 2-5  Pump energy required to reach threshold in a range of rod lengths for a double pass and a four-pass geometry.
2.1.2.1 Gain measurements

The theoretical calculations for the optimum rod length are verified with small signal gain measurements using a 1064nm probe beam. Small signal gain data provides a direct assessment of the population inversion density in the laser crystal. Since both the 1064nm and the 946nm transitions originate from the same manifold, the 946nm population inversion, which is directly proportional the 946nm laser performance, can be deduced from small signal gain measurements made with a 1064nm probe beam.

Figure 2-6 illustrates the experimental set up used for small signal gain measurements. While the laser crystal is pumped under normal operating conditions, the pump volume is probed with a beam whose power is adjusted to ensure unsaturated gain measurements. The angle of incidence of the probe beam is kept consistent with the original resonator geometry. After the 2mm diameter probe beam is focused to reduce its area below that of the pumped volume, it is recollimated on its way back to the Silicon photodiode detector. In order to prevent fluorescence from reaching the detectors, irises and relatively large distances are used to isolate the probe beam from the fluorescence. The detector output is read using an oscilloscope.

![Figure 2-6 Gain measurement set up.](image-url)
Figure 2-7 shows a typical measured gain signal per pulse where minimum voltage corresponds to the probe beam energy while maximum voltage corresponds to the probe beam amplified by the pump pulse. After taking a statistical average of 32 pulses to reduce noise, the ratio of these two values minus the background noise are taken. The result is the gain (G) of that particular configuration at the 1064nm probe wavelength.

\[
G = \frac{V_{\text{max}} - V_{\text{bgd}}}{V_{\text{min}} - V_{\text{bgd}}}
\]

![Figure 2-7 Typical gain curve per pulse.](image)

Taking the natural logarithm of the gain (G) yields the double pass gain \(2g_0L\) at 1064nm from which the upper manifold population density \(N_u\) can be extrapolated by dividing \(2g_0L\) by the effective emission cross section at 1064nm and twice the rod length.

\[
\ln(G) = 2 \cdot \sigma_{1064} \cdot Z_{21064} \cdot N_u \cdot L
\]

Once the upper manifold population density, \(N_u\), is known, the population inversion density of the 946nm laser transition can be calculated using
\[ \Delta N = F_2 \text{Nu} - F_1 (N-Nu) \]  

As small signal gain measurements will be used to investigate the efficiencies of various pump configurations, the gain at 946nm for a 4 pass per round trip configuration in a V-shaped resonator can be obtained using

\[ 4g_0L = 4\sigma_{946} \Delta N L \]

![Figure 2-8 Gain measurements for various 1% Nd:YAG rod lengths and 2.5mm octagonal pump area (taken with a 1064nm probe beam and corrected for 946nm).](image)

Figure 2-8 charts the small signal gain data for various rod lengths pumped with a 2.5mm octagonal area. Highest inversion at 946nm is achieved using a 4mm long rod, with a 5mm long rod a close second, and a 3mm long rod performing the worst. These results agree well with the predicted performance in figure 2-4 where the minimum threshold pump energies are achieved with an approximately 4mm long rod.
2.2 Suppressing the 1064nm losses

As mentioned previously, the 1064nm transition in Nd:YAG shares the same upper energy manifold as the 946nm transition. Since the 1064nm emission cross section ($\sigma_{1064}=6.5 \times 10^{-23} \text{ m}^2$) is stronger than that of the 946nm transition ($\sigma_{946}=6.13 \times 10^{-24} \text{ m}^2$) by almost an order of magnitude, additional precautions to suppress the 1064nm transition must be taken into consideration in designing the 946nm laser oscillator.

The design must combat possible ASE and parasitic lasing losses caused by the much stronger gain of the 1064nm transition by introducing additional losses into the system at 1064nm. Since both the 1064nm and the 946nm transitions originate from the same $^{4}S_{3/2}$ manifold, transitions at 1064nm rob the population inversion available for the 946nm transition. Without adequate precautions, ASE and parasitic lasing on the stronger 1064nm transition will effectively compete with the 946nm transition, thereby decreasing the efficiency [Barnes, N. P. et al., 1999].

Consequently, the laser rod geometry was further defined by schemes tailored to suppress the 1064nm transition. Even with the low reflectivity coatings at 1064nm on all the optical elements, additional measures such as large rod diameters and wedges were taken to prevent the 1064nm radiation from being amplified and parasitically lasing at high pump densities. When energy storage becomes even more critical for Q-switching, Sm doped glass claddings around the laser disk are implemented to further reduce losses caused by the 1064nm transition. Following are the various laser material parameters designed to minimize losses caused by the 1064nm transition.
2.2.1 Rod length and coatings

In section 2.1, a 4mm long rod is found to be the optimum length for the 946nm transition. Fortunately, a relatively short laser crystal length also aids in the reduction of the undesirable 1064nm amplification. In addition to minimizing the ground state absorption and constraining the pump absorption to the tightest area of the pumped volume, the short rod length also reduces the gain length product of the 1064nm transition. In this section, given the 4mm long rod diameter and available dielectric coatings, we examine the feasibility of the 1064nm transition reaching the oscillation threshold in the cavity designed for 946nm. The four level laser rate equations given below were used to investigate the pump energy necessary to reach the threshold of the 1064nm radiation.

Since the lower laser level of the 1064nm transition is quite high above the ground state (2114 cm⁻¹), the thermal population of the lower level, N₁₀, is negligible. However, when pumped, only a fraction of the population density determined by the Boltzmann distribution in Equation 2.1.1 resides in the upper laser. This thermal distribution factor, F₂₁₀₆₄, is calculated to be 0.388 for Nd:YAG at room temperature (300K). The upper level rate equation

\[
\frac{d}{dt} N_2(r,z) = R \cdot r_p(r,z) - \left( \frac{F_2^{1064} \cdot N_2(r,z)}{\tau} \right) \tag{2.29}
\]

can be solved to find the population inversion at threshold.

\[
\Delta N(r,z) = N_2(r,z) = N_{th}(r,z) = F_2^{1064} \cdot R_{th} \cdot r_p(r,z) \cdot \tau \tag{2.30}
\]
The threshold population inversion density can be found by solving

\[ 4 \cdot \sigma_{1064} \int_0^L \int_0^H F_{1064}^{r_p(r,z)} \cdot 2 \cdot \pi \cdot r \cdot I_1(r,z) \cdot dr \cdot dz \cdot L = \delta_{1064}(L) \quad 2.31 \]

where losses in the V shaped resonator for the 1064nm radiation is given by

\[ \delta_{1064}(L) = -\ln(R1_{1064}) - \ln(R2_{1064}) - 2 \cdot \ln(R3_{1064}) + 4 \cdot L \cdot \alpha - 4 \cdot \ln(1 - R_{disk}) \quad 2.32 \]

where all optical coatings are specified for minimum reflection at 1064nm. Table 2-3 lists the cavity losses at the 1064nm transition.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1_{1064}</td>
<td>5%</td>
<td>1064nm reflection at the HR mirror</td>
</tr>
<tr>
<td>R2_{1064}</td>
<td>5%</td>
<td>1064nm reflection at the output coupler</td>
</tr>
<tr>
<td>R3_{1064}</td>
<td>5%</td>
<td>1064nm reflection at the pump side of the Nd:YAG disk</td>
</tr>
<tr>
<td>R_{disk}</td>
<td>0.1%</td>
<td>1064nm reflection at the resonator side of the Nd:YAG disk</td>
</tr>
<tr>
<td>\alpha</td>
<td>0.2m^{-1}</td>
<td>Scatter and absorption losses in the laser material at 1064nm</td>
</tr>
</tbody>
</table>

Table 2-3 Cavity loss parameters and values at 1064nm.

Solving equations 2.30, 2.31 and 2.32 for \( R_{th1064} \) leads to the threshold energy necessary to reach the 1064nm oscillation.

\[ R_{th1064}(L) = \frac{\delta_{1064}(L)}{4 \cdot L \cdot \sigma_{1064} \cdot \tau \cdot Z_{1064} \int_0^L \int_0^H F_{1064}^{r_p(r,z)} \cdot 2 \cdot \pi \cdot r \cdot dr \cdot dz} \quad 2.33 \]

\[ E_{th1064}(L) = \frac{R_{th1064}(L) \cdot h \cdot \nu_{1064} \cdot t_p}{\eta_{1064}(L)} \quad 2.34 \]
Figure 2-9, obtained using equations 2.24 and 2.34, shows the pump energies required to reach threshold for both the 946 and 1064nm transitions in the designed oscillator. Note that as the rod length is shortened, the lasing threshold of the 1064nm transition rises sharply due to the reduction in the absorption efficiency. With the existing dielectric coatings, a 4mm long rod, which is optimized for the 946nm transition, requires a minimum pump energy of 215mJ to reach the oscillation threshold of the 1064nm transition. This is well above the threshold energy of 37mJ for the 946nm oscillation. Hence, the available coatings and selected rod length are sufficient to suppress the 1064nm oscillation in the resonator.

Figure 2-9 Relative pump energies required to reach the lasing threshold of the 946nm and 1064nm transitions in 2mm pump diameter.
2.2.2 Dopant concentration

High dopant densities allow the use of shorter rods for a given stored energy. Reducing the rod length with a higher dopant concentration can yield similar absorption efficiencies within shorter distances. Since the pump beam has a limited depth of focus associated with the tight focus necessary for high pump densities, a high dopant density might be a viable option. Figure 2-10 shows the threshold pump energy required for both a 1% and 1.4% doped Nd:YAG operating under identical conditions. The pump energy required to reach threshold in a 3mm long 1.4% doped rod is similar to that in a 4mm long 1% doped rod. Although high dopant densities might allow the use of shorter rods, the reabsorption and possible ASE losses need further investigation.

![Figure 2-10 Pump energy required to reach lasing threshold as a function of rod length for 2mm and 2.5mm pump diameter.](image-url)
Unfortunately, high doping concentrations worsen the reabsorption losses in quasi-four-level lasers. For a given rod length, the reabsorption losses are higher for high doping concentration due to the increased number of ions in the thermally occupied lower level. However, in this case the additional losses in the higher doping density material can be compensated by the use of a shorter rod length. Figure 2-11 obtained using equation 2.11 indicates similar loses for the 4mm long rod with 1% Nd and the 3mm long rod with 1.4% Nd concentration.

Another possible concern associated with high doping densities is the possibility of increased ASE losses at lower stored energies. ASE losses are investigated by looking at the small signal gain in 1.4% Nd doped YAG disks. As the deviation of the small signal gain from a linear slope indicates the presence of an internal loss mechanism, the
small signal gain measurement is a useful diagnostic in determining the presence of ASE or parasitic lasing within the laser material.

Gain measurements indeed reveal high levels of ASE losses in 1.4% doped disks. The experimental gain-length product \((4g_0L)\) for 1.4% Nd:YAG disks pumped with 2.5mm diameter spot is graphed in Figure 2-12. The flattening of the gain curve for both 3 and 5 mm long disks at high pump densities indicates the depletion of the upper level population density by an internal loss mechanism within the laser disks. On the other hand, the slope of the 1% Nd:YAG gain curve remains linear up to 209mJ of pump energy. Consequently, 1% Nd dopant concentration remains the laser material of choice.

![Figure 2-12 Gain measurements for various lengths of 1.4% Nd:YAG disks and a 4mm long 1% Nd:YAG disk with 2.5mm octagonal pump diameter.](image)
2.2.3 **Rod diameter**

Although the rods are coated with low reflective dielectric coatings of 5% and 0.02% at 1064nm to avoid parasitic lasing from the opposing faces, there are numerous paths which can support the 1064nm oscillation. For example, resonator cavities can be formed via total internal reflection at the boundaries of the active medium including the barrel of the disk. To reduce the probability of lasing off the barrel of the laser rod, a relatively large diameter rod (i.e. disk) is fabricated with a fine ground finish.

To further illustrate this approach, a single possible path of spontaneously emitted radiation from an ion is ray traced in both 4mm and 10mm diameter rods using ORA’s Light Tools optical design software. The model assumes identical spontaneous emission path vectors emanating from identical starting points in both rods. Figure 2-13 shows the reduction in the number of possible ASE paths traveled inside the mode volume of a 10mm diameter disk compared to a 4mm diameter rod. Since gain grows exponentially with the path length, the additional number of passes through the mode volume of the 4mm diameter rod significantly increases the ASE at 1064nm, depleting the available inversion for the 946nm transition.

Small signal gain measurements in both a 4mm diameter rod and a 10mm diameter disk are also conducted to further investigate the validity of this approach. Figure 2-14 plots the small signal gain across the rod and disk diameters with 112mJ of incident pump energy. Although both gains are comparable at this pump level, as seen in Figure 2-15, at higher pump densities the small signal gain profile across the 10mm diameter disk far exceeds the gain across the 4mm diameter rod. The clamping of the
small signal gain in the 4mm diameter rod indicates the presence of an internal loss mechanism that is reducing the population inversion at high pump densities.

Figure 2-13 Ray trace of a possible ASE path within the mode volume of a 4mm diameter rod vs 10mm diameter disk.
Figure 2-14 Small signal gain measurements for both a 1% Nd:YAG rod and disk pumped with 112mJ of energy in a 2.5mm octagonal area.

Figure 2-15 Small signal gain measurements for both a 1% Nd:YAG rod and disk pumped with 209mJ of energy in a 2.5mm octagonal area.
Plotting the small signal gain at the peak of the profile as a function of the incident pump energy in Figure 2-16 displays the clamping effect in the rod clearly. The population inversion in the rod clamps after 150mJ of incident pump energy. The severe flattening of the gain in the 4mm diameter rod indicates the presence of significant ASE losses at 1064nm. On the other hand, the straight slope of the small signal gain in the disk indicates that the larger diameter eliminates ASE losses in the pump volume up to 220 mJ of pump energy.

Figure 2-16 Small signal gain at the center of the 4mm diameter rod and 10mm diameter disk pumped with a 2.5mm octagonal area and 25 bar stack.
2.2.4 Wedges

In addition to hindering parasitic lasing from the opposing surfaces of the disk, wedges also reduce the number of possible ASE paths in the pumped volume. Figure 2-17 traces the path of an arbitrary spontaneously emitted photon in laser disks with varying wedges. As the wedge angle is increased, the number of TIR paths traveling through the pumped volume is reduced. In disks with wedge angles larger than 5 degrees, the ray fails to meet the TIR condition sooner, reducing the path length in which spontaneous emission of the 1064nm radiation can be further amplified.

Figure 2-17 Possible ASE paths in disks with 0, 2, 5, and 7 degree wedge angles.

The effect of various wedge angles is further investigated by measuring the fluorescence of the disks as a function of incident pump energy. As the small signal gain measurement set up is difficult to align consistently for the various wedge angles, fluorescence measurements are taken instead to assess the performance of the wedge angles.
Experimental set-up for fluorescence measurements consist of the laser module followed by interference filters at 1064 or 946nm to detect the desired wavelengths, long wave pass filters to block the pump wavelength at 808nm, neutral density filters, and a PIN detector. The fluorescence as a function of pump energy was measured using a digitizing signal analyzer which took a statistical average of 32 shots to reduce noise. As the pump energy was increased, a flattening at the peak of the fluorescence curve was observed for the 946nm transition as seen in Figure 2-19. This indicates the depletion of the upper level population by an internal loss mechanism such as ASE or parasitic lasing.
Figure 2-19 Fluorescence data for a 10mm diameter, 1% Nd:YAG disk with 2 degree wedge and 169mJ of pump energy in 2mm octagonal area.

Figure 2-20 Fluorescence data for a 10mm diameter, 1% Nd:YAG disk with 2 degree wedge and 273mJ of pump energy in 2mm octagonal area.
Figure 2-21 illustrates the improved performance of the larger wedge angles. Since the clamping of the fluorescence intensity at high pump densities is a symptom of internal losses in the crystal, the delay in the clamping of the fluorescence intensity with the largest wedge angle (7 degrees) indicates a reduction in losses. Although initial designs called for a Nd:YAG disk with 2 minute opposing wedges, all data is taken using disks fabricated with a 2 degree wedge on one side. Subsequent designs will employ disks with larger wedges.

![Figure 2-21 Fluorescence measurements at 946nm for disks with various wedge angles.](image)
2.2.5 Samarium doped glass cladding

Although the use of a 10mm diameter disk instead of a 4mm diameter rod eliminated the parasitic lasing as seen in Figure 2-16, at higher pump densities inversion losses caused by the 1064nm transition recur. As seen from the flattening of the gain curve in Figure 2-22, small signal gain measurements at high pump densities provided with a 30 bar stack and a 2mm pump spot size still indicate the presence parasitic lasing. To further reduce the 1064nm feedback into the mode volume, the laser disk was inserted into a Samarium (Sm) doped glass cladding which absorbs the 1064nm radiation. In addition to preventing parasitic oscillation, the Sm doped cladding also reduces the number of possible total internally reflected ASE paths traveling back into the pump volume where they can get further amplified.

![Graph](image_url)

Figure 2-22 946nm gain data for 4mm long 1% Nd:YAG pumped with 2mm octagonal lens duct and 30 bar stack.
With an absorption coefficient of 100m⁻¹ at 1064nm, the 10% Sm doped, 3.56mm thick cladding around the laser medium absorbs approximately 30% of the 1064 radiation before it is fed back into the pump volume. Introducing this additional loss hinders the parasitic oscillation of the 1064 radiation across the barrel of the laser disk.

In addition to absorption, by reducing the number of passes of the 1064nm radiation through the pump volume, this configuration also prevents the undesired 1064nm radiation from being further amplified and reducing the 946nm upper level laser population. A ray trace of two identical spontaneous emission paths in a disk with and
without the Sm doped cladding in Figure 2-25 illustrates the reduction in the number of total internal reflections in the disk with a Sm doped cladding. The 100 micron thick index matching fluid with n=1.63 is matched to the indices of the Nd:YAG (n_{1064}=1.82) and the Sm glass (n_{1064}=1.56) to minimize the Fresnel reflection of the 1064nm radiation back into the mode volume and to maximize the critical angle requirement the at the interfaces. The critical angle at which the 1064nm radiation can achieve the unwanted TIR at the Nd:YAG/air interface is increased from 33.3 degrees to 63.6 degrees at the Nd:YAG/index matching fluid interface. This increased critical angle requirement reduces the number of ASE paths traveling through the pump volume. Furthermore, the rays that propagate into the Sm cladding now must enter the Sm clad/air boundary at an angle of incidence larger than 40 degrees to meet the TIR condition. Thus, the number of possible ASE and parasitic lasing paths that get fed back into the pump volume are reduced with the use of the Sm doped glass cladding.

The improvement in the upper level population density available for the 946nm transition was verified in small signal gain and fluorescence measurements taken with the Sm doped cladding around the disk. As seen in Figure 2-26, the clamping of the small signal gain curve in Figure 2-22 without the Sm cladding is eliminated with the use of the Sm cladding.
Figure 2-25 Ray trace of a possible ASE path through the disk via TIR with and without Sm cladding.

Figure 2-26 Small signal gain data for a 1% doped 4mm long Nd:YAG disk inserted in a 10% Sm doped cladding and pumped with a 2mm beam diameter and 30 bar stack.
Fluorescence measurements at 946nm and 1064nm also indicate that the internal loss mechanisms at 1064nm under high pump energy densities are reduced significantly with the use of the highly absorbing Sm cladding. At 946nm, the fluorescence curve exhibits a flattening similar to that of the small signal gain measurements under equivalent pump densities. As seen in Figure 2-27, the losses indicated by the change in the slope of the fluorescence curve is removed by the implementation of the Sm cladding. Meanwhile, in Figure 2-28, which shows the 1064nm fluorescence for an identical configuration, the sharply rising curve, indicating a large amount of ASE, is tamed to an exponential growth with the use of the Sm doped cladding. The reduction in the 1064nm activity in the laser material aids the inversion available for the 946nm transition.

To conclude, the Sm cladding indeed succeeds in reducing the undesirable amplification of the 1064nm radiation, improving the population inversion for the 946nm transition. In chapter 4, it will be shown that although antireflection coatings and wedges alone are sufficient to obtain an efficient oscillator operating in the normal mode, the Sm doped cladding is invaluable in improving the storage efficiency in the Q-switched mode.
Figure 2-27 Fluorescence measurements at 946nm with and without Sm doped glass cladding on 4mm long disk with 2 degree wedge.

Figure 2-28 Fluorescence measurements at 1064nm with and without Sm doped glass cladding on 4mm long disk with 2 degree wedge.
2.3 System requirements

As mentioned in the introduction, the laser wavelength is dictated by the atmospheric water vapor absorption lines. With a transition that overlaps the desired wavelength and an absorption band that matches the available 808nm diode array technology, Nd:YAG is the choice of laser material.

High energy output requirement drives the cavity mode to be as large as possible. Although most existing systems employ TEM$_{00}$ mode diameters under 1mm, a relatively large TEM$_{00}$ mode diameter is necessary for high energy extraction while maintaining good beam quality. Since the stacked diode array technology provides sufficient pump energy needed to overcome the reabsorption losses, a large mode diameter is feasible in this case. The mode volume is defined by the resonator length and mirrors, which are selected to obtain a large TEM$_{00}$ mode diameter in the laser crystal. In accordance with Gaussian propagation equations [Koechner, 1999], a highly reflecting end mirror with a 10m radius placed 1m away from a flat output coupler provides a 1.96mm TEM$_{00}$ mode diameter in the laser crystal (Figure 2-29).
As discussed previously in section 2.1, the pump volume must match the mode volume as closely as possible to obtain the highest possible beam overlap efficiency. Consequently, the resonator design with a 1.96mm mode diameter dictates the use of a circular pump spot with a diameter in the order of 2mm. For optimum results, the pump beam must have a low divergence, remaining within the boundaries of the mode volume as it propagates in the laser crystal. Collecting the pump output in a relatively uniform spot size is also critical, as hot spots tend to induce damage in optical coatings.

In addition to improving the laser efficiency, closely matched pump and mode volumes also prevent the higher order transverse modes from oscillating. The TEM$_{00}$ mode oscillation is especially desirable for this system, since efficient injection seeding requires strong transverse mode discrimination in the oscillator [Kedmi, J., 1981]. The
use of a relatively large pump beam also aids in the reduction of thermal lensing, as the focal length of the thermal lens is directly proportional to the pump beam area.

Next chapter will describe how the pump diode array output is shaped to meet these pump beam requirements before it is coupled into the laser crystal. The challenge with the stacked diode technology is to efficiently focus the highly divergent, large active area output of the arrays into the small volume necessary for end pumping with a uniform intensity distribution. Large and fast lenses necessary to collect and focus an extended pump source of this size yield very short depth of focus and highly aberrant intensity distributions. Following chapter discusses the non-imaging concentrator used for this purpose.
3 PUMP SOURCE COUPLING

In this chapter the optical coupling scheme that meets the pump beam requirements discussed in chapter 2 is presented. Each component in the pump module from the diode active area to the lens duct is modeled and analyzed using Optical Research Associates’ Light Tools optical design software. The ray trace model is used to optimize the transmission efficiency of the optical pump components. Pump beam parameters needed as input for the laser model developed in Chapter 2, including power, wavelength, and intensity distribution, are experimentally characterized. The ray trace model is also used to predict other uncertain parameters that are difficult to measure accurately, such as pump beam diameter and divergence in the laser crystal. The overall coupling efficiency and spatial distribution of the pump beam are thoroughly characterized.

As mentioned in Chapter 2, for optimum efficiency and good beam quality, the pump volume must be matched to the mode volume as closely as possible. Consequently, an optical coupling scheme that focuses the 10mm by 24mm emitting area of the diode array stack into approximately a 1.96mm diameter circular area is necessary. The design must achieve this pump size with a high transmission efficiency, low beam divergence, and a well behaved intensity distribution. Since the distribution of the resonator TEM\textsubscript{00} mode peaks at its center, a pump intensity, which also peaks at its center, is desirable for higher efficiency.

The required 2mm pump size from an extended source of this order is difficult to achieve using conventional simple lenses. The highly divergent and astigmatic nature of
diode array stack necessitates the use of aspheric and anamorphic optical elements to minimize astigmatism and spherical aberration [Shannon, D. C. et al., 1991]. Moreover, diverging rays from the off axis points of the extended diode array source spread transversely in the focal plane, resulting in an undesirably large image size which is proportional to the focal length of the system and the angular subtense from the source. Although this implies minimizing the focal length may reduce the pump size, lenses with short focal lengths in general yield highly aberrant images.

Section 3.1 briefly describes the microlens and lens duct combination used for the pump beam coupling. Section 3.2 presents the spectral, spatial, and power output data for the pump diode array stack. Section 3.3 characterizes the transmission efficiency and the spatial output of the lens duct. The ray trace model is applied to further analyze and understand the effect of various lens duct parameters on the transmission efficiency, including the radius of curvature, length, microlens alignment, and compression ratio. The intensity distribution of the lens duct output is presented.
3.1 **Optical pump configuration**

The pump beam requirements are achieved by using a combination of micro lenses and a lens duct. Each 1 cm long diode bar is microlensed to collimate the highly diverging fast axis diode array output before it is coupled into the lens duct. In actuality, the microlenses are fibers aligned parallel to the diode bars. The fibers effectively act as cylindrical collimating lenses placed at a focal length away from the bars.

The microlensed diode stack is followed by a fused silica lens duct whose input surface is matched to the rectangular emitting area of the diode array stack. Since the duct with a rectangular input aperture is difficult to fabricate with a circular output, which is necessary to match the mode volume, it is tapered on 8 sides, terminating in the shape of an octagon (Figure 3-1). The octagonal pump spot is well matched to the mode volume whose diameter is equal to the circle that circumscribes the octagonal output face.

The curved input surface of the lens duct alone is not sufficient to focus the extended diode array source onto a small pump area. The sides of the lens duct are canted such that the lens duct effectively collects the radiation that would otherwise arrive outside the required pump beam size. The canted surfaces of the lens duct guide the off axis diverging rays from the diode via TIR (Figure 3-2). The total internal reflection from the sides of the lens duct combined with the focusing power of the curved entrance surface yields a uniformly illuminated pump area.
Figure 3-1 Light Tools model of the microlensed diode arrays followed by a lens duct.

Figure 3-2 TIR off the canted surfaces of the lens duct redirects the off axis ray bundles to the pump spot.
3.2 Diode array stack characterization

Although initially water (impingement) cooled, 50Watt, 25 GaAlAs diode array bar stack from OptoPower was used at the early phases of the project, the available pump energy was barely enough to reach the 946nm laser threshold. Consequently, a 30 bar stack from Coherent Inc was procured. The upgraded 30 bar stack provides a much higher pump density in a very similar package by employing 100 Watt bars instead of 50 Watt bars. In this section we will define the spectral and spatial performance of the 30 bar diode array stack.

3.2.1 Wavelength

The GaAlAs diode arrays emit in the vicinity of 808nm where Nd:YAG exhibits relatively strong absorption features (Figure 3-3). Since the exact emission wavelength is a function of the diode temperature, the conductively cooled diode array stack spectral output is controlled using a Thermo-Electric Cooler (TEC). Spectral measurements of the diode output show the emission from 30 individual bars peaking around 805nm at 28 degrees. During alignment, the optimum absorption is experimentally verified by manually tuning the temperature of the TEC for maximum absorption in a 4mm long Nd:YAG crystal. The dip in the detected pump energy transmitted through the laser crystal in Figure 3–4 shows that the absorption of the pump beam is optimized at a diode temperature of 28 degrees. Measured absorption efficiency with respect to the 200mJ of incident pump energy is 87%.
Figure 3-3 Nd:YAG absorption features [Barnes, N. P. et al., 1990].

Figure 3-4 Pump beam transmission through 4mm long 1% Nd:YAG disk as a function of diode temperature.
3.2.2 Power

Although diode array bars can be spaced as close as 300 microns apart at moderate average powers [Lacovara], in this application, the use of the 600 micron thick microlenses limits the bar to bar spacing to 800 microns. With thirty 100 Watt bars, the pump diode array stack provides a total of 3000 Watts of pump power in an emitting area of 23.2mm by 10mm. Operating at 1 Hertz with 160 msec pulse width, this translates to $3000 \text{ W} \times 160 \times 10^{-6} \text{sec} = 480 \text{ mJ}$ of pump energy in the pulsed mode.

After the addition of microlenses to collimate the fast axis of each diode array, the output power is reduced by approximately 20%, providing 2400 Watts of pump power or 384mJ of pump energy in the pulsed mode at 1 Hz. Although the diode arrays are rated for operation with up to 100 Amps of drive current, during experiments the maximum drive current was limited to 80 Amps to prolong their operating lifetime. Data in Figure 3-5 shows the output power of both the 25 and 30 bar stacks as a function of the drive current operating at 1Hz.

![Figure 3-5 Output energies of the Coherent 30 bar and OptoPower 25 bar stacks.](image)
3.2.3 Diode array divergence

The diode array bars emit into 13 degrees (FWHM) in the slow axis and 40 (FWHM) degrees in the fast axis. Figure 3-7 a) illustrates the individual diode bar output with a 13 by 40 degree diverging output. In order to contain the pump beam in the lens duct via TIR, the highly diverging fast axis output from each diode array bar is nearly collimated using 600 micron diameter fibers placed at a focal length away from the bars. This drops the fast axis divergence of the microlensed diode array from 40 degrees to 3 degrees, which is illustrated in Figure 3-7 b).

Maintaining a low incident beam divergence at the lens duct is critical. The lower divergence input allows the pump beam to propagate further in the lens duct before it fails to meet TIR condition at the sides of the lens duct. Leakage occurs when the incident angle of the rays at the slanted surfaces exceeds the critical angle requirement of 42.5 degrees (Figure 3-6).

![Ray path for a 1.5 degree and 20 degree incident angles at the lens duct.](image)

Figure 3-6 Ray path for a 1.5 degree and 20 degree incident angles at the lens duct.
Figure 3-7 Diode array output intensity distribution models a) before microlenses, b) after microlenses.
3.3 Lens duct output characterization

Although theoretically the lens duct was designed to achieve larger than 90% transmission, experimental results were quite lower. In this section, we identify the parameters that affect the lens duct performance in efforts to optimize its efficiency. Table 3-1 lists the lens duct variables and their values.

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<th>Value</th>
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<td>Radius of Curvature</td>
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<td>Output aperture</td>
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</table>

Table 3-1 Lens duct specifications.

3.3.1 Transmission efficiency

Although the transmission efficiency is dependent on obvious lens duct parameters such as the material index, surface curvature, length, and entrance to exit surface aperture compression ratio, the microlens alignment with respect to the diode array bars is also found to be highly critical in maximizing the lens duct transmission. Following is an investigation of the lens duct transmission efficiency with respect to these lens duct parameters. A ray trace model created using Light Tools is used for the analysis.

In the model, the 40 by 13 degree diverging output from each individual diode array bar is collimated in one axis with 600 micron diameter fibers. The lens duct input surface with a 25mm radius is placed 1mm away from the microlenses. Both input and
output surfaces are antireflection coated with a single quarter wave layer of MgF₂ at 808nm. The model assumes 1 Watt of output power per diode array bar, and runs a Monte Carlo ray trace simulation of approximately 150,000 rays. By calculating the actual number of rays that arrive at a detector, whose diameter circumscribes the octagonal lens duct output, the transmission is calculated.

3.3.1.1 Radius of curvature

The diverging output of the diode array stack is collected and coupled into the laser crystal using a lens duct, a tapered fused silica wave guide fabricated with a spherical entrance surface. The radiation from the 23.2mm by 10mm emission area of the diodes is captured by a 25mm by 11mm entrance aperture of the lens duct, placed at less than 1mm away. Furthermore, a 25mm radius of curvature which matches the height of the diode array stack is fabricated for additional collecting power [Beach, R. J., 1996]. Although smaller radii provide shorter focal lengths with smaller spot sizes, the minimum radius is limited to one half of the diode array height, where the rays fail to intercept the lens duct at the edges. Radii that fall between half the diode height and the full diode height yield undesirably high angles of incidences at the edges of the lens duct. This reduces the coupling efficiency since the performance of antireflection coatings at a specified wavelength drops with the angle of incidence. The maximum angle of incidence at the lens duct with the current design is 18.8 degrees, and both the input and output surfaces are AR coated at 808nm.
3.3.1.2 Length

Given the 25mm radius, the length of the lens duct is set to match approximately the focal length given by

\[ f = R \left( \frac{n}{n-1} \right) \]  

Hence, for an index of 1.48 in silica and a 25mm radius, the length must be in the vicinity of 80mm. Ideally the tightest waist of the pump beam should be placed at the center of the laser rod. However, since the location of the best focus is dependent on the aberrations originating from the first surface of the lens duct, the optimum length is fine-tuned to 73.8mm by tracing rays for maximum transmission. Figure 3-8 shows the transmission results for various lens duct lengths.

Figure 3-8 Lens duct transmission efficiency as a function of lens duct length for a 2mm octagon.
3.3.1.3 Microlens alignment

At the earlier stages of the project, the 946nm threshold was barely reached using a 25 bar stack composed of 50 Watt bars. During this phase, the inefficient coupling of the pump energy through the lens duct lead to the discovery of a defect in the microlens alignment. The measured output energy of the 25 bar stack before and after the lens duct with a 2.5mm octagonal output is plotted in Figure 3-9 as a function of the pump diode array current. This data yields an experimentally measured, unexpectedly low transmission of 66%. Ray trace models were used to further investigate the lens duct transmission as a function of the microlens alignment.

Figure 3-9 Output energy measurements for the 25 bar stack diode array with and without the lens duct indicate 66% transmission.
The model simulates perfectly parallel microlenses and diode bars, and misaligned microlenses that are tilted by 0.5 degrees with respect to the bars. Figure 3-10 and Figure 3-11 display the calculated encircled energy as a function of aperture radius at the 2.5mm octagonal exit surface of the lens duct. The drop in the predicted 96% transmission for the aligned microlenses to 47% for the misaligned configuration validates the alignment sensitivity of the microlenses with respect to the bars. The encircled energy simulations are repeated for misalignments varying from zero to 0.75 degrees, and the respective drop in the transmission is charted in Figure 3-12. The actual misalignment values can be extrapolated from this graph. The experimentally measured transmission of 66% suggests a misalignment in the vicinity of 0.4 degrees.
Figure 3-10  Encircled energy at the 2.5mm octagonal output aperture of the lens duct as a function of radius with a 25 bar stack with no tilt.

Figure 3-11  Encircled energy at the 2.5mm octagonal output aperture of the lens duct as a function of radius with 0.5 degree misaligned microlenses.
Figure 3-12 Lens duct transmission of the 25 bar stack for various microlens tilt angles.

<table>
<thead>
<tr>
<th></th>
<th>25 bar stack, 2.5mm octagon, NO TILT</th>
<th>25 bar stack, 2.5mm octagon, 0.4° TILT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Transmission</td>
<td>96%</td>
<td>66%</td>
</tr>
<tr>
<td>Experimental Transmission</td>
<td>-----------</td>
<td>66%</td>
</tr>
</tbody>
</table>

Table 3-2 Experimental and theoretical lens duct transmission for the 25 bar stack.

Given the fabrication and mounting process for the microlensed diode array stack, a slight misalignment of the microlenses with respect to the bars is highly possible. Grooves of the same approximate depth and width of the bars and microlenses are fabricated concurrently on their respective individual monolithic substrates [Karpinski, A., 1996]. After the bars and microlenses are dropped into their respective slots, the entire microlens module is aligned and mounted as a unit with respect to the diode substrate. During the mounting process the entire microlens unit may be tilted with respect to the diode bars. A lateral translation of the microlenses with respect to the bars
is also possible. Either configuration will result in reduced transmission efficiency. A close up photo (Figure 3-16) of the 25 bar microlensed diode array stack under a weak current shows tilted microlenses with respect to the bars. A similar picture of the 30 bar stack (Figure 3-17) shows a much more accurate alignment.

Tilted microlenses effectively translate to higher divergent ray bundles exiting the microlens. The lateral displacement caused by the tilt, which is proportional to the sine of the tilt angle, transforms the on axis source into an off axis source from which the rays are deflected at angle with respect to the optical axis of the microlens. Figure 3-13 illustrates the difference in ray paths from an on axis point source (A) and an off axis point source (B). Although still nearly collimated, the deflected rays from the off axis source enter the lens duct at higher incident angles, failing to meet the TIR conditions in the lens duct prematurely (Figure 3-14 and Figure 3-15).

![Figure 3-13 Microlens and diode array bar misalignment configuration.](image-url)
Figure 3-14 Divergence as a function of the diode tilt with respect to the microlenses  
a) No tilt, b) 0.5 degree tilt, c) 1 degree tilt.

Figure 3-15 Ray trace of a single diode array bar followed by a microlens with a) no tilt 
and b) 0.5 degree tilt.
Figure 3-16  OptoPower 25 bar stack.

Figure 3-17  Coherent 30 bar stack.
3.3.1.4 Compression ratio

The compression ratio of the lens duct is the ratio of the input aperture area to the output area. As the compression ratio is increased with smaller output apertures, the taper of the lens duct gets steeper. Hence, the transmission efficiency drops due to the increased angles of incidence at the canted surfaces, failing to meet TIR requirements. As seen in Figure 3-18, the model predicts a sharp drop in transmission for output apertures less than 2mm.

![Graph](image)

Figure 3-18 Lens duct transmission for various octagonal output aperture sizes.
Experimental measurements yield a transmission of 75% for the 2mm and 81% for the 2.5mm octagonal output surface. These results are below the model’s predictions of 94.6% for the 2mm octagonal output, and 96% for the 2.5mm octagonal output. As seen in section 3.3.1.3, the discrepancy between the model and measured values can be attributed to the presence of a slight misalignment in the microlenses. In addition to positioning errors in the actual set up, the losses are speculated to stem from a possible misalignment defect of the microlenses with respect to the diode bars. Following is a chart of the theoretical transmission of a lens duct for a range of microlens tilt angles in both a 2mm and 2.5mm octagonal output. The amount of tilt for the 30 bar stack can be extrapolated from this chart. To obtain 75% transmission through the 2mm octagon, the microlenses must have a 0.2 degree tilt with respect to the diode bars. Concomitantly, the 0.2 degree tilt also corresponds to approximately 85% transmission in the 2.5mm octagon according to the model. This agrees well with the experimental result of 81%.

![Theoretical transmission curves for the 2mm and 2.5mm octagonal output surfaces as a function of microlens tilt.](image)

Figure 3-19 Theoretical transmission curves for the 2mm and 2.5mm octagonal output surfaces as a function of microlens tilt.
<table>
<thead>
<tr>
<th></th>
<th>30 bar stack, 2.5mm octagon</th>
<th>30 bar stack, 2mm octagon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Lens Duct Transmission</td>
<td>96 %</td>
<td>94.6%</td>
</tr>
<tr>
<td>Experimental Lens Duct Transmission</td>
<td>81%</td>
<td>75%</td>
</tr>
<tr>
<td>Microlens Transmission</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>TOTAL Pump Optics Efficiency</td>
<td>65%</td>
<td>60%</td>
</tr>
</tbody>
</table>

Table 3-3 Pump optics transmission efficiencies.

Given the small difference in efficiency for the 2mm and 2.5mm pump beam sizes, the 2mm spot is preferred because of its proximity to the actual TEM\(_{00}\) mode radius. In section 4.3.1, the spatial output beam quality for both pump spot sizes are provided. Closely matched pump and mode diameters also yield higher system efficiency and prevent high order transverse modes from oscillating.
Figure 3-21 Output energy measurements for a 2mm octagonal output aperture with a 30 bar stack yield 75% transmission.

Figure 3-20 Output energy measurements for a 2.5mm octagonal output aperture with a 30 bar stack yield 81% transmission.
3.3.2 Spatial output

The divergence exiting the lens duct conforms to the following etendue invariance law in 2D space [Welford, W. T.].

\[ A_{LD} \sin^2(\theta_{in}) = A_{out} \sin^2(\theta_{out}) \]

Accordingly, the half beam divergence is expected to be roughly 32 degrees at the output of the lens duct. This is verified using the Light Tools ray trace model. Figure 3-22 from the Light Tools model indicates a half divergence angle in air of approximately 34 degrees.

![Figure 3-22 Lens duct output divergence in air.](image)

Due to the high index of Nd:YAG (n=1.82), the angle of incidence in the disk drops to approximately 12 degrees in accordance with Snell's law. Figure 3-23 obtained from the
model predicts an average pump diameter of 1.15mm across the rod length. This value will be used for the laser model developed in chapter 2.

![Graph showing beam radius as a function of distance](image)

**Figure 3-23** Lens duct output beam radius in the Nd:YAG disk as a function of distance.

The ray trace model indicates a minimum spot located at 1mm away from the lens duct. This agrees well with experimental data in which the output energy peaks for a disk placed at approximately 0.8mm away from the lens duct (Figure 3-24). This also can be verified in the intensity distribution diagrams. A close look at the irradiances in the line profiles of the pump beam in Figure 3-27 also indicates a maximum irradiance at about 1mm away from the lens duct.

Figure 3-26, Figure 3-27 and Figure 3-28 show the uniform pump beam intensity distribution at the immediate exit surface of the lens duct. As the beam propagates, it begins to resemble a gaussian distribution function.
Figure 3-24 946nm laser output energy with 174mJ pump energy as a function of rod position from lens duct, (2mm pump, 4mm disk, 82.5%OC, 10mHR).

The integrated distribution of the pump beam in the laser rod can be observed in the small signal gain profile, since the pump distribution imprints itself onto the gain profile. The small signal gain distribution across the diameter of the 4mm long rod in Figure 3-25 exhibits a smoothly tapered intensity profile whose peak is at its center.

Figure 3-25 Small signal gain profile across a 4mm long Nd:YAG disk.
Figure 3-26 Measured 2-D and linear profiles of the pump beam intensity in air at 1mm increment distances from the lens duct.
Figure 3-27 Predicted 2-D and linear profiles of the pump beam intensity in the Nd:YAG disk at 1mm increment distances from the lens duct.
Figure 3-28 Predicted 2-D and linear profiles of the pump beam intensity in air at 1mm increment distances from the lens duct.
4 LASER PERFORMANCE

The theoretical model and small signal gain measurements developed in chapter 2 indicate optimum performance using a 4mm long, 10mm diameter, 1% Nd:YAG disk in a folded resonator. In this chapter, actual laser performance data for this configuration is presented to validate the model, and to refine other variables in the oscillator design. Specifically, the design trade-offs for various output coupler reflectivities, end mirror curvatures, and pump diameters are investigated. These parameters are optimized to obtain the maximum amount of energy in a TEM\textsubscript{00} beam. Experimental results agree reasonably well with the theoretical model developed in Chapter 2.

In section 4.1 the normal mode operation is analyzed and compared to the model predictions. The slope efficiency and threshold pump energy for various output couplers are investigated. The cavity losses for the optimum configuration are extrapolated using Findley's approach and compared to the model estimates. Section 4.2 presents the Q-switched performance while section 4.3 investigates the output beam quality for various resonator configurations.
4.1 Normal mode operation

4.1.1 Output coupler reflectivity optimization

Although losses due to scatter, absorption, and diffraction are inevitable, the loss from the partially transmitting mirror, which provides the energy available as output, is a variable that needs to be optimized. Between zero reflection where the laser fails to meet the threshold and 100% reflection where there is no useful output, there exists an optimum reflectivity value for the output coupler. Figure 4-1, obtained by charting equation 2.20 as a function of output coupler reflectivity, shows the variation in the laser output energy for maximum pump energy available (273mJ). The results show a relatively broad range of optimum reflectivities that provide high output energies, ranging from approximately 80% to 92%.

![Figure 4-1 Theoretical and measured output energy vs output coupler reflectivity at the maximum available pump energy (273mJ) for a 4mm long 1% Nd:YAG disk pumped with a 2mm octagonal pump diameter.](image)
To validate the model predictions, the normal mode laser performance for various output couplers is obtained. The experimental efficiency curves for available output couplers with 73, 82.5, 92, and 96 % reflectivities are collectively graphed in Figure 4-2. The measured peak output energy for each output coupler is overlapped with the model predictions in Figure 4-1 for comparison. Results show that for the available output couplers, highest output energy at room temperature is obtained using the 82.5% output coupler reflector. The theoretical model consistently predicts peak output energies slightly above the experimental results for all the output couplers. The following paragraph offers a possible explanation for the deviation of the experimental data from the theoretical model as seen in Figure 4-1.

Figure 4-2 Output energy and slope efficiencies for various output coupler reflectivities.
A close look at the slope efficiencies in Figure 4-2 reveals a slight flattening of the slopes at the peak pump density. For example, for the 82.5% output coupler, the slope efficiency at mid-level pump energy in the 150-170mJ region is 29.3%, whereas at the maximum available pump energy, it drops to 24%. A possible explanation for this drop in the efficiency at high pump densities could be Excited State Absorption (ESA) at the pump wavelength. An investigation of ESA in Nd:YAG shows a transition from the metastable state in the vicinity of the pump wavelength [Zeidle, G. et al., 1968]. It is possible that at high pump densities the ESA losses adversely affects the laser performance and reduce the slope efficiency in a nonlinear manner [Powell, R. C., 1998]. Another possible explanation for the high end non-linearity could be heating of the laser diode array at high drive currents. A temperature rise in the diode arrays may shift the emission center wavelength, causing a drop in the absorption efficiency.

Another close look at the curves in Figure 4-2 also reveals steeper slopes at mid-level pump densities than the slopes near the threshold region. For example, the 29.3% slope efficiency for the 82.5% output coupler in the 150-170mJ pump region drops to 18.5% between the first two data points near the threshold. This gradual increase in the slope efficiency with higher pump densities can be attributed to reduced reabsorption losses at high pump densities. As mentioned in chapter 2, reabsorption losses saturate with increased intracavity energy, improving the laser efficiency at higher pump densities. The effect of the reabsorption losses is most apparent at the threshold region where the intracavity photon number is minimal. Another possible explanation for the improved slope efficiency at higher pump densities could be the improved storage
efficiency. As seen in equation 2.19, the output energy is proportional to the pump pulse width, $t_p$. However, to be more accurate, the output energy is proportional to $t_p - t_0$, where $t_0$ is the time interval required for pumping to reach threshold (see Figure 4-3). Thus, as the laser is pumped harder, $t_0$ shrinks, improving the overall storage efficiency of the laser.

![Graph](image)

Figure 4-3 Normal mode temporal output.

Given these variations in the slope efficiency for the available incident pump energies, the best fit to the experimental data is not linear, but a 3rd order polynomial. Figure 4-4 displays the 3rd order polynomial fit to the data associated with the optimum 82.5% output coupler reflectivity.
Figure 4-4 Theoretical and experimental laser output at room temperature (300K) for a 82.5% output coupler, 10m end mirror, and 4mm long 1% Nd:YAG disk pumped with a 2mm octagonal spot size.

The theoretical curve for an identical configuration is overlapped with the polynomial fit to the experimental data in Figure 4-4. Although linear, the 25% theoretical slope efficiency for the 82.5% output coupler is in close agreement with the 26% slope of the linear fit to the experimental results. Table 4-1 lists the calculated efficiency factors that lead to the 25% optical and 13% electrical slope efficiencies with respect to the incident pump energy for this configuration operating at 1 Hz.
<table>
<thead>
<tr>
<th>PROCESS</th>
<th>SYMBOL</th>
<th>VALUE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode Slope Efficiency</td>
<td>$\eta_d$</td>
<td>0.50</td>
<td>Vendor</td>
</tr>
<tr>
<td>Pump Optics Efficiency</td>
<td>$\eta_o$</td>
<td>0.60</td>
<td>Table 3.2</td>
</tr>
<tr>
<td>Absorption Efficiency</td>
<td>$\eta_a$</td>
<td>0.77</td>
<td>Equation 2.10</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>$\eta_q$</td>
<td>0.95</td>
<td>Koechner</td>
</tr>
<tr>
<td>Storage Efficiency</td>
<td>$\eta_s$</td>
<td>0.72</td>
<td>Equation 2.13</td>
</tr>
<tr>
<td>Photon Efficiency</td>
<td>$\eta_p$</td>
<td>0.85</td>
<td>Equation 2.12</td>
</tr>
<tr>
<td>Beam Overlap Efficiency</td>
<td>$\eta_b$</td>
<td>0.74</td>
<td>Equation 2.11</td>
</tr>
<tr>
<td>Coupling Efficiency</td>
<td>$\eta_c$</td>
<td>0.80</td>
<td>Equation 2.20</td>
</tr>
<tr>
<td>Optical Slope Efficiency</td>
<td>$\sigma_s$</td>
<td>0.16</td>
<td>Equation 2.19</td>
</tr>
<tr>
<td>Electrical Slope Efficiency</td>
<td>$\sigma_e$</td>
<td>0.08</td>
<td>$\eta_d\sigma_s$</td>
</tr>
</tbody>
</table>

Table 4-1 Energy transfer process efficiencies.

Meanwhile, the theoretical threshold energy of 37mJ is in good agreement with the measured 42mJ of threshold pump energy. As seen in Figure 4-5, the model predicts threshold pump energies slightly below the experimental values for all output couplers. This minor difference can be attributed to measurement errors, and/or additional cavity losses that the model does not take into account.
Figure 4-5 Theoretical and experimental threshold pump energy values for various output coupler reflectivities using a 4mm long 1% Nd:YAG pumped with a 2mm diameter beam.

4.1.2 Cavity losses

The actual losses in the laser can be extrapolated from the experimental data. Following Findley’s approach, the pump energies required to reach threshold for the available output couplers are charted in Figure 4-6 as a function of -\( \ln(R_2) \). The slope and y intercept of the linear fit of the experimental data yield measured values for the efficiency parameter \( \eta \) and the losses respectively. This information can be used to verify the efficiency factors and the resonator losses used in the theoretical model.
Extrapolating the efficiency factor, \( \eta \), from the slope of the linear fit requires the following derivation. Since the laser threshold energy is proportional to the rate at which the ions are excited to the upper energy level, the small signal gain from equation 2.7 in Chapter 2 can be described in terms of the threshold pump energy from equation 2.16.

![Graph showing the relationship between threshold pump energy and output coupler losses.](image)

**Figure 4-6** Experimental threshold pump energy data plotted as a function of the output coupler losses.

\[
g_o = (F_1 + F_2)\sigma \cdot \left( \frac{\eta \cdot E_{th}}{h \cdot \nu_p \cdot t_p \cdot \nu} \right) - \sigma \cdot F_1 \cdot N
\]

4.1

Hence, the round trip gain, which equals the losses at threshold, can be traced as a function of the threshold pump energy [Koechner].

\[
4g_o L = \text{loss} = 4K E_{th}
\]

4.2

where

\[
\text{loss} = -\ln(R_2) - \ln(R_1) - 2\ln(R_3) + 4\alpha L + L_{\text{reab}}
\]

4.3
\[ L_{\text{reab}}(T) = 4 \cdot L \cdot F_1(T) \cdot N \cdot \sigma \]  \hspace{1cm} 4.4

and

\[ K = \left( \frac{(F_1 + F_2) \cdot L \cdot \sigma \cdot \tau \cdot \eta}{h \cdot \nu_p \cdot t_p \cdot V} \right) \]  \hspace{1cm} 4.5

Since the slope of the curve is equal to \( 4K \), equation 4.5 can be solved for \( \eta \) given the rest of the variables in \( K \) are relatively well defined. The measured \( \eta \) can then be used as a benchmark from which the theoretical values of the uncertain efficiency factors can be adjusted. Since \( \eta_p \) and \( \eta_q \) are well defined, and \( \eta_a \) is calculated with reasonable accuracy, the beam overlap efficiency \( \eta_b \) is the uncertain variable that can be adjusted to greater accuracy. Accordingly the pump radius used in the theoretical models is fined tuned to 1.15mm.

Extrapolating the cavity losses from the y intercept is simpler. For an unpumped cavity \((E_{\text{th}}=0)\), the system round trip losses excluding the output coupling loses are equal to the y intercept where

\[ \ln(R_2) = -\ln(R_1) - 2 \ln(R_3) + 4 \cdot \alpha \cdot L_{\text{reab}} \]  \hspace{1cm} 4.6

Note that the measured value includes reabsorption losses. Accordingly, the experimental data from Figure 4-6 indicates a round trip loss of 18% in the resonator. This value is slightly higher than the estimates used in the theoretical model, which predicts a 10% reabsorption loss in addition to the 2% internal losses for a total of 12%.

In addition to measurement errors and uncertain variable values, there is another factor that can account for difference in the measured and predicted losses in the
resonator. Additional ground state reabsorption losses due to elevated temperatures in the pump volume can also raise the round trip losses in the cavity.

The ground state reabsorption loss is a function of the laser rod temperature. Figure 4-7 illustrates the significant rise in reabsorption losses at elevated temperatures. At high pump densities the rod temperature rises, increasing the ground state population density responsible for the reabsorption losses in the laser crystal. This increase in the ground state population density raises the pump energy required to reach threshold (Figure 4-8).

![Figure 4-7 Reabsorption losses as a function of laser rod temperature.](image)

Figure 4-7 Reabsorption losses as a function of laser rod temperature.
Figure 4-8 Threshold pump energy for a range of temperatures in a 4mm long 1% Nd:YAG rod pumped with a 2mm beam diameter.

If Boltzmann’s equations are manipulated to match the measured threshold pump energy values with the theoretical predictions, results indicate a 25K degree temperature rise in the laser crystal. Figure 4-9 shows the shift in the predicted threshold pump values for a rod temperature of 325K instead of 300K. The threshold pump energies from the model and experiments now overlap. Furthermore, the theoretical losses including reabsorption losses at 325K grow to 16% which is closer to the 18% losses that were extrapolated using Findley’s method in Figure 4-6.
Figure 4-9 Experimental and theoretical laser threshold energies at elevated temperature for various output couplers, 10m end mirror, and 4mm long 1% Nd:YAG disk pumped with a 2mm octagonal spot size.

Given the mounting scheme of the crystal, which lacks a cooling mechanism, the temperature increase is highly possible. The localized, intense heat distribution in end pumped disks leads to highly non-uniform and complex temperature profiles [Cousins, A. K., 1992], [Weber, R. et al., 1998]. Although originally the laser disk was wrapped in indium foil and inserted into a copper mount for good thermal contact, gain measurements with the Indium, as seen in Figure 4-10, indicate clamping of the population inversion. It is suspected that the reflecting indium foil around the barrel supports the parasitic oscillation of the 1064nm radiation. Consequently, the disk is
suspended in air by a three point kinematic mount that provides minimal thermal management (Figure 4-11).

Figure 4-10 Small signal gain measurements for a 3mm long, 1.4% Nd:YAG disk with and without indium foil around the barrel.

Figure 4-11 Kinematic mounting scheme holding the Nd:YAG disk.
4.2 Q-switched operation

In the normal mode operation, the clamping of the gain at the loss level prevents the population inversion from reaching the high inversion densities possible with the available pump energy. However, the introduction of high losses associated with the closing of the Q-switch allows the population inversion to reach extremely high levels in the Q-switched mode, far exceeding the inversion in the normal mode. This creates a tremendous energy storage problem. At the high inversion densities achieved in the Q-switched mode, ASE and parasitic lasing at the 1064nm transition depletes the inversion available for the 946nm transition. This is very apparent in Figure 4-13 and Figure 4-14 where the output energy of the q-switched oscillator clamps at a given pump energy due to parasitic lasing in the laser disk.

The experimental Q-switched and normal mode energy outputs as a function of incident pump energy for both 82.5% and 73% reflective output couplers are plotted in Figure 4-13 and Figure 4-14. The results are given for a 1 Hz operation of a 4mm long 1% Nd:YAG laser rod pumped by a 2mm octagonal spot. The normal mode output with an acousto-optic Q-switch is degraded slightly due to insertion losses for both output couplers. The q-switched output clamps at 16mJ and 10mJ for the 82.5% and 73% output couplers respectively. The energy clamping occurs sooner at 10mJ for the lower reflectivity of 73% due to the higher population inversion attained to meet the higher intracavity losses. The additional inversion allows the undesirable amplified spontaneous emission at 1064nm to build up and deplete the population inversion available for the 946nm transition. Figure 4-12 shows the temporal output of the q-
switched oscillator employing the 82.5% output coupler. The output pulse width is 124 nsec at full width half maximum.

Figure 4-12 Temporal output of the Q-switched laser for a 82.5% output coupler.

As seen in the small signal gain measurements in chapter 2, the parasitic lasing, can be eliminated with the use of a cladding that absorbs the 1064nm radiation. Indeed, when the disk is inserted into a 10% Sm doped glass tube, the storage efficiency improves and the clamping of the Q-switched energy output is eliminated for both output couplers.
Figure 4-13 Laser output energy as a function of incident pump energy on the rod for 2mm octagonal lens duct exit aperture and 73% output coupler reflectivity.

Figure 4-14 Laser output energy as a function of incident pump energy on the rod for 2mm octagonal lens duct exit aperture and 82.5% output coupler reflectivity.
Although the Sm doped cladding eliminates parasitic lasing, it doesn’t alleviate the ASE losses completely. The significant drop in the slope efficiency for the q-switched operation compared to that of the normal mode operation indicates the presence of significant ASE losses in the disk. The extremely high inversions achieved in the q-switched mode prior to the opening of the Q-switch contribute to the exponential growth of ASE at 1064nm. These ASE losses depopulate the stored energy in the upper laser level and reduce the efficiency of the laser by $\eta_{\text{ex}}$. In the case of the 82.5% output coupler, the slope efficiency is reduced from 26% to 11%, corresponding to an extraction efficiency $\eta_{\text{ex}}$ of 43%.

The inversion densities that can be achieved at the available pump energies for both transitions are plotted in Figure 4-15. For the 946nm transition, starting from equation 2.6, the inversion density at threshold is calculated using

$$\Delta N_{946}(E_p) = \int_0^L \int_0^H ((F_1 + F_2) \cdot R(E_p) \cdot \tau \cdot r_p(r, z) - N_{10}) \cdot I_0(r, z) \cdot 2 \cdot \pi \cdot r \cdot dr \cdot dz$$  \hspace{1cm} 4.7

where

$$R(E_p) = \frac{E_p \cdot h \cdot v \cdot t_p}{\eta}$$  \hspace{1cm} 4.8

The corresponding inversion density for the 1064nm transition is given by

$$\Delta N_{1064}(E_p) = \int_0^L \int_0^H Z_{1064} \cdot R(E_p) \cdot \tau \cdot r_p(r, z) \cdot I_0(r, z) \cdot 2 \cdot \pi \cdot r \cdot dr \cdot dz$$  \hspace{1cm} 4.9

The inversion density for the 946nm transition in the normal mode is clamped at the threshold value of $2.17 \times 10^{24} \text{m}^{-3}$ calculated by using

$$\Delta N_{\text{th}} = \frac{\text{loss}}{4 \cdot L \cdot \sigma}$$  \hspace{1cm} 4.10
This corresponds to a comparable upper level population of $2.0 \times 10^{24} \text{ m}^{-3}$ for the 1064nm transition at the threshold of the 946nm oscillation.

![Inversion densities of the 946nm and the 1064nm transitions for a range of available pump energies.](image)

Figure 4-15 Inversion densities of the 946nm and the 1064nm transitions for a range of available pump energies.

Consequently, using the inversion densities at the 946nm oscillation threshold, the single pass gains given by

$$G_{946}(E_p) = \exp(\Delta N_{946}(E_p) \cdot \sigma \cdot L)$$  \hspace{1cm} 4.11

$$G_{1064}(E_p) = \exp(\Delta N_{1064}(E_p) \cdot \sigma_{1064} \cdot L)$$  \hspace{1cm} 4.12

remain comparable at 1.06 and 1.69 for the 946nm and 1064nm transitions respectively.

The horizontal line in Figure 4-15 marks the level at which the inversion density clamps for both wavelengths during the normal mode operation. However, it is also apparent
that although the inversion densities clamp at a low value in the normal mode, the high losses in the Q-switched mode can drive the inversion densities to much higher levels. Consequently, the 1064nm population inversion density can go as high as $\Delta N_{1064}=1.5 \times 10^{25} \text{ m}^{-3}$ in the Q-switched mode. This corresponds to a single pass gain of $G_{1064}=45$. Compared to the 1064nm gain of 1.69 at the threshold of the 946nm normal mode oscillation, this is significantly high and difficult to suppress from being spontaneously amplified.

![Graph showing single pass gain at 946nm and 1064nm for available pump energies.](image)

Figure 4-16 Single pass gain at 946nm and 1064nm for the available pump energies.

To conclude, for higher efficiency operation in the Q-switched mode, the design must further reduce the ASE losses at the 1064nm transition. Approaches to improve the extraction efficiency are presented in Chapter 5.
4.3 Beam quality

4.3.1 Pump spot size

As discussed in chapter 3, the efficiency of the lens duct improves with smaller concentration ratio. In this section the trade off between the improved pump coupling efficiency of a larger pump diameter, and the higher pump density of a smaller pump diameter are investigated.

Specifically, the laser output performance of a 4mm long disk pumped with a 2mm is compared to the performance with a 2.5mm pump diameter. The output energy for a 2.5mm octagonal pump spot is plotted as a function of the incident pump energy in Figure 4-17. The normal mode and Q-switched slope efficiencies for the 2.5mm pump diameter drop only slightly when compared to the results for the 2mm pump diameter. However, the beam quality for both pump sizes is quite different. A donut shaped output beam profile is obtained using the 2.5mm octagonal pump spot (Figure 4-19). The inverted medium between the 1.96mm TEM\(_{00}\) mode diameter and the 2.5mm pump diameter allows high order transverse mode oscillation, possibly a combination of TEM\(_{01}\) and TEM\(_{10}\) in the resonator. On the contrary, as seen in Figure 4-18, the 2mm octagonal pump area provides a well behaved TEM\(_{00}\) gaussian output beam profile which is necessary for efficient injection seeding.
Figure 4-17  Normal mode and Q-switched output energy for a 4mm long, 1% Nd:YAG disk pumped with a 2.5mm octagonal spot diameter.
Figure 4-18 946nm laser output spatial profile when pumped with a 2.5mm octagonal pump spot (82.5% OC, 10m HR, 4mm long 1% Nd:YAG disk, 80A).

Figure 4-19 946nm laser output spatial profile when pumped with a 2mm octagonal pump spot (82.5% OC, 10m HR, 4mm long 1% Nd:YAG disk, 80A).
4.3.2 End mirror radius of curvature

The beam quality and output energy for various end mirror curvatures are investigated for a 2mm pump diameter. Figure 4-20 charts the 946nm laser output energy for end mirror radii of curvatures ranging from 1m to 10m in the resonator. Although the output energy for these various end mirror curvatures remains comparable, the output beam quality is affected significantly. As the radius of curvature of the end mirror is decreased, the beam waist in the laser crystal shrinks, allowing higher transverse modes within the pump volume to oscillate. Table 4-2 lists the $M^2$ values for various highly reflecting end mirror curvatures used in the Q-switched mode. The $M^2$ values are calculated using

$$M^2 = \pi w_o w_f / \lambda$$

4.13

after measuring the near field beam radius $w_o$, and the far field beam radius $w_f$ using a 1m focal length lens.

![Figure 4-20](image.png)

Figure 4-20 Output energies for various end mirror curvatures using a 4mm long Nd:YAG disk pumped with a 2mm spot size.
Table 4-2  Beam quality measurements for various end mirror curvatures.

<table>
<thead>
<tr>
<th>HR Mirror Radius</th>
<th>10m</th>
<th>5m</th>
<th>2m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Diameter (mm)</td>
<td>1.65</td>
<td>1.52</td>
<td>1.22</td>
</tr>
<tr>
<td>Beam Dia @ f=1m</td>
<td>0.78</td>
<td>0.97</td>
<td>1.46</td>
</tr>
<tr>
<td>Beam Quality</td>
<td>1.07</td>
<td>1.22</td>
<td>1.48</td>
</tr>
</tbody>
</table>

In the normal mode operation, the optimum configuration with a 10m highly reflecting mirror and 82.5% reflective output coupler, yields a measured $M_2$ value of 1.06. Thus, for a 2mm beam waist the divergence of the Gaussian, TEM$_{00}$ laser output is calculated to be approximately 0.65 mrad using the following equation [Koechner].

$$\theta = \frac{M^2 \cdot 1.27 \cdot \lambda}{w_o}$$  \hspace{1cm} 4.14

To summarize, highest output energy in a TEM$_{00}$ mode is obtained using an 82.5% output coupler. An end mirror with a 10m radius of curvature supports a mode volume that is well matched to the 2mm pump diameter, providing good beam quality in a TEM$_{00}$ mode.
5 SUMMARY AND CONCLUSIONS

We have demonstrated highest output energy to date for a normal mode and Q-switched 946nm oscillator operating at room temperature. Although there is still room for further improvement, issues associated with quasi-four-level operation of Nd doped materials have been identified, and solutions that address these issues have been applied successfully.

This information can be applied to the future adaptation of other host materials doped with Nd. Host materials whose spectroscopic parameters are optimized for quasi-four-level laser operation of Nd could further improve the laser performance. For instance, a material with a larger splitting of the ground state manifold will have a smaller ground state population, reducing the reabsorption losses at the laser wavelength. A lower stimulated emission cross section ratio ($\sigma_{1064}/\sigma_{946}$) will aid in the reduction of the ASE losses and improve the storage efficiency needed for the q-switched operation. Research and development in search of such a host is ongoing, however, in the mean time the existing design may be further improved in the following areas.

The major issues are ASE and ground state absorption. Given the system requirements, the next phase of the design must reduce ASE losses at the 1064nm to improve the storage efficiency and Q-switched operation. The ground state absorption may also be reduced further to lower the energy required to reach threshold. Furthermore, the pump coupling efficiency can be improved to increase slope efficiency, and the pump density can be raised for higher output energy.
In this chapter we present suggestions for future work to improve oscillator efficiency and increase output power. An approach to demonstrate energy scalability is also presented.

5.1 Amplified spontaneous emission losses

This is the most difficult, yet most important task in trying to improve the q-switched oscillator performance. As seen in chapter 4, although the Sm doped cladding eliminates parasitic lasing at 1064nm, the Q-switching efficiency is still severely degraded by ASE losses in the mode volume at 1064nm.

We have implemented designs that reduce ASE tremendously. Optimum pump architectures and rod geometries are defined and reviewed in chapter 2. We began with a 4mm diameter rod, modified it to a 10mm diameter disk, and then added a cladding around the barrel. Figure 5-1 illustrates and summarizes the improvement in the ASE losses for these design options. As the ASE losses grow with the number of paths traveling in the pump volume, ray trace models can be used to estimate the relative amount of ASE in the mode volume for various configurations. A Monte Carlo simulation of 50,000 rays was run, using a cylindrical volume emitting into a sphere to model the spontaneous emission in the pumped volume. The first plot was obtained by modeling the 4mm diameter rod with a Lambertian scattering barrel simulating a roughly ground surface. In the second plot, the diameter is increased to 10mm with the same scattering properties around the barrel. Ultimately, the final configuration is modeled by applying a Sm doped cladding around the disk. A close look at the irradiances indicate a 60% drop in the number of passes through the center of the pump volume for a disk when
compared to a rod. Another 70% reduction is seen after the addition of Sm doped cladding around the disk. As a matter of fact, the addition of a Sm doped cladding brings the irradiance level to that of the source representing the pump volume. Thus, it can be concluded that the Sm doped cladding minimizes the feedback of the spontaneous emission into the pump volume, and that the design at this point is limited by single pass ASE losses at 1064nm.

Figure 5-1 ASE analysis results for a) 4mm diameter rod, b) 10mm diameter disk, c) 10mm diameter disk with Sm doped cladding.
For further improvement, other ideas geared to further deflect the ASE reflections away from the mode volume were also investigated. Two options that were analyzed include increasing the wedge angle, and diffusion bonding Sm doped YAG at one end of the rod. With an absorption coefficient of 0.05 mm\(^{-1}\) at 1064nm, Sm doped YAG could further absorb the 1064nm fluorescence, and also aid the walk-off of ASE paths by lengthening the rod. In agreement with the previous ray trace analysis, the models indicate negligible improvement for the implementation of the wedge and diffusion bonded ends.

Since the rod geometry seems optimized, and at this point the only improvements that can be made is in the dielectric coatings. With a 5% reflection at both laser disk surfaces and a 2% reflection at the lens duct exit surface, ASE at 1064nm still can get amplified slightly. The 2% feedback into the pump volume from the lens duct surface can be reduced further with the use of W coatings optimized for two wavelengths. Current coatings utilize V coatings designed for single wavelength of 808nm, leaving a residual reflectivity of 2% at 1064nm. On the other hand, the dielectric coatings on the rod were already specified for minimum reflection at 1064nm.

The ray trace analysis this rod geometry suggests that the feedback from the rod/air interfaces is insignificant, and that ASE is single pass gain-length product limited in the pump volume. Reducing the dopant concentration or shortening the rod length might be viable options.
5.2 Reabsorption losses

Given the 10Hz repetition rate requirement, it is inevitable that the laser material will experience increased ground state population due to elevated temperatures. The lower laser level thermal population responsible for the reabsorption losses can be reduced by cooling the laser material. As discussed in chapter 4, the temperature rise in the laser crystal raises the pump energy required to reach threshold due to the increased lower level thermal population. Figure 5-2 illustrates the improved laser output energy with the cooling of the laser material.

Furthermore, in addition to reducing the lower level population of the 946nm transition, cooling the rod also reduces the thermal occupation factor \( (F_2_{1064}) \) of the upper level of the 1064nm transition. The reduced inversion at 1064nm will further alleviate the ASE losses encountered during the Q-switched operation. To conclude, as the laser repetition rate is ramped up to meet system requirements, a cooling scheme will have to be integrated around the laser disk to prevent subsequent temperature rise in the crystal.

![Figure 5-2 Output energy as a function of rod temperature.](image)
5.3 Beam quality requirement

In order to meet the high energy and low beam divergence requirements, a TEM\(_{00}\) mode with a diameter as large as possible was selected. This placed very stringent requirements on the pump size, which was achieved using microlensed diode bars with a lens duct. The lens duct parameters were optimized for maximum transmission efficiency using ray trace models in chapter 3.

With the aid of the models, it was concluded that the pump beam coupling efficiency is limited by the accuracy of the microlens alignment. Although theoretically up to 96% transmission efficiency is feasible for a 2mm octagonal pump diameter, only 80% has been demonstrated in the lab prototypes. For better alignment accuracy, each bar may be mounted and aligned individually, however this approach is very labor intensive and costly.

5.4 High energy requirement

In chapter 2, we showed the necessity for high pump densities to reach threshold in quasi-four-level lasers with significant ground state population. We also discuss the improved ground state absorption at high pump densities due to saturation. Higher output energies are feasible with the application of higher pump densities. This can be achieved by employing pump diode array stacks composed of more bars followed by a larger lens duct input aperture, more bars mounted with a tighter spacing, or bars with higher peak power. Stacking additional bars with the same spacing will require the redesign of the lens duct whose transmission might drop due to the steeper angles on the canted surfaces. Mounting more bars with a tighter spacing might give rise to thermal issues and
complicate the mounting of smaller microlenses. Higher peak power per bar option might be feasible due to the recent availability of 500W bars.

5.4.1 Energy scalability

As discussed in Chapter 1, although a single oscillator with 50mJ output might be sufficient for airborne lidar measurements, a transmitter with an energy output of 500mJ is necessary for space borne applications. A design concept for the high energy laser transmitter to be used for space based lidar applications is sketched in Figure 5-3. In order to reach the energy requirements, several laser modules can be stacked consecutively in a single resonator.

![Figure 5-3 Design concept for energy scalability.](image)

Once the Q-switched operation is improved, the oscillator will be injection seeded to meet the linewidth requirements. Other space application issues include the replacement of the index matching fluid with optical adhesive between the cladding and the laser disk.
5.5 Conclusion

The advantages of the solid state 946nm laser developed herein are substantial in terms of the development of the science and the importance of the system applications. It is hoped that this work will lead to the deployment of a satellite based DIAL system operating at 946nm in the near future.
APPENDIX A: DERIVATION OF ENERGY LEVEL RATE EQUATIONS

Following is the derivation of the space resolved rate equations 2.2 and 2.3 with respect to the upper and lower laser levels (N₂ and N₁) starting from the manifold populations (N_up and N_low). Table 2.1 gives the laser parameter descriptions and values.

Rate equation for UPPER MANIFOLD is given by

\[
\frac{dN_{\text{up}}}{dt} = \frac{R \cdot r_p(r, z) - N_{\text{up}}}{\tau} - N_{\text{up}} \cdot \sigma_{\text{eff}} \cdot \Phi \cdot l_0(r, z) \cdot \frac{c}{n} + N_{\text{low}} \cdot \sigma_{\text{eff}} \cdot \Phi \cdot l_0(r, z) \cdot \frac{c}{n}
\]

\( \sigma_{\text{eff}} \) from the upper level (F₂*\( \sigma_{R1-ZS} \)) ≠ \( \sigma_{\text{eff}} \) from the lower level (F₁*\( \sigma_{R1-ZS} \))

Since N₂=F₂ N_up,

\[
\frac{dN_2}{dt} = F_2 \cdot R \cdot r_p(r, z) - \frac{F_2 \cdot N_{\text{up}}}{\tau} - F_2 \cdot N_{\text{up}} \cdot F_2 \cdot \sigma_{R1-ZS} \cdot \Phi \cdot l_0(r, z) \cdot \frac{c}{n} +
\]

Substituting N=N_up+N_low
\[
\frac{dN_2}{dt} = F_2 \cdot R \cdot r_p (r,z) - \frac{N_2}{\tau} + F_2 \cdot (N - N_{\text{up}}) \cdot F_1 \cdot \sigma_{\text{R1-Z5}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n} \\
- F_2 \cdot N_2 \cdot \sigma_{\text{R1-Z5}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n}
\]

and \( N_1 = F_1 \cdot N_{\text{low}} \)

\[
\frac{dN_2}{dt} = F_2 \cdot R \cdot r_p (r,z) - \frac{N_2}{\tau} - (F_1 + F_2) \cdot N_2 \cdot \sigma_{\text{R1-Z5}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n} + \\
N_{\text{low}} \cdot F_2 \cdot \sigma_{\text{R1-Z5}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n}
\]

Note that \( \sigma_{\text{R1-Z5}} = \sigma_{\text{eff}} / F_2 = 3.75 \times 10^{-24} \text{ m}^2 / 0.612 = 6.13 \times 10^{-24} \text{ m}^2 \) is the stimulated emission cross section, \( \sigma_{\text{R1-Z5}} \), not the effective stimulated emission cross section.

Rate equation for the LOWER MANIFOLD is given by

\[
\frac{dN_{\text{low}}}{dt} = -R \cdot r_p (r,z) + \frac{N_{\text{up}}}{\tau} + N_{\text{up}} \cdot \sigma_{\text{eff}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n} - N_{\text{low}} \cdot \sigma_{\text{eff}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n}
\]

Substituting \( N = N_{\text{up}} + N_{\text{low}} \), \( N_2 = F_2 \cdot N_{\text{up}} \), and \( N_1 = F_1 \cdot N_{\text{low}} \) into the above lower manifold rate equality, equation 2.3 for the lower level is derived.

\[
\frac{dN_1}{dt} = -F_1 \cdot R \cdot r_p (r,z) + \frac{F_1 \cdot N_{\text{up}}}{\tau} + F_1 \cdot N_{\text{up}} \cdot F_2 \cdot \sigma_{\text{R1-Z5}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n} - \\
F_1 \cdot N_{\text{low}} \cdot F_1 \cdot \sigma_{\text{R1-Z5}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n}
\]

\[
\frac{dN_1}{dt} = -F_1 \cdot R \cdot r_p (r,z) + \frac{F_1 \cdot (N - N_{\text{low}})}{\tau} + F_1 \cdot (N - N_{\text{low}}) \cdot F_2 \cdot \sigma_{\text{R1-Z5}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n} - \\
F_1 \cdot N_1 \cdot \sigma_{\text{R1-Z5}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n}
\]

\[
\frac{dN_1}{dt} = -F_1 \cdot R \cdot r_p (r,z) + \frac{N_{\text{low}} - N_1}{\tau} - (F_1 + F_2) \cdot N_1 \cdot \sigma_{\text{R1-Z5}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n} + \\
N_{\text{low}} \cdot F_2 \cdot \sigma_{\text{R1-Z5}} \cdot \Phi \cdot l_o (r,z) \cdot \frac{c}{n}
\]
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