Room temperature and cryogenic Yb:YAG thin disk laser : single crystal and ceramic

Natasa Vretenar

Follow this and additional works at: http://digitalrepository.unm.edu/ose_etds

Recommended Citation
http://digitalrepository.unm.edu/ose_etds/43

This Dissertation is brought to you for free and open access by the Engineering ETDs at UNM Digital Repository. It has been accepted for inclusion in Optical Science and Engineering ETDs by an authorized administrator of UNM Digital Repository. For more information, please contact disc@unm.edu.
This dissertation is approved, and it is acceptable in quality and form for publication:

Approved by the Dissertation Committee:

Ganesh Balakrishnan, Chairperson

Tim Newell

Luke Lester

Sanjay Krishna

Kevin Malloy
“Room Temperature and Cryogenic Yb:YAG Thin Disk Laser: Single Crystal and Ceramic”

by

Nataša Vretenar

B.S. Optical Engineering (1997), University of Arizona

MBA (2001), University of New Mexico (UNM)

M.Sc. Optical Science and Engineering (2003), UNM

DISSERTATION
Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy
Optical Science and Engineering

The University of New Mexico
Albuquerque, New Mexico
December 2011
I wish to express my gratitude to my research advisor Dr. Tim Newell (AFRL) for his guidance, insight and constant support throughout my Ph.D. research. I humbly acknowledge the support provided to me by the members of my dissertation committee: Dr. Ganesh Balakrishnan, Dr. Sanjay Krishna, Dr. Luke Lester, and Dr. Kevin Malloy. I am also eternally grateful to the members of my research team for their kind help and stimulating interactions. I would like to thank Dr. Ahmed Lobad for teaching me how to run the labs and Dr. Phillip Peterson for many fruitful discussions regarding theoretical modeling of our complicated systems. Furthermore, I would like to thank Lieutenant Carson, Mr. Tim Lucas, Mr. Mark Revak and Dr. Pete Latham for all of their support, hard work and dedication to the project.

I would also like to thank Dr. Howard Schlossberg and Center of Excellence for supporting me on the Grant Title: "High Power Lasers" AFOSR Award No. FA9550-10-1-0463.
“Room Temperature and Cryogenic Yb:YAG Thin Disk Laser: Single Crystal and Ceramic”

by

Nataša Vretenar

B.S. Optical Engineering (1997), University of Arizona

MBA (2001), University of New Mexico (UNM)

M.Sc. Optical Science and Engineering (2003), UNM

DISSERTATION
Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy
Optical Science and Engineering

The University of New Mexico
Albuquerque, New Mexico
December 2011
Abstract

The focus of this dissertation is to design, optimize and build an efficient high power multi kilowatt thin-disk laser system. We improve the thin-disk beam quality by eliminating thermally induced lensing and disk bowing. The characteristics and performance of a ceramic and single crystal Yb:YAG thin disk (TD) lasers are analyzed both experimentally and theoretically. We perform these experiments at room and at cryogenic temperatures. Novel composite substrate materials are explored for thermal management. Thermal and stress computations are modeled in detail using the finite element analysis COMSOL software. Geometrical and physical optics models, employing ZEMAX and other numerical techniques, are used to evaluate beam quality. Theoretical modeling results are combined to further explain physical mechanisms that influence a high power output laser beam. An analytical amplified spontaneous emission (ASE) model in thin-disk laser is developed. Experimental data includes: thermal measurements of thin-disk and output couplers; small signal gain; wavefront; spectrum; lifetime and fluorescence measurements.

Most importantly, for the first time, thin-disk laser performance at room and cryogenic temperatures using a novel two phase boiling cooling system is investigated. Our unique setup allows us to directly compare the same material
performance at these two temperatures. Our cryogenic results show that operating the laser as a four level system could be the key in achieving very high output power with less complicated system since there is a higher cross-section, and a fewer number of pump bounces is required. Thin-disks for cryogenic operation do not have to be as thin, which also makes it easier to manufacture them.

Techniques developed in these experiments are of fundamental importance in future work related to high power solid state lasers; material science, particularly ceramic lasers, and composite materials manufacturing; and cryogenic operation lasers. A thorough and detailed design of a high power thin-disk laser supported by experimental data is presented.
Table of Contents

Acknowledgments .......................................................... iii
Abstract ........................................................................... v
List of Figures .................................................................... x
List of Tables ..................................................................... xiv

Chapter 1 Introduction .................................................. 1
  1.1 Motivation for Research ................................................ 1
  1.2 Thin-Disk Laser Concept ............................................... 2
  1.3 Material Overview for the High Power Laser Operation .... 6
  1.4 Cryogenic Thin-Disk Laser Operation ............................. 8
  1.5 Challenges ................................................................. 10
  1.6 Summary ..................................................................... 11

Chapter 2 Experimental Setups ................................. 12
  2.1 Introduction ............................................................... 12
  2.2 Materials ................................................................... 13
    2.2.1 Ytterbium (Yb) Doped Gain Media Characteristics .... 15
    2.2.1.a Lifetime Measurements ....................................... 17
    2.2.1.b Spectroscopic Measurements ................................. 21
    2.2.1.c Gain Measurement ............................................... 27
Chapter 3 Experimental Results ............... 74

3.1 Introduction ................................................................. 74
3.2 Large Thin-Disk Test Platform ........................................... 75
  3.2.1 High Power Operation ................................................. 75
  3.2.2 Thermal Lensing ...................................................... 78
  3.3 Performance Between YAG Capped and Un-capped Yb:YAG Material ...... 81
  3.2.4 The Role of Heat Sinks in the Large Setup ............................ 84
3.3 Small Thin Disk Platform .................................................. 85
  3.3.1 Jet Impingement Cooling .............................................. 86
  3.3.2 R-134A Refrigerant Cooling ........................................ 87
  3.3.3 Liquid Nitrogen Cryogenic Cooling .................................. 95
Chapter 4 Theoretical Analysis

4.1 Introduction................................................................. 107
4.2 COMSOL Modeling......................................................... 108
   4.2.1 Large Thin-Disk Test Platform.................................... 111
   4.2.1.a No Heat Sink Yb:YAG/YAG Assembly.......................... 112
   4.2.1.b Assemblies with SiC, Diamond and Sapphire Heat Sinks ...... 115
   4.2.2 Small Thin-Disk Test Platform.................................... 121
4.3 Analytical Modeling of Amplified Spontaneous Emission ............. 132
4.4 Multi-Pass Thin-Disk Laser Theory.................................... 135
4.5 Beam Quality.................................................................. 136
4.6 Cavity Stability.............................................................. 139
4.7 Beam Divergence............................................................ 142
4.8 Summary......................................................................... 145

Chapter 5 Conclusion......................................................... 147

Appendices..................................................................... 152
   A Fused silica rod specifications............................................. 152
   B Versadisk Laser Information............................................. 153

List of References........................................................... 154
List of Figures

Figure 1 Thin-disk laser concept .......................................................... 4
Figure 2 Pump chamber back view and cross sectional view ....................... 5
Figure 3 Konoshima ceramics SEM image ............................................ 15
Figure 4 Energy levels of Yb$^{3+}$ ............................................................ 16
Figure 5 Lifetime measurement with a pinhole and in transmission .............. 18
Figure 6 Lifetime measurement in reflection with a pinhole ....................... 19
Figure 7 Lifetime measurement, cryogenic and room temperature .............. 20
Figure 8 Raytheon ceramics absorption and emission spectra ................. 21
Figure 9 Konoshima 200 micron 9.8 % doping absorption spectra ............. 22
Figure 10 Cryogenic single crystal spectra ........................................... 23
Figure 11 Zero phonon line at cryogenic temperature; single crystal and ceramics ..................................................................................... 24
Figure 12 Ceramics spectra at room and cryogenic temperatures .............. 25
Figure 13 Lasing spectra on and off axis R-134a ................................... 26
Figure 14 Reference beam used for gain measurement ............................ 27
Figure 15 Experimental gain at cryogenic and room temperatures for small test platform .................................................................. 28
Figure 16 Room temperature computed and experimental gain ................ 29
Figure 17 Thin-disk assembly .................................................................. 31
Figure 18 Precision Photonics AR coating design ................................ 33
Figure 19 Precision Photonics HR coating for 1030 and 941 nm ................ 34
Figure 20 Two ceramic disks showing different density of scattering centers .... 38
Figure 21 Diode laser pump collimating optics ....................................... 40
Figure 22 One stacked array optics train ............................................... 42
Figure 23 Coupling of diode stacked arrays into one homogenizing rod ........ 43
Figure 24 25 bar laser diode stack ................................................................. 44
Figure 25 Pump chamber large setup .............................................................. 45
Figure 26 Homogenizing rod ......................................................................... 46
Figure 27 Large thin-disk assembly ................................................................. 47
Figure 28 Experimental arrangement large platform a) I cavity, b) V cavity, c) 35 mm mounted assembly ................................................................. 49
Figure 29 Misaligned pump beam .................................................................. 51
Figure 30 Aligned pump beam ....................................................................... 52
Figure 31 Pump beam profile 11 and 18 mm diameter ..................................... 53
Figure 32 Small thin-disk test platform ......................................................... 56
Figure 33 Small jet impingement cooling mounting cap .................................. 58
Figure 34 Aligned pump beam on small jet-impingement cooled platform .... 58
Figure 35 Pumping scheme and cavity configuration (left), experimental setup of a small platform ................................................................................. 60
Figure 36 R134a two phase spray boiling ....................................................... 62
Figure 37 R-134a ESC system performance ................................................... 62
Figure 38 Solid cap mount for R-134a and LN₂ setups .................................. 63
Figure 39 Mounted small thin-disk on RINI cap ........................................... 64
Figure 40 R-134a refrigerant mount assembly .............................................. 65
Figure 41 Pump beam centered on the R-134 thin-disk setup ....................... 66
Figure 42 Cryogenic LN₂ cooling chamber ................................................... 67
Figure 43 Cryogenic ESC performance ......................................................... 68
Figure 44 Pump beam profile on the cryogenic setup ...................................... 69
Figure 45 Laser power and efficiency of I cavity .......................................... 77
Figure 46 Laser power and efficiency of V cavity .......................................... 77
Figure 47 Thermal lensing probe beam setup ............................................... 79
Figure 48 Thermal lensing (jet impingement) ................................................ 80
Figure 49 CFD Simulation for large setup with water jet impingement .......... 81
Figure 50 A comparison of ASE in uncapped and capped assemblies ..........82
Figure 51 Laser output curves for YAG/Yb:YAG and uncapped Yb:YAG samples .................................................................83
Figure 52 ASE in a large disk temperature measurement .........................84
Figure 53 Shift of the pump beam peak with increasing pump power ........85
Figure 54 Water cooled 300W lasing and non-lasing ..........................87
Figure 55 Slope efficiency and laser output power vs. incident pump power at room temperature R-134a cooling .......................................88
Figure 56 Thin-disk wavefront deformation .......................................91
Figure 57 Wavefront measurement at two different pump power levels .....92
Figure 58 CADB bonded YAG-CuW structure ..................................93
Figure 59 Temperature of CADB YAG/CuW surface ..........................94
Figure 60 Laser performance at room and cryogenic temperature ..........96
Figure 61 Slope efficiency at cryogenic temperature ..........................97
Figure 62 Up-converted light diagram ...........................................100
Figure 63 Spectra of the upconverted light .....................................101
Figure 64 Output coupler thermal camera image ................................103
Figure 65 Damaged thin-disk at cryogenic operation ...........................104
Figure 66 Pump power induced laser damage ..................................105
Figure 67 Setup of COMSOL geometry for the large platform. The blue arrow indicates radial symmetry about the solid blue line. .......................112
Figure 68 Water cooled large thin-disk ..........................................113
Figure 69 Water cooled large thin-disk ..........................................114
Figure 70 Temperature of the uncapped and capped disks with SiC heat sink.117
Figure 71 Deformation of the capped (blue) and uncapped (red) thin-disks with SiC heat sinks .........................................................118
Figure 72 Surface temperature across thin-disk for SiC, sapphire and diamond heat sinks .............................................................119
Figure 73 RINI cap views.................................................................122
Figure 74 RINI R-134a with 33 micron Indium solder temperature plot........123
Figure 75 R-134a thermal and structural plot .....................................125
Figure 76 R-134a displacement..........................................................125
Figure 77 RINI stress R-134a (with cap) .............................................127
Figure 78 RINI R-134a stress no cap ...................................................127
Figure 79 LN$_2$ thermal and structural plot ........................................129
Figure 80 LN$_2$ z-displacement ..........................................................130
Figure 81 CADB stress plot at cryogenic temperature .........................131
Figure 82 Stress plot no CADB at cryogenic temperature .................132
Figure 83 I and V cavity configurations...............................................139
Figure 84 Stability of V and I cavities..................................................142
Figure 85 Divergence of the beam .......................................................145
List of Tables

Table 1 Material parameters for Yb:YAG.......................................................... 13
Table 2 Lifetime measurements ........................................................................ 20
Table 3 Material constants.................................................................................... 109
Table 4 CuW and Cu/Diamond material constants............................................. 109
Table 5 Comparison of SiC, diamond and sapphire heat sink materials.......... 119
Table 6 Liquid nitrogen model parameters ........................................................ 127
Table 7 Beam quality values for the thin-disk laser ............................................. 137
Chapter 1 Introduction

1.1 Motivation for Research

Research presented in the following focuses on progress towards designing an optimal high power, multi-kilowatt class, thin-disk laser\(^1\) with a good beam quality (close to diffraction limit). An aircraft mounted system requires a robust, nearly maintenance free setup, with good pointing stability and high wall-plug efficiency. The most important reason for choosing the thin-disk geometry for high power research is that thermal loading is adjacent to the cooled face. This means that the thin-disk can generate tens of kilowatts of power. It is perhaps the only geometry for a solid-state laser that can achieve such high powers. The thin-disk laser is thus interesting for directed energy applications, both commercial – laser welding, and defense related.

There are several requirements for high power directed energy applications. One is the mounting of the system on a mobile platform such as an airplane or a ship. The main disadvantage of the thin-disk is the rather complex optical and power supply system required to achieve multi-pass pumping and efficient pump absorption. Another requirement is the need for laser beams with a high, practically single mode Gaussian, beam quality. Commercially available
thin-disk lasers exhibit poor beam quality and are geared primarily towards laser welding where good beam quality is not crucial for satisfying laser performance. One factor responsible for poor beam quality is the high heat load generated in the YAG media and this is a focus of the following research. The primary cause of heat generation is the quantum defect between the 940nm pump and 1030nm lasing light. In addition, spurious generation of amplified spontaneous emission (ASE) takes place. The fraction of this light that is reabsorbed in the media also generates a heat load.

Finally, excess absorption of light due to multiple causes such as impurities, color-centers, defects in the YAG, grain boundaries in Yb:YAG ceramics, Ytterbium clusters, bonding layers, coating and polishing issues add to the problem. Much of this research was established to investigate methods to remedy these issues.

1.2 Thin-Disk Laser Concept

Typically, thin-disk materials have a small dimension along optical axis in comparison to its transverse extent. The laser gain medium is several hundred microns thick with diameters ranging from several mm to several cm. Since the thickness is small, heat removal is large in this direction on the order of $1\text{ kW/cm}^2$. One face is coated with highly reflecting (HR) coating at both the
pump and laser wavelengths ($\lambda_p = 940$ and $\lambda_l = 1030$ nm), and the opposite surface is coated with a dual antireflection (AR) coating for these wavelengths. The gain medium is cooled on the high reflector coated face. Cooling is either via water jet impingement or two-phase boiling with either liquid nitrogen ($\text{LN}_2$) or R-134a refrigerant. Thin-disk lasers can have an index-of-refraction matching anti-ASE cap attached to the top of the gain medium. The HR coating then forms one mirror of a laser cavity. The output coupler is positioned a free space distance from the Yb:Yag, which completes the laser cavity.

The gain medium is pumped by a high power diode laser either free space coupled or fiber coupled with a wavelength ideally centered at 940 nm. The pump beam impinges on the gain medium at an oblique angle and since only a small amount of pump light is absorbed in the gain medium within one double pass the pump chamber is specially designed to have multiple pump passes through the thin-disk. By using semiconductor diode lasers it is possible to match the emission spectrum of the diode laser to the absorption spectrum of the laser gain medium to achieve higher efficiency and reduce the thermal load on the laser crystal.
The thin-disk setup also allows many different cavity configurations: I, V, or Z cavity shape. Also, other optical components can be easily inserted in the free space between the gain medium and output coupler. Figure 1 shows the basic thin-disk concept, with gain medium size exaggerated with respect to output coupler size and distance from the thin-disk.

The thin-disk laser has a large surface to volume ratio that allows for efficient cooling. However, the axial heat flow causes a thermal and stress lens due to thermally induced change in index-of-refraction. Furthermore, multiple pump beam passes lead to good pump light absorption, low absorption of the laser light, and the ability to produce high pump power density. Consequently, laser output power is scalable with increased pump diameter.
We used two setups: large and small. The small setup consists of a disk with a 14 mm diameter and pump power up to 1 kW. The large setup consists of a disk with diameter 35 mm and pumped up to 15 kW.

Figure 2 depicts the large setup pump chamber. It shows the back view of the pump chamber with a pump beam entrance hole visible, and the location of the thin-disk assembly. The pump beam is directed onto the entrance of the pump chamber via free space relay optics. Figure 2 also shows the cross-section of the pump chamber with prisms coated with HR coating in blue and HR coated parabolic mirror that focuses the light onto a thin-disk in green. Light bounces off the prisms 8 times and makes a double pass through the thin-disk gain medium.

![Figure 2 Pump chamber back view and cross sectional view](image)

Prisms are designed in such a way that they redirect the light onto a parabolic mirror at different angles, allowing that the pump beam is focused onto a thin-disk using a different section of the parabolic mirror upon each reflection.
This distribution of the pump beam reflections effectively reduces the potential damage to the pump chamber optics. Disadvantage of this design is that the pump chamber is heavy, making it difficult to physically move, and cumbersome to align so that a sharp pump profile is on the thin-disk. Furthermore, replacing damaged pump chamber optics proves to be a difficult task in current design configuration for both the small and large platform, due to limited spatial accessibility of individual optical components.

1.3 Material Overview for the High Power Laser Operation

The past 15 years of research\textsuperscript{3} show that Yb\textsuperscript{3+} doped materials are well suited for the design of lasers with extremely high output power (multi-kW). The quantum defect, energy difference between pump photon and laser photon, responsible for the waste heat in the laser crystal is lower for Yb\textsuperscript{3+} than for most other laser active ions. For example, the waste heat in Yb\textsuperscript{3+}-doped materials is a factor of 3 to 6 lower, depending of the host material and the pump wavelength, than that of Nd-doped materials, which is the most commonly used laser active ion other than Yb\textsuperscript{3+}.

Single crystal Yb:YAG thin-disk lasers (TDL) now operate at kW powers with greater than 60\% slope efficiencies and “wall-plug” efficiencies more than 20\%\textsuperscript{4,5}. Thin-disk lasers have reached an exceptional power generation in the
multi-kilowatt levels for single disk resonators and nearly 30 kW for multiple disk resonators since the invention in the early 1990s\textsuperscript{6}. Single crystal materials have produced outstanding results, and ceramic gain mediums are now used as novel materials.

The majority of the gain materials tested here are polycrystalline ceramics. The ceramics manufacturing process has come a long way in the past decade, gaining importance in development of novel solid-state lasers\textsuperscript{7}. Ceramic laser materials offer several advantages over single crystal gain media: they are easier to fabricate (require smaller fabrication facilities and shorter time); larger substrates can be made easier than single crystal; and it is possible to produce multifunctional material with doping process\textsuperscript{8}. Ceramic materials that are highly translucent and exhibit low scattering have been produced using chemical reactions and nano-crystalline powder sintering in vacuum ovens\textsuperscript{9,10}. The advantage of using ceramics is that sintering process can potentially produce large diameter polycrystalline Yb:YAG that can be used for area scaling of single thin-disk high power lasers at a lower cost. Making multifunctional single crystal may not be feasible using the existing manufacturing technology, and doped ceramics could significantly improve the beam quality of the output laser\textsuperscript{11}.

Spectroscopic and laser characteristics of ceramic Yb:YAG are very similar to those of single crystal. Low power laser tests with ceramics have been quite promising with greater than 60\% slope efficiency\textsuperscript{12}. Taira et. al.
demonstrated output power intensity of 3.9 kW/cm² from a composite all-ceramic Yb:Y₃Al₅O₁₂ microchip laser with the maximum thermal stress exceeding twice the tensile strength of single crystal⁷. 6.5kW output power from a single thin-disk ceramic laser is the highest power obtained from a single disk reported to date⁸.

Several interacting physical processes affect the performance of thin-disk laser. The most deleterious effect in designing a high power laser is the heat distribution in the disk. After heating flow and pumping are defined one can move onto laser oscillator analysis and laser performance, even though they are not strictly independent. We describe material properties in detail in Chapter 2.

1.4 Cryogenic Thin-Disk Laser Operation

In order to investigate four level lasing issues, we did cryogenic thin-disk experiments. Operating solid-state laser materials at cryogenic temperature offers many advantages. Rather than listing these improvements we refer the reader to the following literature review and leave detailed discussions to the experimental sections. Our first reference to the literature⁹, concerns with the lasing properties of a relative thick disk of 20% doped Yb:YAG crystal. The maximum fiber coupled pump power was 12W at a wavelength of 970nm with a spot size of 0.4mm. They studied various lasing characteristics over a
temperature range of 80-300K and noted the decrease in threshold and increase in slope efficiency as the temperature decreases. Furthermore, they showed a maximum in the output lasing power at a temperature near 150K for their laser configuration.

The next cryogenic study was a cryogenic Yb:YAG oscillator with a 15mm, 5% doped Yb:YAG crystal sandwiched between two undoped YAG caps maintained near 100K\(^{16}\). A 165W output for an input of 215W gave a slope efficiency of 85%, optical-to-optical efficiency of 76% and a threshold near 22W. Furthermore, same research group returns to a similar configuration to measure a threshold of 50W, an optical-to-optical efficiency of 60%, and a pump power of 500W with a laser output of around 300W. In the intervening years\(^{17}\) a cryogenic sapphire-Yb:YAG sandwich gave a 75W output at a pump power of 106W with an optical-to-optical efficiency of 70% and a slope efficiency of 80%\(^{18}\). In a study initiated in 2007 and continued into subsequent years\(^{19,20}\) multiple cryogenic sapphire sandwiched Yb:YAG disks eventually gave an optical-to-optical efficiency of 42.2% with an output of 963W for an input of 1.871kW\(^{21}\). The introduction of a total-reflection active-mirror (TRAM) Yb:YAG disk sandwiched between a trapezoidal YAG prism and an LN\(_2\) bath gave 275W, and optical-to-optical efficiency of 65%, slope efficiency of 72% at an absorbed power of 450W\(^{22,23,24}\). Finally, we note a paper on cryogenic Yb:YAG 10%-at. doped crystal at high peak and average power\(^{25}\). They obtain 0.5J at a 1kHz rate and in
doing so they measure the small signal gain and show that it rolls over at a pump power of 200-300W for a spot size of 6mm.

1.5 Challenges

The Air Force Research Laboratories (AFRL) has two thin-disk laser laboratories. The large device is impingement water cooled with a diameter of 35 mm and is capable of pump powers up to 15 kW. The smaller disk of diameter 14 mm is either cooled with R-134a refrigerant to 273K, or cooled to temperature near 77K by the liquid nitrogen (LN₂), and pumped up to 1kW. Both devices are burdened with several technical difficulties due to their initial design.

There are several existing technical difficulties in the design of the system. Pump sources are bulky and have low wall-plug efficiency. Both systems have a complex optical setup for multi-pass pumping, and alignment of the entire free space coupled system takes a significant amount of time and manpower. Furthermore, substantial fraction of pump power is converted into heat and TD fracture is possible due to thermal lensing, dust particles and other factors. With the existing large setup it is difficult to achieve robust, maintenance-free operation and good pointing stability.

In spite of the above, we demonstrate high power scaling of Yb:YAG ceramic TDL, and investigate gain saturation, amplified spontaneous emission
(ASE) and thermal lensing contributions at all four different experimental setups: the small setup with three different cooling configurations, and the large setup.

Our experimental results illustrate that polycrystalline Yb:YAG ceramic thin disks exhibit excellent laser characteristics. With further developments in ceramics production disk design, the materials similar to what those tested have strong potential for operation at multi kW output level.

1.6 Summary

The thin-disk concept was illustrated in this chapter. We presented a short history of related research and a literature review regarding up-to-date findings for both room and cryogenic solid-state laser operation. Basic material properties and advantages of operating the laser at cryogenic temperature were briefly explained. We also introduced different experimental setups which will be described in detail in Chapter 2. Furthermore, challenges we faced in our research were presented.
Chapter 2 Experimental Setups

2.1 Introduction

This chapter describes characteristics of the Yb:YAG material, and why it is chosen for our thin-disk gain material, and its advantages for high power laser use. Our experimental lifetime and spectroscopic data is presented for both room temperature and cryogenic performance. Our data was taken for both ceramics and single crystal samples. Non-trivial thin-disk manufacturing process is described – from fabrication of raw materials to a final assembly ready for testing. Furthermore, all the experimental setups are separately described. Four different thin-disk laser experimental setups have been built:

- Large setup with water jet-impingement capable of multi kW operation
- Small setup using 1kW maximum pump power:
  - water jet impingement cooled,
  - R-134a refrigerant cooling system,
  - LN$_2$ cooling system.

Finally, we explain laboratory maintenance duties and introduce experimental procedures.
2.2 Materials

The first step in building a high quality, high power laser is to obtain laser quality raw material. Although almost all laser materials can be operated in a thin-disk design the research on high power thin-disk lasers has been mainly focused on single crystal Yb:YAG - a quasi-three level gain media\textsuperscript{26}. YAG (Yttrium-aluminum-garnet) is the most widely used host material because of its good thermal, optical and mechanical properties. Another material that would be a great thin-disk laser gain medium is Yb:Lutetia. However, this material is not readily available today due to difficulties in fabrication. Table 1 shows the important parameters of Yb:YAG and Yb:Lutetia for comparison.

Table 1 Material parameters for Yb:YAG

<table>
<thead>
<tr>
<th>Material Parameters</th>
<th>Yb:YAG</th>
<th>Yb:Lutetia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump Laser Center Wavelength (nm)</td>
<td>940</td>
<td>976</td>
</tr>
<tr>
<td>Absorption Cross Section, (x10^{-21} cm^2)</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>Maximum Phonon Energy, (cm^{-1})</td>
<td>857</td>
<td>618</td>
</tr>
<tr>
<td>Thermal Conductivity, 3%-Yb (W cm^{-1} K^{-1})</td>
<td>7.1</td>
<td>10.8</td>
</tr>
<tr>
<td>CTE (ppm K^{-1})</td>
<td>7.8</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Computations (identical pump conditions)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Temperature (C\textdegree)</td>
<td>37</td>
<td>27</td>
</tr>
<tr>
<td>Deformation at Top Center (\mu m)</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>\langle F_r \rangle Bottom Surface Radial Stress (Mpa)</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>\langle F_r \rangle Top Surface Radial Stress (Mpa)</td>
<td>0.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>
YAG crystals have been used for more than 50 years and growing process is well established. Therefore, it is easily available and relatively inexpensive. YAG ceramics of laser quality are fairly new, developed within last 10 years. Several different Yb-YAG ceramic and single crystal lasers have been tested in our experiments. Yb:YAG ceramic thin-disks manufactured by the Konoshima Corporation (Japan) and Raytheon (USA) are used. Polycrystalline ceramic is an advance ceramic material, which can be used for laser generation. Researchers have utilized ceramics as a gain medium since 1964. However, only recent advances in ceramic material manufacturing, in the past 10 years, have lead to production of materials with high optical quality and with low percentage of scattering sources (a few % per mm). Figure 3 shows the SEM image of the Yb:YAG ceramic sample. It shows the grain size and structure that consists of grains with different crystal orientations. There are impurities in material, and strong local scattering at grain boundaries have been observed. To improve the laser efficiency and eliminate damage, the source of optical scattering at boundaries has to be eliminated.
Single crystal growth technology is based on a process of melting raw materials and then solidifying them. There is a limited number of materials that can be manufactured this way due to high melting point. This process requires high energy consumption and initial cost, as well as long production times\textsuperscript{30,31,32}. The optical grade ceramics industry is fairly young and promises to create innovative technologies that could produce laser gain materials with properties that could surpass the performance of single crystals lasers.

### 2.2.1 Ytterbium (Yb) Doped Gain Media Characteristics

In a true four level laser medium, the lower laser level is always mostly unpopulated and threshold is reached when the pumping process compensates for cavity losses. However, Yb\textsuperscript{3+} doped system is a quasi three level laser medium at room temperature and exhibits re-absorption at the laser wavelength due to population in the lower laser level. Thus, internal power loss in the
medium is increased and more heat load is introduced in the medium. Figure 4 shows the energy level diagram of an Yb$^{3+}$ ion.

Figure 4 Energy levels of Yb$^{3+}$

The Yb$^{3+}$ lower level is split into 4 levels (Stark splitting). The upper level is split into three levels, including a wide pumping band at 940 nm and a dominant lasing transition at 1030 nm, corresponding to the transition between the $^2F_{5/2}$ and $^2F_{7/2}$ for the Yb$^{3+}$. The simple electronic structure of Yb$^{3+}$ ion avoids or reduces
most of the parasitic effects such as upconversion, cross relaxation or excited-state absorption, which are present in Nd-doped materials. These deleterious effects have two main consequences. First, they increase the thermal load, and, subsequently, the thermal problems, because the main paths of the high-excited state levels are non-radiative. They also modify the gain by inducing strong depopulation of the $^4F_{3/2}$ level implicated in the laser inversion population.

When pumped at 980nm the quantum defect of ytterbium is around 5% compared to 30% for neodymium (in YAG). This is a real benefit for reducing the thermal problems, and, thus to attain very high average powers. Yb-doped materials have a longer lifetime (around 950 µs) allowing for a better storage of the pump energy. Furthermore, the bandwidth of the emission lines is about 9 nm, which is good for femtosecond pulse generation.

We next present spectroscopic data that has to be known to describe a laser. This data includes absorption and emission cross-sections and fluorescence lifetimes.

**2.2.1.a Lifetime Measurements**

Measuring the effective Yb:YAG upper state lifetime, under laser operation and including ASE effects, is important to determine gain and stored energy in the active medium and to further understand the limiting factors for power scaling of thin-disk lasers. Power scaling with increasing pump spot diameter is limited
mainly by ASE; ASE is even more important for pulsed laser operation.

We used three different techniques to measure the lifetime. The reason for this is that we took great care to eliminate radiation re-trapping, since we were able to use only a 25W pump power laser, and as a result our signal was weak.

First, we measured the HR coated thin-disks in a reflection setup with a pinhole method\textsuperscript{38} to consider the radiation trapping effects. Second method was possible with the uncoated Raytheon materials using a transmission setup and a pinhole – see Figure 5. Ultimately, we measured the lifetime using the 50 and 100 micron core fibers directly in our R-134a and cryogenic setups.

The Raytheon material tested is a 1 mm thick, optically polished, and uncoated sample. It is a 10% Yb doped YAG, with a 40 mm diameter.

The pump beam used for lifetime measurement is 915 nm 25W fiber coupled diode laser (Apollo). The lifetime was measured using pinhole sizes 200, 300, 400, 500, 700, 800, 1000, 1500 and 1800 microns. Finally, the pulse was a FWHM 40 microseconds generated by an ILX Lightwave LDX36000 High power

Figure 5 Lifetime measurement with a pinhole and in transmission

18
laser diode current source – up to 40 A to produce 25W. A Wavetek 187 pulse generator was used to trigger the signal.

A pinhole was placed in the mount which allowed to the pinhole to be close to the thin disk without touching the surface of the TD. The thickness of the thin disk assembly with 1 mm cap was 1.2 mm.

![Diagram of laser diode setup](image)

**Figure 6 Lifetime measurement in reflection with a pinhole**

We tested both the ceramic and single crystal gain materials at room and cryogenic temperatures. Our results are listed in Table 2. The differences from sample to sample were within the measurement error of ±50μs. This indicates that there were no major differences in the material quality. The values obtained for the lifetime measurements fit well to known literature data, ranging from 950 to 1100 μs. This data also shows that no significant defects or concentration quenching are present. The data was fit using IGOR software and a simple decaying exponential.
Table 2 Lifetime measurements

<table>
<thead>
<tr>
<th>Material</th>
<th>Room Temperature Lifetime (μs)</th>
<th>Cryogenic Temperature Lifetime (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramics</td>
<td>1014</td>
<td>993</td>
</tr>
<tr>
<td>Single Crystal</td>
<td>1000</td>
<td>881</td>
</tr>
</tbody>
</table>

Figure 7 Shows the measurement of the lifetime for both cryogenic and room temperature. This plot is on a logarithmic scale that we fit with a line using IGOR.

Figure 7 Lifetime measurement, cryogenic and room temperature
2.2.1.b Spectroscopic Measurements

We used a Cary 5E spectrophotometer to measure the absorption spectra of Raytheon and Konoshima materials. Figure 8 shows the absorption and emission spectra of Raytheon ceramics material with thickness 2.16 mm and 10% Yb doping. The absorption spectrum exhibits the same characteristics as Konoshima spectrum of a 200 micron thick sample doped with 9.8% Yb as seen in Figure 9.

![Spectra graph](image)

*Figure 8 Raytheon ceramics absorption and emission spectra*

The spectrum of Konoshima and Raytheon ceramics are comparable to published spectra of single crystal Yb:YAG material doped with approximately 10% Yb$^{3+}$. 
Figure 9 Konoshima 200 micron 9.8 % doping absorption spectra

Figure 10 shows the cryogenic single crystal spectra. This figure is very similar to the cryogenic ceramics spectra, except for the zero phonon line wavelength range. At room temperature, the emission is the typically observed curve with peaks at the 968.8nm (zero phonon line), 1030.2nm and a weaker peak at 1048.4nm. When chilled to 77K the spectra exhibits stronger features and a much wider range in intensity. The zero phonon line (ZPL) at 968nm is particularly interesting. It has intensified and narrowed for a FWHM less than 0.4nm. The ZPL wavelength has shifted down 0.4nm.

Strong emission suppression on both sides of the peak, a characteristic of the homogeneous broadening, is observed. There are also strong increases in emission at 1029nm as well. The cryogenic 1029nm peak is over 10 times larger
than at the room temperature.

**Figure 10 Cryogenic single crystal spectra**

There is a strong dip in the cryogenic emission spectra around the 968nm zero phonon line, indicating a suppression of homogeneous broadening due to the weaker phonon energy. The width of this dip is 8.2nm on both sides of the line, and for ceramic thin-disk the dip is not symmetrical, see Figure 11.
Figure 11 Zero phonon line at cryogenic temperature; single crystal and ceramics

Figure 12 shows the on-axis spontaneous emission when thin-disk is pumped with a low power, 25W, 915nm pump source. No output coupler optic is in place. The material is ceramic Yb:YAG. The initial spectral sweep is taken at room temperature using a fiber probe positioned near to the surface of the disk. The pump is directed at a low incident angle onto the surface. A Yokagawa AQ6319 OSA was used to record the spectra with a 0.2nm resolution. The intensity is quite weak due to poor coupling of the emission into a 50-μm fiber, which is positioned near normal to the surface plane. The disk is subsequently cooled to 77°C and the measurement repeated. The integrated emission curves show that the emission at cryogenic temperatures is 1.8 times greater than the room temperature emission.
Furthermore, we set up the laser cavity in a simple I configuration with an optical coupler in place, and measured the emission of the output laser on and off-axis. In the lasing situation, amplified spontaneous emission (ASE) emitted on-axis, as well as at a high angle (~80°) off of the optical axis of the disk was measured. Light is coupled into a 50µm multimode fiber attached to an Agilent 86146B Optical Spectrum Analyzer. Figure 13 shows the spectra of the output laser measured on axis and at small and large angle off axis.

Figure 12 Ceramics spectra at room and cryogenic temperatures
The emission peaks are amplified and narrowed. Instead of comparing ASE spectra between room and cryogenic cases, which is difficult due to different experimental arrangements, and power levels, we examine the relative differences in the spectra of each. For example, the collection angle of the fiber and its position is similar between the room and cryogenic experiments, but not identical due to a difference in the setup. The pump laser power is 180W giving laser outputs of $P_{77^\circ K} = 72W$, $P_{290^\circ K} = 7W$. The predominant emission is scattered lasing light at 1030nm (1029nm at cryogenic). At $77^\circ K$ there is a strong reduction in emission away from the laser line. The zero-phonon 969nm line is 17.1dBm less than the 1029nm peak while the peak at 1048.8nm is 20.23dBm lower. In contrast at room temperature the 969nm and 1048.8nm peaks are only 4.4dBm and 8.2dBm less than the laser peak intensity.

Figure 13 Lasing spectra on and off axis R-134a
There is a strong reduction in spurious ASE generated when Yb:YAG is behaving as a 4-level laser.

2.2.1.c Gain Measurement

For the gain measurement we used VersaDisk laser. Since the VersaDisk output is centered at 1030 nm, it is possible to utilize it as a probe beam for gain experiments. The power of the probe was kept at 10W. Versadisk output fluctuated, and we used integrating sphere and averaged over 30 measurements during the pump power ramp. Pump power ramp was computer controlled.

Figure 14 Reference beam used for gain measurement

Figure 14 shows the Versadisk laser 1030nm probe beam. The beam was expanded to approximately the same size as the pump beam (18 mm for the large setup and 7 mm for the small setup). Figure 15 shows the experimental gain at cryogenic (blue) and room temperatures (red) vs. input power in Watts.
The system is at transparency near 0W at cryogenic temperature. This graph is for the small test platform experiments.

Figure 15 Experimental gain at cryogenic and room temperatures for small test platform

In the next figure, Figure 16, we show the room temperature computed and experimental gain. The linear plot does not take into account ASE, while the non-linear plot includes ASE and is fitted to the experimental data. Red dots represent experimental data.
Figure 16 Room temperature computed and experimental gain

Figure 16 shows the measured gain along the optical axis in percent versus the input pump power for power less than 3kW. This was measured in a pump probe configuration. The measured gain shows a marked decrease from the linear case, the black line.

A theory of thin-disk gain was derived by Dr. Phil Peterson of our group. This theory is based on rate equations for quasi-three level lasers and takes into account both pump absorption and laser re-absorption. The theory is anchored to experimental data by an effective gain length parameter, S. The gain-length product, gS, models the gain experienced by ASE. ASE strongly detracts from the effective gain.

This exponential like decrease is fit with our transcendental ASE gain equation\(^6^9\), to within 10% up to a gain of about 6%. At this point the measured
gain rolls over into a flat top while our ASE equation just continues. The measured roll over is conjectured to be due to nonlinear processes. This fitting process establishes the gain length $S$ at about 43% of the disk diameter, which is in the expected range.

2.3. Thin Disk Fabrication

The fabrication of the thin disk lasers is not a trivial process. Raw material has to be polished to optical quality on both sides, and to a thickness of 200 microns. When dealing with a thin disk with a large diameter, it becomes a challenge to polish the disk to an excellent optical quality (flatness, parallelism). YAG caps (thickness 0.5 mm to 1 mm) are also polished to high optical quality and coated with the AR coating on one side. The uncoated side of YAG cap is attached to the thin disk laser medium using Chemically Activated Direct Bonding (CADB) technique. The bottom side of the thin disk is coated with HR coating for both 940 and 1030 nm wavelengths. The coatings must have high damage threshold. This assembly is attached using epoxy or indium soldered to the specially designed mount/heat sink. Mounting the disks must take into account thermally and stress induced deformations at high power operation.
Figure 17 Thin-disk assembly

Figure 17 illustrates all the parts/layers that are necessary to fabricate a final thin-disk assembly (photo shown to the right). It is important to note that almost all of the steps in the fabrication process of thin-disks used in this project involved new designs and novel techniques (new ceramics raw materials, polishing, coating and bonding). Several vendors were involved in the fabrication and delivery times to get a final product were quite long. We now describe in detail all the fabrication steps.

2.3.1 Polishing

This is one of the first and most important steps in making the thin-disk. Raw material needs to be polished to a thickness within a few microns throughout the entire diameter of the disk. Thin-disks also need to be polished to low surface roughness, low scratch/dig number indicating minimal surface damage. Furthermore, flatness and parallelism must be excellent. All of these
requirements present a challenge when the substrate is thin with a large
diameter. Precision Photonics processed most of our raw materials. They are
able to polish the disks with <0.05 waves peak to valley over 90% of the clear
aperture, with a wedge angle < 10 arc seconds, 10-5 scratch/dig, and surface
roughness < 10 Å (Angstrom) rms. These requirements are quite tight, but
necessary for a good quality thin-disk laser.

2.3.2 Coating

The coatings used consist of layers of different dielectric materials. The high
reflecting coating needs to reflect more than 99.9% at 1030 nm at 0 to 5 degrees
angle of incidence, since the HR on the thin disk is used as an end mirror of the
resonator. At the same time coating needs to reflect more than 99.5 % of the
pump wavelength 940 nm for 15-50 degrees angle of incidence (AOI). The higher
the reflectivity the better it is for the resonator performance, but one must take
care to not have too many layers and make the coating too thick. If the coating
does not meet these requirements too much heat is generated in the coating and
optical to optical efficiency of the output laser is greatly reduced after 8 double
passes through the crystal. Since 940 and 1030 nm wavelengths are close to
each other it is possible to design a coating with high reflectivity (greater than
99.99%) that covers both wavelengths.
Precision Photonics coated a large number of our disks using the Ion Beam Sputtering (IBS) technology. IBS coatings exhibit low scatter and absorption losses, superior durability and environmental stability (better than conventional and ion-assisted evaporated coatings)\textsuperscript{39}. IBS coating process is automated and produces coatings close to theoretical design, is repeatable from run to run and can produce coatings with $R< 0.05\%$. Internal stress in the coatings is stable over time as well, which makes the disks more durable and easier to clean. Figure 18 shows Precision Photonics’ theoretical design for an AR coating for 1030 nm at 0 deg AOI and 941 nm at 44 deg AOI.

**Figure 18 Precision Photonics AR coating design**
Figure 19 shows a model of a high reflector coating stack designed to be HR at both 941 and 1030 nm (Precision Photonics). An HR coating design centered at 1030nm will shift shorter and be centered at 941nm at 22.5° internal AOI in YAG (this corresponds to ~44deg external AOI).

![Figure 19 Precision Photonics HR coating for 1030 and 941 nm](image)

Coatings for the relay optics and free space coupling and reflecting optics must be coated with high damage threshold coatings for either 940 and 1030 nm wavelengths to handle the high power density of both pump beam and laser output beam.
2.3.3 Bonding

Chemically Activated Direct Bonding (CADB) bonding has been used to bond the ASE caps to the gain material. The surfaces are chemically activated to increase the density of available bonds at the surface (using a proprietary technology) by Precision Photonics. CADB provides an optically transparent epoxy free path and has proven to work excellent at high power operation. The ultimate test of the strength of the bond and coating laser threshold was performed by AFRL where thin-disks were subjected to 12.7 kW CW pump power, or 5 kW/cm² power density, without thin-disk and coatings being damaged. CADB bonding has been used for bonding the sapphire heat sinks to the bottom of the thin disks for large setup, but this has not been very successful so far. Sapphire heat sinks delaminated when the thin-disk assembly was mounted on the large mount for the large setup – mechanical stress from epoxy curing broke the CADB bond. CADB bonding has also been used to directly bond the disk to the small setup CuW mount cap with initial promising results.

2.3.4 Finished Thin-Disk Gain Material

It takes at least six months to fabricate a finished thin-disk. However, it took even longer to obtain our finished materials due to all the new processes and new
materials that were developed at the same time we were building our experiments. Thin-disks used in these experiments represent a success of an enormous engineering design effort, and collaboration between different suppliers, and a milestone in high optical quality ceramics manufacturing.

First and foremost, Konoshima Corporation manufactured a high quality laser raw ceramics material. This raw material was then polished and coated by several vendors – the process of doing so proved not to be much different than processing the single crystal raw material. Coating the ceramics has also been successful. The final product proved that it has superior performance to a comparable single crystal (6.5 kW of CW power has been obtained with a single ceramic thin-disk laser).

2.4 Large Thin Disk Experimental Test Platform

2.4.1 Processed Materials and Assemblies

Capped Yb:YAG ceramic thin disks consist of a 200 μm thick, 9.8% doped, Konoshima Yb:YAG gain medium. The disk is CADB bonded to a 1 mm undoped YAG ceramic cap processed by Precision Photonics. The undoped cap serves two purposes. First, it aids the suppression of amplified spontaneous emission generated. By being index matched a significant fraction of the spontaneous emission escapes upward through the undoped cap rather than
being total internally reflected within the Yb:YAG material. The other important reason for the undoped cap is to provide rigid support. 200 micron thick Yb:YAG disk will immediately disintegrate when subjected to the water jet impingement cooling without the cap. The bonding process of Yb:YAG to YAG is performed by Precision Photonics using their chemically activated direct bonding (CADB) technique. The diameter of the disks is 35-37 mm with a clear aperture of 26 mm. The top side of the thin disk assembly is coated with a dichroic antireflection (AR) coating (940/1030 nm). The bottom side of the assembly is coated with a high reflective (HR) coating at both the 940 nm pump and the 1030 nm laser wavelengths. Coating is optimized for 1030 nm wavelength for normal incidence.

The YAG assemblies are either attached to heat sinks or directly to the CuW cooling mount. The heat sinks tested are SiC, sapphire, and diamond all with a thickness of 0.5mm. The Yb:YAG/YAG assemblies are attached to the sub mounts either using an epoxy (for diamond and SiC) or the CADB process (Sapphire). The finished unit is epoxied to a CuW holder around the periphery. With the CuW unit, a 26 mm clear aperture is available to pump. The laser pump spot diameter used is 18 mm. A water spray then cools the back side of the assembly. In this work, cooling of the Yb:YAG or heat sink is accomplished by jet-impingement cooling, 2.5 gal/min at 20°C, directly against the back of the disk assembly.
Since the submounts provide sufficient mechanical rigidity to withstand the water pressures of the cooling spray, the opportunity to examine laser performance without the undoped YAG cap is created. Thus some of the Yb:YAG samples are mounted to the heat sinks without an undoped YAG cap. It is possible to examine the deleterious role of amplified spontaneous emission in this case. Figure 20 shows photos of two different disks illuminated with the same pump power but showing different densities of scattering centers.

![Figure 20 Two ceramic disks showing different density of scattering centers](image)

For the output coupler we used both 1” and 2” diameter optics since the diameter of the beam in the cavity remains small. One inch diameter optical couplers had either 0.5 or 1 m radius of curvature, and 2” optics 1 or 2 m radius of curvature.
2.4.2 Experimental Lab Setup

2.4.2.a Pumping

Large thin-disk test platform capable of operating at multi-kW power levels contains high power sources, multiple optical systems, IR and thermal cameras, chilled water and dry nitrogen supplies and high power diode pump lasers. It is important to follow the safety procedures\textsuperscript{41}. Entire system is placed in a clean room enclosure which maintains a particulate free air through use of HEPA filter placed on top so the air can move downwards to the floor and out through the bottom of the drapes.

To operate the laser system two people need to be present at all times, due to operation of high current sources, and other safety reasons related to operating a laser at multi-kW power. The large thin disk test bed uses water jet impingement cooling and 8 double pass configuration for pumping the thin-disk. Jet impingement cooling uses chilled water temperature set around 22°C. The water chiller is situated outside the lab building and water is routed to all the labs. It is necessary to check the water temperature before turning the power supplies on in case of chiller failure. The entire system is rather complex.

Figure 21 shows the intricate optical train design used to collect the light from the diode
stacks. The physical size of the box holding the optics in the lab is about 1 m tall and 1 m wide. There are many spherical and cylindrical lenses that direct the light onto a thin polarizing plate where they are combined and focused onto a homogenizing rod. Two sets of three diode stacks outputs are optically combined.

Figure 21 Diode laser pump collimating optics

Since the diode stacks produce beams with different foci in the fast and slow axes, imaging lenses are different for each. ZEMAX optical design program was used for optimization of the entire system\textsuperscript{43}.
Figure 22 shows the optics train used to focus the pump beam light into the homogenizing rod. For the slow axis, which is the direction with the worse beam quality, upper part of the picture, we use first a cylindrical and a spherical lens for collimation. After passing a thin film polarizer the radiation is imaged into the quartz rod using a 3-lens objective. In this case the aperture of the optical elements is completely used.

For the fast-axis, which is the direction with the better beam quality, lower part of the picture, the first spherical lens and the two cylindrical lenses form a telescope for reducing the diameter of the collimated beam. After passing the thin film polarizer the radiation is imaged into the quartz rod with the 3-lens objective so that the beam diameter on the quartz rod is nearly the same as for the slow axis. The ratio of the beam widths in x- and y-direction on the thin film polarizer reflects the ratio of the beam qualities in both axes. For our stacked arrays this ratio is between 3 and 5.
Figure 22 One stacked array optics train

Optical system for coupling the diode laser power from one stacked array into one homogenizing rod is shown in Figure 23, designed by Dr. Giesen’s group. The figure shows the stacked lens arrays in fast and slow axes, used to image the beam in one single quartz rod. Fast axis has a better beam quality and its beam’s width is similar to the beam width of the slow axis.

Three other stacked arrays are combined in the same way but rotated by 90° and are transmitted through the thin film polarizer and imaged into the quartz rod. With this technique more than 15 kW pump power can be used for pumping. With additional six stacked arrays the pump power can be increased to more than 30 kW. One advantage of the beam combining system is its simplicity and
its high efficiency. The only source of significant losses is the thin film polarizer, but this loss should be less than 10%.

**Figure 23 Coupling of diode stacked arrays into one homogenizing rod**

The resultant beam is not useable to pump the thin-disk laser, and must be homogenized with a homogenizing rod in order to scramble the modes and produce a supergaussian beam profile.
Figure 24 shows the 25 bar laser diode stack that produces 2.5 kW CW power. Each stack is actively cooled with deionized (DI) water and powered with a high current power supply. Stacked diode arrays are used to pump the gain medium in the large setup. The free space 940 nm laser diode pumping system consists of six Jenoptiks 2.5 kW/25 bar stack laser diodes\textsuperscript{42}. The electrical efficiency for these stacks is more than 51\%. It is necessary to combine the beams emitted by each one of six stacks, homogenize them and image them onto a thin-disk.

Figure 25 shows the pump chamber in the large setup. Copper tubing is used to direct the cooled water onto the back surfaces of the parabolic and reflecting mirrors within the pump chamber.
After passing the thin plate polarizer, light is imaged onto a homogenizing rod with three lenses so both fast and slow axis beams have roughly the same diameter. Ratio of the beam widths in fast and slow axis after passing the thin plate polarizer is directly related to the beam quality in both axes and for our stacks this ratio is between 3 and 5\(^{43}\). Homogenizing rod is a 20 cm UV grade fused silica Suprasil\textregistered{} (F300- Appendix A, and 3001)\(^{44}\) rod capable of handling the 15 kW of maximum pump power. Using the IR camera at approximately 12 kW of pump power temperature of the rod was measured to be 350°C. Each one of these optical components is cooled with chilled water. Additionally, end faces of the Suprasil\textregistered{} rod are cooled with dry nitrogen. The entire system has to be carefully maintained daily and checked for water leaks and dust particles.
Homogenizing rod plays a major role in operation of the large thin-disk experimental platform. Several different high quality quartz materials failed before Suprasil® was chosen. Figure 26 shows the rod that was used for three years continuously and still did not show any signs of damage.

Figure 26 Homogenizing rod

The pump power distribution on the disk needs to be as uniform as possible to reduce the tensile stress and thermally induced deformations. All six diode stacks beams are imaged onto one end of the rod. The output of the homogenizing rod is relay-imaged to produce a ninth order super Gaussian pump profile. Figure 26 shows the lenses used to focus the light onto one end of the rod, and lenses used to collect and collimate the homogenized beam coming out of the other end of the rod. There is approximately 10% loss of light from the diode stacks until it reaches the thin-disk in the pump chamber. Power was measured using the 10kW thermopile during multi-kW operation of the pump laser right before the pump chamber to determine the loss and compared to power internally calculated by the diode laser. All of the free space optics are
antireflection coated at 940 nm. The pump beam is reimaged eight times on the thin disk using a parabolic mirror, and 16 total passes through the gain medium provide 90% absorption of the incident pump power during operation for our disks’ doping and thickness. This pumping scheme allows us to use a quasi-three level material such as Yb:YAG for thin-disk laser.

The disks are attached with epoxy to CuW mount along the disk perimeter. The back of the disk is directly water jet-impingement cooled (2.5 gal/min) at 22°C. Figure 27 shows the nozzle design and mount for the large disk assembly.

![Thin disk assembly](image)

**Figure 27 Large thin-disk assembly**

We have made modifications to the existing nozzle in house and still got the water jet imprint on the disk. It was clearly visible during high power operation.
indicating that more serious redesign of the nozzle has to be implemented to improve the beam quality of the jet impingement cooling and reduce the distinct thermal imprint.

2.4.2.b Cavity Arrangements

Figure 28 shows the cavity arrangement for the experiments. The main thin disk chamber, dotted line box, contains the Yb:YAG media, multi-pass reflecting mirrors for the pump, and cooling. In the figure, M refers to highly reflective mirrors, OC is the output coupler mirror with a 2m radius of curvature and coated with an HR ranging from 94% to 99% reflectivity at 1030nm. The path of the pump light is portrayed by the narrow dotted lines. The laser light is indicated by the double dotted lines. The pump mirrors are also cooled with chilled water. The Yb:YAG assembly is water jet impingement cooled. The bottom surface of the Yb:YAG is HR coated so as to define one end of the laser resonator cavity. Figure (a) is a straight-forward ‘l’ cavity built so the other end of the cavity is a concave output coupling mirror with high damage threshold coatings. Figure (b) incorporates an external high damage threshold mirror along with the output coupler optic to define a ‘V’ cavity. This provides a two-pass through the thin-disk. In the experiment, along with the usual power measurements, a thermal
camera and Silicon CCD camera film the ramp up to full power. Figure (c) is a photograph of a mounted large thin-disk assembly.

![Photograph of a mounted large thin-disk assembly](image)

**Figure 28 Experimental arrangement large platform a) I cavity, b) V cavity, c) 35 mm mounted assembly**

The absorbed pump power in the TD drops (saturates) to 80% in the fluorescence mode (blocked cavity). During multiple single shot operations, the laser diodes’ current was ramped over a 10 sec period and held at the operating pump level for 5 sec. This “ramping” was necessary to avoid overheating of the air cooled input and output faces of the homogenizing Suprasil® rod. The thermal diffusivity of YAG, 4.5 mm²/s, yields a thermal diffusion time constant of ~ 0.35 sec in our 1.2 mm thick YAG composite structure. The actual time constant is much shorter considering that the heat generation occurs mostly in the 200 µm doped region. This insures equilibrium lasing and thermal conditions during our ramp and hold operation. The ramp and hold time is shorter than the time constant of our large thermopile power meter (> 40 sec), therefore a pickoff beam
splitter and a large-area biased photodiode were used to measure the power. The photodiode was calibrated with the thermopile power meter at a CW output power of 500W. A sudden drop in the slope efficiency during the ramp stage or the output power during the hold was used to turn off the pump diodes in order to avert catastrophic damage to the thin disk or other optical elements.

2.4.3 Alignment of the Pump Beam

Aligning the pump beam is an extremely important step in operation of the thin-disk laser. Since the pump beam bounces 8 times off the parabolic mirror – there are eight visible spots that need to overlap on the disk. Figure 29 shows the misaligned pump beam in the large setup. The alignment target is placed into the pump beam path and the image of the hole in the target is observed with a camera. The pump beam is held at the lowest power possible needed to see the image of the spots on the camera for safety reasons (around 20W). In this case it is obvious that the pump chamber is grossly misaligned. It is then tilted with respect to the optical axis, and parabolic mirror directing the pump beam onto a disk is also out of focus. The entire pump chamber has to be moved in focus as well as tilted to get a good pump spot on the disk. This is not a trivial task since the pump chamber with the parabolic mirror is heavy and the alignment process is manual. The operator must take care to stay away from the pump beam path.
while aligning the chamber and be careful to turn the aligning knobs slightly. The optical setup is extremely sensitive to focus/defocus and a bit less sensitive to angular alignment. Once all the spots overlap, the alignment target can be removed and the entire pump beam can be observed with a camera, and then finely aligned if necessary. During this process one has to continuously observe the pump profile sharpness and uniformity on the TD using the camera.

Figure 29 Misaligned pump beam

Figure 30 shows how the 11 mm diameter pump beam looks when aligned on the center of the disk with all reflections overlapping uniformly to form a sharp pump beam profile. One large scattering center is visible on this particular thin-disk – this did not affect the output of the laser at lower operating powers, but it did lead to damage of the disk at multi-kW operation. To change the beam size it is necessary to replace and realign several lenses located right after the homogenizing rod.
Figure 30 Aligned pump beam

Figure 31 shows the pump beam profile for both 11 mm and 18 mm pump beam diameter. It was possible to change the beam diameter on the large setup in order to demonstrate power scaling of the thin-disk laser. Experiments were performed with these two beam diameters on thin-disks with ASE caps, and disks with heat sinks with and without the ASE caps. The profile of the pump spot is the ninth order super Gaussian beam.
Figure 31 Pump beam profile 11 and 18 mm diameter

Output coupler also needs to be aligned properly with a reference HeNe laser. Once the lasing is achieved we used remotely controlled motor drivers to maximize the output power of the 1030 nm laser slightly above the threshold, where output laser is more stable, but not yet operating at too high power. Output couplers used had 1m or 2m radius of curvature.

2.5 1 kW Thin Disk Test Platform

The small thin-disk test platform operates using the same principles for pumping as the large thin-disk setup. The difference is that a fiber coupled pump laser is
used in all small test platform experiments. Furthermore, the scale of the laboratory setup is much smaller and therefore easier to adjust and modify.

Three different test platforms were built: first with water jet impingement; second with R-134a refrigerant; and third with liquid nitrogen cooling. Two new cooling systems were developed. The first operates with R-134a refrigerant, and the second utilizes LN$_2$ for cryogenic operation. This technology provides more uniform cooling than water jet impingement, and improves both the phase distortion and the power extraction. The laser is pumped with 1kW of 940nm fiber delivered pump light. The pump is imaged for 8 double passes on the thin-disk.

Small 1 kW test platform is used to test smaller size disks (up to 14 mm in diameter). 1kW fiber coupled diode pump laser beam at 930-935 nm (Laserline) is used with a pump beam diameter of approximately 7 mm. The center wavelength of the Laserline laser can be slightly shifted by changing the temperature of the diode cooling system. To avoid damage to the laser diode stacks, temperature was set at setting 2 in the lab and for that temperature setting laser wavelength range is 930-935 nm. In order to improve the efficiency of the output laser, pump beam should be centered around 940 nm.

These experiments enable testing with multiple thin-disk configurations to compare thermal distortion effects and power extraction capability. The tests with good disks require measurement of laser wavefront, power extracted and
temperature rise in the thin-disk, as well as detailed analysis of ASE and optical spectrum.

2.5.1 Small Test Platform Processed Materials and Assemblies

Konoshima and Raytheon (USA) supplied materials tested on a small platform, and single crystals are supplied by VLOC. The disks mounted on RINI caps are 14 mm in diameter, 200 micron thick Yb:YAG and undoped YAG caps are 1 mm. These thin-disks tested were with and without the undoped YAG caps. Konoshima, Japan supplied the majority of materials tested. One of the goals of this project was to find a raw material supplier in USA, so the entire thin-disk fabrication can be performed in the States. Raytheon delivered polished samples which we tested with results indicating that material provided is of a high optical quality and spectral characteristics similar to Konoshima ceramics and single crystal. Raw material was processed by Precision Photonics (polishing, bonding and coating) and Enerdyne (bonding, soldering). These two companies collaborated closely to achieve the void-free bonding procedures for the RINI solid CuW mounting caps. Some of our materials were also coated at the AFRL.
Figure 32 Small thin-disk test platform shows a 2-D cross section of our setup.

The cooling unit (S) directs coolant into the interior of the cooling cap (C). Yb:YAG is attached to the cap using a void-free thin layer of Indium solder. The pump is introduced into the cavity through the lens train (L). The pump is actually out-of-plane and does not propagate through the mirror (M2). It reflects off the one piece parabolic mirror (M3) and corner mirrors (M1 and M2 are shown, and two additional corner mirrors are perpendicular to the plane of the paper) onto the disk surface to image the light for 16 passes of absorption.

The laser cavity is defined on one end by the ion-beam sputtered HR (>99.9%) coatings applied to the Yb:YAG and the output coupler (OC R=95-99%) on the other. The resonator is approximately 35cm long (for jet-impingement and R-134a refrigerant) and 50 cm long (for LN$_2$ system). Alignment of the small setup is much more manageable than the large setup because of the lower pump power used, easier
access to individual components in the setup and the pump beam is fiber coupled instead of free space coupled. Fiber coupled laser is more compact and easier to handle and it allowed us to move the pump laser easily around the laboratory to utilize in our several different experimental setups. With fiber coupled laser many free space optics were eliminated and therefore the maintenance of the system became a lot more manageable.

2.5.2 Water Jet Impingement Cooled System

Initially our thin-disk lasers were operated at room temperature with water jet impingement cooling. However, there are a number of limitations with this scheme. For one, jet impingement produces a severe phase distortion on the beam and reduces the useful gain area. Second, there is only limited temperature control of the jet spray, and obviously cryogenic cooling is not feasible. Jet impingement cooling cap can accommodate disks up to 20 mm in diameter, with effective clear aperture of 12 mm. Disks are attached to the mount with a simple Epotek\textsuperscript{47} epoxy applied around periphery of disk.
Figure 33 Small jet impingement cooling mounting cap

Figure 33 shows the mounting cap design for the jet impingement cooled setup. Disks were indium soldered to the top of the mounting cap.

Figure 34 Aligned pump beam on small jet-impingement cooled platform

Figure 34 shows the pump beam centered on the disk and properly aligned. Alignment of the small setup is tedious as well but it is not as complicated and time consuming as the alignment of the large thin-disk setup. DALSA camera was used to monitor the pump beam on the thin-disk during the
alignment process as well as while running the laser ramps. We also used a
Germanium (Ge) window in our setup to block the green fluorescence light.

### 2.5.3 R-134a Refrigerant Cooling System

Figure 35 shows the expanded and physical layout of the small beam setup and
a photo of the R-134a refrigerant setup in the lab. The small platform setup is
much more compact due to using the fiber coupled pump laser instead of a free
space coupled system. There are only five lenses positioned between the laser
fiber and pump chamber in order to collimate the pump light. These lenses are
neatly placed into a cylindrical lens holder with spacers, and require little
adjustment after they are positioned in the holder. We were able to use the same
pump beam laser for three different experimental setups and it was fairly easy
and quick to move the laser from one experiment to the other.
The design from University of Stuttgart\textsuperscript{48,49} ensures that efficient pump absorption is obtained by using a multi-pass configuration. In the pump chamber there are two sets of beam directing prism pairs, and a parabolic mirror, both coated with a highly reflective dielectric coating, designed for 8 double passes through the thin disk. The parabolic mirror has an on-axis hole and laser cavity is formed with the output coupler positioned in the free space 50 cm away from the...
thin disk.

The pump beam, Laserline fiber coupled laser centered at 940 nm is incident on a large dielectric HR coated parabolic mirror. The disk is positioned on the axis of the parabola at its focal point and the pump beam is focused upon it. The pump is reflected off the HR coating on the rear surface of the disk and passes through the gain material twice. The pump light not absorbed in the gain material is bounced by the parabolic mirror and redirected onto the disk. By moving the remaining pump light via dielectric coated prisms onto a new sector of the parabola, 8 total pump double passes can be implemented. This ensures that more than 99% of the pump beam is absorbed. In our setup, the original water jet impingement cooling is replaced by a custom sealed spray nozzle and mounting cap design.

The new cooling setup, manufactured by the RINI Corporation (Orlando, FL)\textsuperscript{50}, utilizes a two-phase spray boiling technology (Figure 36). A small nozzle placed inside and near the rear of the cap aims the R134A at the backside. The interior cap surface is deliberately roughened to improve the heat transfer. The system is designed for a cooling flux rate of near 125W/cm\textsuperscript{2}. This cooling capacity is similar to performance to previously used water jet impingement. The convective heat transfer coefficient is 123,000 W/mK.
Figure 36 R134a two phase spray boiling

Figure 37 illustrates the R-134a system performance. The thermal run-away happens at about 225 W.
The R-134a ESC system temperature performance is measured using a resistive heat load of 1 cm² area. \( q_{\text{flux}} = \) Heat flux [W/cm²], \( Q = \) Heat Load [Watts], \( T_{\text{spray_surface}} = \) Calculated temperature at the spray impingement surface, \( T_{\text{sat}} = \) LN₂ saturation temperature of fluid being sprayed (77-83K).

\[
h_{\text{conv}} = \frac{q_{\text{flux}}}{\Delta T_{\text{sat}}} = \frac{Q/\text{Area}}{T_{\text{spray_surface}} - T_{\text{sat}}}
\]

The spray system requires that the thin-disk be attached to the mounting cap over its entire area, which is a non-trivial endeavor. Solid mounting CuW cap, shown in Figure 38, was designed so it can be used for both RINI devices (R-134a and LN₂). This is important because we can then test the same material on both setups using the mounting cap.

![Figure 38 Solid cap mount for R-134a and LN₂ setups](image)

63
An initial process was developed in which the gain material was attached to the cap using thermally conductive epoxy and then evacuated in a vacuum chamber. With this effort voids and uneven bond lines remained present. An alternative process using flux-less Indium solder was developed by Precision Photonics\textsuperscript{51} (Boulder, CO) and Enerdyne Solutions\textsuperscript{52} (North Bend, WA). Major challenges including elimination of voids in the solder layer, delamination due to poor adhesion of the layers and disk edge chipping have been overcome. There is also a problem with CTE mismatch of different heat sinks and the CuW cap. Special polishing, cleaning and handling procedures had to be developed to handle the disks. Ultimately this new process has demonstrated very thin and even bond lines with the absence of solder voids.

Figure 39 shows the mounted thin-disk on RINI cap. The disk diameter is 14 mm. Indium solder is visible on the perimeter of the thin-disk and at the edge of the mounting cap.

\textbf{Figure 39 Mounted small thin-disk on RINI cap}
R-134a cooling chamber that the disk cap mounts onto is shown in Figure 40. It is possible to move the whole assembly back and forth and also pivot the top part with thin-disk mount. The bottom part of the assembly needs to be secured in place before the tilt can be properly adjusted. Every disk is mounted slightly differently on the cap due to variations in thickness of the Indium solder. The hoses for R-134a in/out lines are visible on the photo and they needed to be safely secured to the table to avoid misaligning the thin-disk.

Figure 40 R-134a refrigerant mount assembly

The alignment process for the R-134a setup is similar to jet-impingement alignment in terms of aligning the pump laser beam and the pump chamber. The difference is in the thin-disk mount, which in this case has a pivot point mount to
adjust the angle of the mounted thin-disk platform. This is useful because every
disk is mounted onto a cap slightly differently, due to difference in Indium solder
thickness.

Figure 41 shows the pump beam centered on the R-134a thin-disk setup. The beam
is approximately 7 mm in diameter and ninth order super Gaussian.

2.5.4 Cryogenic Cooling System

The cryogenic setup is essentially a modified R-134a refrigerant 1 kW pump
power setup shown in Figure 42. The LN₂ spray is forced through the system at a
pressure of 40 to 50 psi through a single nozzle and onto the inner surface of a gold-plated CuW cap. The vaporized nitrogen gas, along with any remaining LN$_2$ droplets, was removed from the cap and is subsequently routed through the pump mirror chamber in order to cool the mirrors. This modification was an important improvement, since water cooling of the pump chamber was removed and therefore source of extra humidity in the chamber was eliminated. Sixty liter nitrogen tank was used which allowed to run the experiment for about 4 hours maximum. For safety reasons, there needs to be proper ventilation system in place, as well as oxygen deficiency gas monitor installed in the laboratory.

Figure 42 Cryogenic LN$_2$ cooling chamber
At room temperature lasing occurs at a pump power of 150-160W. This threshold drops below 10W at cryogenic temperature. Such a low threshold is a beneficial result of the low loss resonator, the high material gain, and the lack of thermally energized electrons in the two manifolds, characteristic of a four level laser. In fact, the laser equations for a 4-level system do predict such a threshold with these conditions. Figure 43 shows the liquid nitrogen spray cooling performance. The system can handle up to 180W thermal load for a short period of time.

![Liquid Nitrogen Spray Cooling Performance](image)

**Figure 43 Cryogenic ESC performance**

To align the pump beam in the cryogenic setup we modified the collimating optics lens train, because the pump laser was situated outside the vacuum chamber and the existing lenses did not physically fit in the setup. The pump beam passes through the vacuum chamber window, coated AR for 940
nm, introducing a slight tilt as well. The resulting aligned and centered pump spot is shown in the photo below (see Figure 44).

![Figure 44 Pump beam profile on the cryogenic setup](image)

The pump beam is approximately 7 mm in diameter. Out output coupler was not water cooled in this setup to further reduce the amount of water in the vacuum chamber, and to prevent possible leaks from extra water tubes.

### 2.6 Software

Thin-disk laser ramps are controlled by ever-changing Labview programs that are written in-house. Modifications to the software were necessary as experiments evolved and new setups built. The large setup program controls the six power
supplies for the laser diode stacks. The laser can be operated in continuous mode which has a power limit of 7.5 kW as a safety precaution, or in ramp mode up to a maximum power of 15 kW. Hold time for ramp can be adjusted as well as the number of steps. Our program calculates the pump power, and data can be taken simultaneously for several experiments and is saved in separate files. All the data is also displayed as graphs so one can immediately see if the experiment is going as planned. A similar Labview program is used for the small setup. It is modified to run Laserline laser, so it is possible to adjust the temperature setting of the laser, and power is adjusted for up to 1 kW power. Both programs have a control feature to shut the pump power in case of lasing disruption determined by a slope efficiency below 30%.

The DALSA camera is controlled by Spiricon software, the Jenoptik IR thermal cameras run with software Variocapture. EPIX software is used for imaging the probe beams and fluorescence images of the disks, and for processing the images and data. Most of the data obtained was analyzed using IGOR or MATLAB softwares.

Labview programs for taking data with monochromators, spectrophotometers, and other equipment were written by Dr. Newell.
2.7 Experimental Test Procedures

Before the experiments can be completed, there are a variety of tasks that need to be performed. The thermal response time constants of different size power meters have to be characterized to determine the appropriate method for measuring output laser power during the ramp and hold period. The pump power has to be calibrated to diode current and the laser optics need to be tested for reflectance and setup and aligned. The initial setup is time consuming and a process that requires a lot of patience and careful attention to detail. All the optics in the free space coupling setup also have to be checked and cleaned (dusted off with air) – this is especially important for high power operation.

The following measurements and characterization were performed in our experiments to properly evaluate different thin-disk configurations and determine the effect of the heat sinks, undoped caps and efficiency and effectiveness of new spray cooling technology as compared to the existing single phase water jet impingement cooling. These measurements are:

- The fluorescent thin-disk needs to be imaged onto a Spiricon camera to insure pump spot sharpness and to determine the pump spot size and shape.
• Record the top surface temperature, for both uncapped disk surface or undoped cap with a 8-14 µm IR Jenoptik camera. Also, take either videos or snapshots to determine temperature profile at several pump intensities with lasing and non-lasing conditions to determine the disk heating slope vs. pump power.

• Execute a pump ramp to obtain the slope efficiency and lasing threshold.

• Measure the output coupler temperature during the ramp using IR Jenoptics camera.

• Quantify the thin disk thermal lensing.

• Measure the unsaturated gain of a 1030 nm probe beam (Versadisk laser) for blocked cavity (non-lasing condition).

• Determine the pump power, output laser power and slope efficiency.

• Measure higher order wavefront distortions using Shack-Hartmann Wavefront Analyzer (output laser beam).

• Find the output power vs. output coupling for output coupler with R = 95-99%.

Furthermore, the cryogenic setup required us to make minor modifications such as new venting. Also, liquid nitrogen tanks had to be refilled regularly, since one full tank would provide enough nitrogen for approximately 4 hours of continuous operation. Maintenance of the labs and buildings required daily commitment from the entire team to keep experiments running. The chilled water
chiller and its pumps required careful monitoring and maintenance by the entire team as well. Chiller water for cooling the pump laser diodes had to be replenished periodically.

2.8 Summary

In Chapter 2 we described the experimental setups for both large and small test platforms. We included our measurements necessary to describe properties of the gain materials we tested, as well as a detailed description of the thin-disk fabrication process. We explained in detail setups for cryogenic and room temperature thin-disk lasers as well. It is important to note that we built our RINI setups (room and cryogenic temperature) from ground up. We did this in a short amount of time, and with limited resources. In Chapter 3 we present our experimental results for all four different setups.
Chapter 3 Experimental Results

3.1 Introduction

The results for continuous wave (CW) operation of the thin-disk laser for four different experimental setups are presented. The first experiments were done on the large test platform where it was possible to demonstrate the power scaling by using two different pump beam sizes. Furthermore, we investigated the beam quality while running the laser at high power. We conducted experiments on assemblies with heat sinks made of diamond, Sic or sapphire, as well as thin-disks with and without the anti-ASE YAG caps.

At the same time, the experiments on the small test platform with jet impingement cooling were performed. Furthermore, we built two completely new experimental setups with novel cooling designs by modifying the existing small platform design.

Due to complexity of our experimental systems, and a variety of materials used for testing, similar experimental procedures were employed in all of the experiments. This systematic approach allowed us to directly compare the performance of thin-disk lasers at room and cryogenic temperatures. This chapter presents experimental data, and analysis for each case.
3.2 Large Thin-Disk Test Platform

We performed a variety of experiments on the large test platform. After the highest power from a ceramic disk was extracted from a single disk, we focused our research towards understanding physical processes taking place in the thin-disk laser. We first started with measuring the output laser power using different output couplers and obtained data for two different cavity configurations (I and V shape). The temperature of the disk cap was measured for lasing and non-lasing conditions, and thermal lensing effects were recorded. We were also able to test thin-disks with different heat sinks and compare the capped vs. uncapped thin-disk lasers and investigate the ASE in more depth.

3.2.1 High Power Operation

To investigate the thin-disk gain saturation, both I-cavity and V-cavity configurations were examined. The typical power measurements are presented. We utilized output coupler mirrors with a reflectance ranging from 95% to 99% to measure slope and threshold power. Also, Rigrod\textsuperscript{53} curve data for an 11 mm and 18 mm diameter pump spot sizes were collected and compared. The purpose was to evaluate the gain saturation characteristics of the two resonant cavities
and to quantify the role (if any) of transverse amplified spontaneous emission in the capped thin disks. During operation, the laser diodes current was ramped up in roughly 10 sec and held at the operating pump level for 5 sec. Since the ramp time is shorter than the time constant of a large thermopile power meters (> 40 sec), a pickoff mirror and a large-area biased photodiode were used to measure the power. The photodiode was calibrated to a thermopile power meter at a continuous wave (CW) output power of ~500W. During the ramping stage, the slope efficiency was monitored so that the pump diodes could be turned off in case of a sudden drop in the slope efficiency in order to prevent disk or optical coating damage. The thermal diffusivity of YAG (4.5 mm$^2$/s) yields a thermal diffusion time constant of ~ 0.35 sec in our 1.2 mm thick doped/undoped YAG composite structure. The actual time constant is much shorter considering that the heat generation occurs mostly in the 200 μm doped region. Therefore, the ramp and hold duration enabled equilibrium lasing and thermal conditions.

Figure 45 and Figure 46 show the output power and slope efficiency measured during the ramp as a function of pump power and intensity for both the V-fold cavity (4% output coupling) and the linear cavity (2% output coupling) for high power. The linear cavity achieved 6.5 kW output at ~ 60% slope efficiency for the pump beam power 12.7 kW, but the V-fold cavity achieved a maximum of 5.5 kW, before the control program shuts down the pump diodes due to a sudden drop in the slope efficiency at a pump intensity of 4.5 kW/cm$^2$. 
This repeatable slope efficiency drop and shut-down at this pump intensity was a precursor to the cavity becoming unstable due to the thermal expansion.
induced disk flexure leading to a convex radius of curvature of -3m. This
curvature estimate amounts to > 20 waves sag across the disk, which agrees
with thermal lensing measurement of a 980 nm probe beam bouncing off of the
TD as will be shown below. The linear cavity, on the other hand, was stable up to
a stronger disk curvature of -1.5m. This is due to the shorter linear cavity
involving half the number of bounces off of the thin disk per round trip compared
to the V-fold cavity. The ratio of the pump spot size to that of the fundamental
cavity mode was ~ 10 at low pump power and approached ~ 5 before the V-fold
cavity became unstable. This is due to the increase in the size of the lowest order
fundamental cavity mode caused by the disk flexure.

3.2.2 Thermal Lensing

Figure 47 Shows the setup for the thermal lens measurement with a probe
beam at 980 nm wavelength. The beam was expanded and positioned on the
thin-disk at an incidence angle as close to the optical axis as possible. It bounces
off the pumped thin-disk and the image is captured by a camera.
Figure 47 Thermal lensing probe beam setup

The far-field profile of the 7mm diameter probe beam reflecting off of the unpumped disk is shown in Figure 48. This figure also shows the probe near-field profile off of the pumped disk for the 18 mm pump spot of equal pump intensity, respectively. Thermal expansion induced negative lensing and the nozzle imprint is clearly demonstrated for the large pump spot for the disk without the heat sink. It is worth pointing out that thermal expansion induced disk flexure scales with the total pump power and not with pump intensity. It is possible that the preferential cooling of the disk may be alleviated by a redesign of the water cooling impingement mechanism. Furthermore, the effect this will place on the heat removal capacity needs to be further examined. The use of the intermediary heat sink improves the outlook. Figure 48 also shows the probe beam from a disk assembly that is mounted onto a SiC submount. The nozzle imprint is removed if disk is mounted on a heat sink.
Thermal lensing of the lasing disk was measured by an expanded and collimated 980 nm fiber coupled semiconductor laser probe (7mm diameter). The beam far-field profile was imaged on a camera 2.2m away from the thin-disk. Three thermal lensing contributions were identified; (1) thermal expansion induced negative lensing (disk acquiring a convex radius of curvature), (2) positive lensing due to the temperature profile towards the pump spot edge, and (3) a thermal imprint of the cooling nozzle.

A fluid flow/thermal conduction simulation using cfDesign software (done by AFRL previously) of our jet impingement cooling nozzle showed strong temperature variations of up to 40°C for a heat load of 0.8 kW/cm² between 2009: Thermal lensing attributed to jet impingement cooling No heat sink $\rightarrow$ thermal lensing = poor beam quality

Spring 2010: SiC heat sink
No thermal lensing imprint $\rightarrow$ Improvement in beam quality

Figure 48 Thermal lensing (jet impingement)
points directly cooled and locations in between jets (Figure 49). The simulation points to complete washout of this transverse temperature variation, through radial heat conduction, in the interior of the undoped cap. This pattern complicated proper wavefront characterization.

![CFD Simulation](image)

**Figure 49 CFD Simulation for large setup with water jet impingement**

### 3.2.3 Performance Between YAG Capped and Un-capped Yb:YAG Material

With the availability of heat sinks to provide structural stability, Yb:YAG lasing can be examined with and without the undoped YAG caps. Figure 50 shows the gain-length in capped and uncapped samples. ASE in the uncapped thin-disk is trapped and experiences a larger optical path, whereas ASE light in the capped sample is able to escape through the cap. Clearly, S is longer in the Yb:YAG
case only, which means ASE production is higher and so is the heat generation. ASE generation and absorption is difficult to model accurately.

**Figure 50** A comparison of ASE in uncapped and capped assemblies

In this case, a comparison of capped and uncapped thin-disks is striking. For the tests presented here, the particular material used in both cases is similar, but unfortunately not of the highest quality. Although disks were mounted upon diamond heat sinks, the vendor inadvertently used a thermally insulating epoxy for attachment. This epoxy layer affected the performance of the laser and optimal results could not be obtained. However, since the two samples are identical, a direct comparison can be made. The disk diameter is 35mm with a clear aperture of 25mm. **Figure 51** shows the laser power versus pump for the two cases. The capped disk reaches a slope efficiency of 40%, but this is substantially greater than the uncapped sample, which only exhibits 20%. Furthermore, the latter’s slope efficiency turns sub-linear at higher powers.
This result is significant since without the heat sink attachment providing rigid support, it was not possible to directly compare capped and uncapped disks before. Figure 52 shows the temperature photos of the uncapped and capped samples under test conditions. Absorbed power is 2kW and pump beam is 18 mm diameter. The uncapped thin-disk’s temperature is 54°C higher than the capped disk.
Figure 52 ASE in a large disk temperature measurement

### 3.2.4 The Role of Heat Sinks in the Large Setup

Through experiment and COMSOL modeling, we found out that the epoxy used to attach the heat sink onto thin-disk was not a good choice. Epoxy used (Epotek 302-3M) has a low thermal conductivity ($k<1$). Epoxy effectively acts as an insulator and induces a huge temperature rise across the thin epoxy layer. Thermally conductive epoxy is required. We tested thin-disks with SiC and diamond heat sinks, both with and without the ASE suppression caps. All of the disks tested were heated to a much higher temperature than the disks that did not have any heat sinks (approximately double the temperature).
3.3 Small Thin Disk Platform

The pump beam laser used in all of our small platform experiments is made by Laserline. Its peak is centered at 931 nm wavelength near threshold, and the peak shifts to longer wavelength of approximately 935 nm at 400 W pump power.

![Figure 53 Shift of the pump beam peak with increasing pump power](image)

**Figure 53 Shift of the pump beam peak with increasing pump power**

Ideally, the pump should be centered at 940 nm in order to most efficiently pump the
Yb:YAG gain medium. Figure 53 clearly shows that our pump beam is not optimal for pumping Yb:YAG, since at 400W pump power it is centered at 935.31 nm. We tried to shift the pump beam by increasing the temperature of the Laserline water cooling system. Our efforts to red-shift the pump laser by thermal manipulation were not successful.

3.3.1 Jet Impingement Cooling

The water jet impingement cooling setup for the small thin-disk test platform was used to test lasers with a maximum pump power of 1 kW. As we continued our testing the Laserline’s maximum power deteriorated over time and the maximum power was reduced to about 850W.

Figure 54 and shows pictures of the thin-disk under lasing and non-lasing conditions. Both pictures were taken at 300W pump power;
first one with the output coupler in place, and second, one without the output coupler.

![Water cooled 300W lasing and non-lasing](image)

In this figure one can see a slight imprint of the water jets. They are not as visible as on the large thin-disk test platform, since there is a smaller number of jets and power is not as high, but imprint of the jets is still there.

3.3.2 R-134a Refrigerant Cooling

The R-134a cooling unit (see section 2.5.3) replaced the water impingement
cooling system. Yb:YAG is attached to CuW caps, see Figure 38 and Figure 39.

This unit is placed in the thin-disk resonator and the pump aligned on the Yb:YAG thin-disk assembly. The first measurement is of the pump power and slope efficiency as shown in Figure 55.

The pump beam diameter is 7 mm.

Threshold occurs between 155 and 160W of
pump power incident into the resonator. The ramp hold time is 5 seconds. Here the 2m radius of curvature output coupler has reflectance R= 98%. At 600W incident pump power, we get 300W laser output power. The maximum slope efficiency is 54%, which is in line with other published work. The slope efficiency depends on the effectiveness at aligning the cavity so that each pump pass onto the disk overlaps the others. At 600W pumping the laser remains in the linear regime, which means there is no roll-over in laser output power.

The pump was limited at this point in order to minimize the possibility of damage to the disk. The center of the lasing wavelength is 1030.25nm. The temperature
of the disk surface is monitored as the power is increased. The surface temperature increases from 15°C to 90°C at 700W pump, a rise of 0.12°C/W. Since Indium melts at 155°C an absolute maximum laser power limit to this arrangement would be 525W. However at this high of a pump, the thermal load exceeds the cooling capability of the system. Consequently the realistic maximum power that can be achieved is much less.

Figure 56 shows the deformation of the thin-disk wavefront as it is pumped up to 250W. A wavefront measurement was taken at the output laser beam for ramps up to 250W pump power. A collimated Gaussian TEM$_{00}$ 1064 nm beam was used as a reference beam that was bounced off the Yb:YAG disk and imaged onto a wavefront analyzer camera (Wavemetrics (Abbott Medical) CLAS-2D)).
Due to complexity of our setup at cryogenic temperature wavefront measurement was not taken for LN$_2$ experiment. Figure 57 shows the measurement at two different pump levels – 25W and 250W. Wavefront slightly flattens as power is increased. There is a small asymmetry in disk (possibly due to astigmatism or coma).
Figure 57 Wavefront measurement at two different pump power levels

One of the major issues in the fabrication of the thin-disk laser is that assemblies are complicated and have many layers of materials including epoxies or solder. Eliminating any one of the steps in fabrication process and simplifying the design would also lead to better management of thermal issues. To aid us in our effort to improve the thermal management of a thin-disk laser, Precision Photonics provided one more novel composite structure to test shown in Figure 58.
Sample of a capped YAG/Yb:YAG thin-disk was coated and processed as usual. The difference is that this time the CuW mounting cap for the small experimental setup was also prepared to be of a high optical quality. HR coated Yb:YAG surface was then directly CADB (precision Photonics proprietary procedure) bonded to a CuW substrate without any visible voids between the two surfaces. This sample was tested on a small test platform with a R-134a refrigerant cooling.

Our initial temperature test results look promising and comparable to non-CADB bonded thin-disk lasers tested on the same test platform (see Figure 59). The sample was pumped with 300W power. Temperature plot shows an increase in temperature at about 240W at which point disk seemed to have flexed and partially delaminated. We can see Newton fringes on the tested sample after it was removed from the setup.
We also note that the humidity in the lab was very high the day we measured this test piece, which is highly unusual for New Mexico climate and could have affected the performance of the thin-disk.

Figure 60 shows the spectral broadening of the laser output at room temperature for two different laser output powers.
Figure 60 Spectral broadening of laser output at room temperature

3.3.3 Liquid Nitrogen Cryogenic Cooling

We moved towards cryogenic liquid nitrogen cooling system because operating the laser at 77K can produce a higher efficiency laser due in part to superior thermal properties of materials. RINI LN$_2$ setup with a two-phase boiling system can handle as high as 180 W heat load for a short amount of time.

For cryogenic operation, the entire thin-disk laser chamber is placed within a vacuum chamber to eliminate the ambient humidity. Air in the chamber is initially evacuated, and then the dry gas overflow of LN$_2$ is introduced to create a slight overpressure. This is sufficient to prevent condensation on optical surfaces and to cool the optics. The pump light is coupled into a vacuum chamber through a port. This necessitated a different set of optics to effectively collimate and launch the pump light into the thin-disk resonator. This resulted in a modest degradation in the cumulative beam that is incident on the disk surface.

The 98% output coupler optic and 0.2mm disk thickness are optimal for R-134a or water cooling methods. It is not likely to be so for the cryogenic case. They were used here for direct comparison. Brown computed pump absorption optimization at room and cryogenic temperatures as a function of pump wavelength and the optical thickness (doping density x penetration distance), which can be applied here
experimentally. Furthermore, Contag\textsuperscript{45} computed that the optical efficiency approaches \(~85\%\) at low temperatures regardless of the number of pump passes on the disk surface. Hence another parameter to consider is the number of pump passes. It is simpler and easier to experimentally align a few pass resonator than the 8-pass one used here. These options make the cryogenic thin-disk laser an appealing system to simultaneously pursue very high power and efficient lasers.

![Figure 61 Laser performance at room and cryogenic temperature](image)

*Figure 61 Laser performance at room and cryogenic temperature*
Figure 61 and Figure 62 show the lasing power versus the incident pump power at room and 77°C, and slope efficiency at the cryogenic temperature. At room temperatures this peak is near 1030.2nm. The resonator uses a 98% reflective output coupler with a 2m radius of curvature. The pump spot size is approximately 7mm at room temperature with a nearly top hat profile. In the cryogenic case the profile is not an ideal flat top with a spot size slightly greater than 7mm. The room temperature lowest lasing threshold is 155W at which point the disk surface temperature is 308°C. The slope efficiency is 54%, which remained linear throughout the 500W pump range. At 510W the power reached 184W.

In stark contrast to the R-134a results, Figure 62 shows that the cryogenic laser threshold plummets to near 10W. This is a demonstration of the superiority of a 4-level laser over the quasi 3-level system. And it also shows the
improvement in emission and absorption cross sections at cold temperatures. For the cryogenic operation, the initial slope efficiency was only 43%. Above 200W pump the efficiency increased to 63% and remained linear beyond this point. At 520W pump the maximum power achieved was 277W. We believe that this increase in slope efficiency can be traced to two factors. The first factor is the pump wavelength, which is just above 932nm at low powers. The diodes heat as the driving current increases causing a wavelength red-shift of 0.0076 nm/W. Figure 63 shows the laser output spectrum for power 180W at cryogenic temperature.

![Cryogenic Laser Output Spectrum](image)

**Figure 63 Cryogenic laser output spectrum**

At cryogenic temperatures the absorption cross-section increases substantially as the wavelength shifts from 932nm to 935nm. Thus the absorbed pump increases super-linearly with respect to the incident pump. Attempts to red-shift the light via the cooling water temperature were unsuccessful. In contrast at room temperature the
absorption profile increases slowly at these wavelengths. A second reason for the improvement is the lack of the ideal top hat shape of the pump spot. At powers very near threshold the laser operates with few transverse modes oscillating. Yb at the center of the disk is inverted prior to the periphery. As the pump power increases more modes reach the threshold condition and augment the total power. This effect is quite small but observable.

3.4 Up-converted Light

There is a strong green light emission from the thin disk, that our eyes are sensitive to. We carried out the experiments on ceramic samples to investigate if upconverted light has an important role in depleting the upper manifold population and could cause the gain curve to flatten our. Cooperative luminescence is a special type of upconversion in which two interacting ions in the excited state return to the ground
state simultaneously. They emit one photon of the sum of the energies of the single ion transitions.

Figure 64 Up-converted light diagram

Upconverted light in our experiments was very weak, and it appears not to have a negative influence on the gain.
Upconverted light peaked at 539 nm. Literature\textsuperscript{54} suggests that this transition can be attributed to the presence of Er\textsuperscript{3+} ions in Yb:YAG crystal. We believe that upconversion luminescence should be further researched as its influence on thin-disk laser performance at high muti-kW powers is not known. Since we are also
interested in different doping concentrations
being used for future cryogenic
experiments, upconversion measurements
as a function of Yb concentration should be
performed.
3.5 Damage

Many factors contribute to damage of the thin-disk lasers under high power operation. In addition to carefully monitoring the temperature of the thin-disk surface during the high power operation, we also monitored the output coupler temperature. We found out that the output coupler without water cooling heated up 50% more at 3 kW pump power than the cooled output coupler. More significantly, the output power of the laser improved by 8% for the same output coupler with chilled jet impingement water cooling.

Figure 66 Output coupler thermal camera image

Figure 66 shows the image of the output coupler at high power operation taken with Jenoptik IR camera. In this image there are also a few spots that are at a higher temperature and appear brighter – these spots indicate the damage on the output coupler. These damage spots eventually led to failure of the output
coupler. Monitoring the output coupler during the laser operation and keeping its temperature lower by water cooling it significantly improves the performance of the laser at high power. Furthermore, early detection of the output coupler failure is possible by observing the hot spots.

Figure 67 shows the thin-disk that was damaged during the cryogenic operation. It was damaged during our early stages of setting the experiment and working out the problems in experimental design setup. At that time we used water cooling for the pump chamber and a lot of water was introduced into the vacuum chamber. It is possible that the small ice particle that formed in the chamber caused initial small damage to the disk, and as we ramped up the power the disk damaged.

Figure 67 Damaged thin-disk at cryogenic operation

Figure 68 shows a 1 mm diameter burn mark on the disk after it was operated at high pump power conditions.
Further studies should be conducted to investigate the cause of damage in the thin-disks at both room and cryogenic temperatures.

3.6 Summary

In Chapter 3 we presented our experimental data. We started with the large test platform and showed the high power operation results, and improvements made by using the heat sinks regarding the beam quality. Then we moved to our novel cooling setup results and discussed the exciting new results, especially those obtained at the cryogenic temperature. Furthermore, we showed the damage that
can occur during high power operation and discussed up-converted light measurements.
4.1 Introduction

Theoretical models have been developed to describe several physical processes that affect the performance of the thin-disk laser. Analysis takes into account the small signal gain profiles, temperature distributions in the gain material under different cooling setups, optical phase distortions and amplified spontaneous emission. To describe our system in detail we employ both COMSOL modeling (finite element analysis) and analytical modeling.

Simulations embrace experimental measurements obtained during the course of developing the models. The experimental data is included in models to make accurate predictions about performance at multi kW high powers. We develop models for ASE and multi-pass pumping for the thin-disk laser. Furthermore, we look at the beam quality, cavity stability and beam divergence.
4.2 COMSOL Modeling

In this chapter heating, stress and thermal deformations in thin-disk laser are evaluated using COMSOL modeling. Concurrent with the experimental inquiry, analytical and numerical techniques are employed. COMSOL is a commercial software that applies numerical techniques based on the finite element method for the spatial discretization. Finite element method provides solution to a wide range of physical problems and gives a possibility of coupling different physical processes. In our case it is thermal conduction and elastic deformations.

COMSOL can solve a wide range of user-defined geometries and we develop and analyze the disk geometry along with the appropriate material constants for each experimental setup and temperature. Cooling is assumed to be constant across the bottom surface of the disk. This is unlike the real situation where cooling is via water jet impingement. This assumption is sufficient to compute the overall disk deformation and surface temperatures. Our solutions are presented in axisymmetric geometry to save computation time. Table 3 shows the material constants used for the assemblies containing heat sinks. Epoxy values are the best estimates, and all values are representative at

\[ T = 100^\circ \text{C}. \text{Tensil strength of YAG is } 175 \text{ MPa}^{55}. \]
Table 3 Material constants

<table>
<thead>
<tr>
<th></th>
<th>Diamond</th>
<th>SiC*</th>
<th>Epoxy (EpoTeK)</th>
<th>Yb:YAG</th>
<th>YAG*</th>
</tr>
</thead>
<tbody>
<tr>
<td>K [W/m°K]</td>
<td>2000</td>
<td>105</td>
<td>0.1&lt;</td>
<td>12.6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>C_p [J/(kg°K)]</td>
<td>800</td>
<td>800</td>
<td>1000</td>
<td>1000</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>ρ [kg/m³]</td>
<td>3520</td>
<td>2975</td>
<td>1200</td>
<td>1200</td>
<td>5200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4540</td>
<td></td>
</tr>
<tr>
<td>E [GPa]</td>
<td>1400</td>
<td>430</td>
<td>3.45</td>
<td>3.45</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>ν</td>
<td>0.07</td>
<td>0.16</td>
<td>0.34</td>
<td>0.34</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>α [ppm°K]</td>
<td>1.2</td>
<td>3.4</td>
<td>193</td>
<td>94</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

Constants in this table are defined as: K = thermal conductivity, C_p = heat capacity, ρ = density, E = Young’s modulus, ν = Poisson’s ratio, and α = thermal diffusion. Index of refraction for Yb:YAG n = 1.82. In Table 4 we list the CuW and Cu/Diamond material constants, as well as known values for EPO-TEC epoxy.

Table 4 CuW and Cu/Diamond material constants

<table>
<thead>
<tr>
<th></th>
<th>CuW 10/90</th>
<th>EPO-TEC EK1000</th>
<th>Cu/Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>K [W/m°K]</td>
<td>195</td>
<td>12.6</td>
<td>545</td>
</tr>
<tr>
<td>C_p [J/(kg°K)]</td>
<td>160</td>
<td>N/A</td>
<td>417.5</td>
</tr>
<tr>
<td>ρ [kg/m³]</td>
<td>1700</td>
<td>N/A</td>
<td>6059.1</td>
</tr>
<tr>
<td>E [GPa]</td>
<td>330</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>ν</td>
<td>0.28</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
CTE for Copper-diamond composites is 7.8 ppm/K between 26-100° C. The Cp is estimated from rule of mixtures, density is measured using Archimedes method, CTE is measured using Dilatometer and thermal diffusivity with Laser flash technique.

There are several challenges we faced while working on COMSOL modeling. For example, thin epoxy layers require generating a fine mesh for convergence. Computations were sped up by scaling z coordinate in the mesh generator by a factor of 10. Going to 3D model requires much longer computing time because of the multiple layers and mainly because of thin epoxy layers. In axisymmetric geometry, computations require second/minutes on the desktop. Introducing one extra dimension would require hours to compute. Due to complexity of our assemblies and limited time frame, we decided that 2D
axisymmetric model is sufficient and accurately describes real thin-disk thermal and stress characteristics.

4.2.1 Large Thin-Disk Test Platform

Figure 69 shows a setup of COMSOL geometry for the large test platform. This is a general geometry that includes YAG cap, thin-disk, heat sink and epoxy layers. We developed several models based on this generalized one, depending on materials, and if the assembly had a cap or a heat sink.

Pump power is common for all computations (3.5 kW). Capped disk heat load is 275W and uncapped load is 375W. These values are determined by fitting the measured data. Doping is 9.8%. Laser output power is 1.3 kW. Thin-disk thickness is 200 microns and diameter of the spot size is 1.8 cm. The YAG ASE cap thickness is 1 mm, and the epoxy layer thickness is 7 microns; in reality this thickness can vary from several microns to 20-30 microns. Four cases are considered – three with a heat sink, and one without. Heat sinks modeled are SiC, diamond, and sapphire. All different thin-disk assembly configurations are set for the jet impingement water cooling.
The model does include thin layer of the epoxy that is necessary to attach SiC and Diamond to the HR coatings on the Yb:YAG. There is also a thin layer of epoxy on the perimeter of the thin-disk attaching it to the CuW solid mount. For the jet water cooled disk, the temperature at the bottom is specified to be constant and non-uniform cooling due to jet impingement is ignored. A ninth order super-Gaussian power distribution is used in the disk. The temperature throughout the disk, as well as the stresses and strains, are computed for various cases.

4.2.1.a No Heat Sink Yb:YAG/YAG Assembly
Our first and simplest configuration is without the heat sink. Yb:YAG gain medium of thickness 200 microns is CADB bonded to 1 mm thick YAG anti-ASE cap. There is a 30 micron layer of epoxy around the edges where the disk is attached to the CuW mount. We model the temperature distribution and plot the surface temperature across the thin-disk, and use 18 mm diameter pump beam.

![Temperature cross-cut and Surface temperature](image)

Figure 70 Water cooled large thin-disk
Figure 70 depicts temperature cross-section and surface temperature plot for the large water cooled thin-disk. Maximum temperature reached is 90°C.

Figure 71 shows the displacement in the z-direction and a graph of surface z-displacement. This displacement is 1.5 microns across the surface of the disk.

COMSOL model for the jet impingement water cooled large setup shows that there is
a relatively small displacement, and surface temperature increase which should not affect the performance of the thin-disk at high power pump power. As we made progress with our experiments, we tested our model as well, and finely tuned heat load parameters to get a more accurate prediction of performance at high power levels.

4.2.1.b Assemblies with SiC, Diamond and Sapphire Heat Sinks

In our effort to further improve the beam quality of the water cooled thin-disk laser, we obtained and tested assemblies with SiC, diamond or sapphire heat sinks. These heat sinks also provided rigid support to our thin-disk assemblies and we were able to test them capped and uncapped.
In this model we consider thermal properties of our heat sink materials. Diamond has a thermal conductivity nearly 5 times greater than that of SiC. However, the thermal expansion coefficient of SiC is much closer to that of Yb:YAG than that of diamond, which will be of significance if extreme thermal cycling is expected.

Figure 72 shows the heating for the case of the capped Yb:YAG/YAG and the uncapped Yb:YAG sample (both with SiC heat sink). It is not possible to utilize COMSOL to describe ASE. ASE heating in the model is incorporated by increasing the pump’s absorption heating term in the Yb:YAG gain media. Excess ASE absorption leads to a significant increase in the temperature of the disk. As seen experimentally in Figure 51 Laser output curves for YAG/Yb:YAG and uncapped Yb:YAG samples, the laser slope efficiency suffers since thermally energized electrons increasingly populate the lower lasing level.
Figure 72 Temperature of the uncapped and capped disks with SiC heat sink

Figure 73 shows the deformation of the capped disk, shown in blue, and uncapped thin-disk, shown in red. This graph is for the thin-disks mounted on the SiC heat sink. There is a difference of 5 microns. This is a small difference in deformation and our thin-disks mechanically performed well in experiments.
Furthermore, we compare the surface temperature across the disk for all three heat sink materials as shown in Figure 74.

![Deformation graph](image)

**Figure 73 Deformation of the capped (blue) and uncapped (red) thin-disks with SiC heat sinks**

Here we see that thin-disk with a diamond heat sink only heats up to 40°C, sapphire up to 60°C, and SiC up to 120°C. In our experiments, diamond and SiC heat sinks were attached to the thin-disk with an epoxy, and sapphire thin-disks were the only ones that could be CADB bonded. However, in the process of the mounting the disk onto a CuW mount our disks with the sapphire heat sink delaminated due to the pressure induced by the epoxy curing process.
Figure 74 Surface temperature across thin-disk for SiC, sapphire and diamond heat sinks

Table 5 summarizes diamond, sapphire and SiC thermal properties, with data for Yb:YAG and CuW.

Table 5 Comparison of SiC, diamond and sapphire heat sink materials

<table>
<thead>
<tr>
<th>Material</th>
<th>CTE (ppm K⁻¹)</th>
<th>Thermal Conductivity (W/cm K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yb:YAG</td>
<td>7.8</td>
<td>0.07</td>
</tr>
<tr>
<td>Diamond</td>
<td>1.5</td>
<td>12</td>
</tr>
<tr>
<td>SiC</td>
<td>2.4</td>
<td>3.6</td>
</tr>
<tr>
<td>CuW-90</td>
<td>6.5</td>
<td>1.47</td>
</tr>
</tbody>
</table>
Under the high power operating conditions, a thin-disk tends to heat up to about 200°C at 12.7kW pump power. The heating leads to elastic deformation of the disk. In order to accurately compute the deformation due to thermal expansion, COMSOL computations in the realistic configuration were performed. The thin YAG disk (200µm) is topped with a 1 mm YAG cap on the bottom, and connected to a copper mount using a thin epoxy layer (10µm). Note that the small thickness of the YAG cap results in some problems for convergence for COMSOL calculations, and a relatively coarse grid on the epoxy is used in order to achieve reliable convergence. We also model the proper cooling of the heat sink from the bottom by using the boundary conditions for the heat flux, \( q = h_0(T - T_0) \), and \( h_0 \) is in the range 10-20X10^4 W/(m^2 K).

For the diamond heat sink max temperature is about 150°C, which is about 30 degrees improvement over the SiC heat sink. Correspondingly, the thermal deformation is also lower (about 15µm compared to 17 in SiC), both due to lower temperature and increased stiffness of the diamond.

During the experiment the high power laser with a diamond heat sink ultimately succumbed to cavity instability and was damaged. The COMSOL model suggests that this occurred due to flexing of the disk assembly. Heat induced stress made the thin-disk to detach from the heat sink. As it turns out,
even very thin layer of epoxy used in the previous calculations acts as a thermal insulator and leads to a substantial increase in the temperature.

The COMSOL modeling results for the large test platform indicate that the layer of epoxy acts as a strong insulator, severely raising temperature of the thin-disk and stresses within the disk. Directly water-cooled Yb:YAG/YAG assembly provides the best thermal management. However, the problem with non-uniformity of the cooling remains due to jet impingement. This thermal imprint was not considered in our modeling effort. We showed that the disk heats up when epoxy is present regardless of what material the heat sink is made of. The sapphire heat sink that is CADB bonded dramatically lowers the temperature of the thin-disk, allowing higher pump power. Stresses and deformations are reduced by direct chemical bonding as well.

4.2.2 Small Thin-Disk Test Platform

We modeled the small thin-disk platform and compared the R-134a with the LN$_2$ cooling systems. Figure 75 shows the 3D image of the RINI cap with the anti-ASE disk on top of it.
The R-134a disk shown in Figure 76, has a maximum temperature at the center of 309°K with a decrease of 16°K at the edge of the spot size. There is a drop of 28°K across the entire disk. Figure 77 shows the thermal and structural plot for the R-134a cooling. There is no flexing of the mount structure, and there is a sag of .2μm for the R134a case, as shown in Figure 78 across the pump beam spot size.
Our model includes all the layers of the assembly, including the YAG ASE suppression cap and Indium solder. The cap is a 1mm YAG disk that is index matched to the active 200μm thick Yb: YAG. This reduces the trapped ASE rays in the doped region and, hence, decreases heating. These two disk configurations were determined by availability of disks and experimental
constraints. The thermal/structural constants of Yb:YAG at these two temperatures are: R-134a: $K = 5 \text{W/m}^\circ\text{K}$, $E=280\times10^9 \text{Pa}$, $\alpha=7.6\times10^{-6}/\circ\text{K}$; LN$_2$: $K=40 \text{W/mK}$, $E=311\times10^9 \text{Pa}$, $\alpha=2.1\times10^{-6}/\circ\text{K}$. $K$ is the thermal conductivity, $E$ is Young’s constant, and $\alpha$ is the thermal expansion coefficient. For the Yb cap $K = 10 \text{W/m}^\circ\text{K}$ and the 33$\mu$m Indium solder layer, constants are constant and determined by COMSOL default values. The absorbed heat load is $180\text{W/m}^3$ modeled as a ninth order super-Gaussian profile. The coloring in these figures shows the temperature distribution of the cross-section.
Figure 77 R-134a thermal and structural plot

Figure 78 R-134a displacement

An estimate of the beam quality due to these small sags in made later in this chapter.
The stress plots for the uncapped and capped disks at R-134a temperatures are shown in Figure 79 and in Figure 80. Azymuthal stress is compressive up to the beam edge then tensile to the edge caused by the radial tensile stress in the un-pumped gain volume. This non-uniformity can lead to disk and bonding failure.
Finally, we model the liquid nitrogen small test platform. This model is particularly important since the heat conductivity increases drastically at cryogenic temperature, and hence, more heat is extracted. For the liquid nitrogen model we use the following parameters shown in Table 6:

### Table 6 Liquid nitrogen model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{abs}}$</td>
<td>65 W</td>
<td>Absorbed Power about 13% incident</td>
</tr>
<tr>
<td>Signal</td>
<td>3.5e-3[m]</td>
<td>Beam Waist/2</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1000 m$^{-1}$</td>
<td>Absorption coefficient</td>
</tr>
<tr>
<td>$P_{\text{in}}$</td>
<td>500 W</td>
<td>Incident pump power</td>
</tr>
<tr>
<td>$P_{\text{out}}$</td>
<td>184 W</td>
<td>Laser Output power</td>
</tr>
<tr>
<td>$T_{\text{oc}}$</td>
<td>.035</td>
<td>Output coupler transmission</td>
</tr>
<tr>
<td>$P_{fr}$</td>
<td>.004</td>
<td>Fraction of laser flux converted to heat flux</td>
</tr>
</tbody>
</table>
For the LN$_2$ case, shown in Figure 81, the center temperature is 93°C to 84°C at the end of the pump spot size and a 15°C drop across the entire disk to 78°C. Thus, for the same heat load the cryogenic temperature decrease is about half of the R-134a temperatures. The deformation presented in Figure 82, shows that the side of the mount caves in as the disk bends convexly. The top and bottom of the 200μm Yb:YAG gain layer are important because the bottom is the HR side and presents a curvature to the cavity, and the difference between the top and bottom contribute to the $dn/dT$ and stress phases.
The major difference between cryogenic and room temperature figures is that the entire disk is pulled down by 24μm due to cooling of the mount at LN$_2$ temperatures; at R-134a temperatures this does not occur.
Finally, we briefly note the stresses. For the uncapped disk at cryogenic temperatures, shown in Figure 83, both the radial and azimuthal stresses are compressive and
uniform, except at the edge.

**Figure 83** CADB stress plot at cryogenic temperature

Furthermore, Figure 84 shows the stress for the case where there is CADB bonding only – in this case the stress is further reduced by an order of magnitude.
Figure 84 Stress plot no CADB at cryogenic temperature

4.3 Analytical Modeling of Amplified Spontaneous Emission

There are two general approaches quantifying various fluorescence problems, such as spontaneous emission, amplified spontaneous emission ASE, and peripherally one may include photon trapping. The first method is mostly analytic typified by following references\textsuperscript{56,57,58,59,60,61,62,63}. The second method is numerical like numerical ray tracing, based on a merging of analytics and ray tracing embodied in references\textsuperscript{64,65,66,67,68}. All of these methods contain their own
particular set of assumptions. The reason for distinct approaches is the complexity of these problem typified, in part, by: a random distribution of emitters, the emitted frequency line shape, polarization, random propagation directions, temperatures and the attendant cross section variations, and stress induced variations. Additionally, the emitted fields are subject to the geometry, pumping volume, indices-of-refraction, surface shape, and so forth.

As can be seen from the above references, ASE in thin-disk lasers is an important and persistent problem. Similarly, ASE has been sporadically studied for several years at AFRL. In the process of taking data for Section 3.1.1, particularly Figure 45 Laser power and efficiency of I cavity, and Figure 46 Laser power and efficiency of V cavity, we measured the gain as a function of input pump power and plotted this data along with the AFRL ASE theory. This fit is good up to gains near 6% at which point the data rolls over due to higher order non-linear processes. Briefly, the theory is built on integration over a Lorentzian emission lineshape, followed by and spatial integration of an
amplified spontaneous point source up to an effective gain length. This length represents the disk geometry, gain volume, and boundary condition. For this experiment it is 43% of the disk diameter.
This section refers to our paper in which we present analytic solutions for multi-pass pump and multi-pass laser configuration for quasi-three level, and four-level (cryogenic) Yb:YAG thin-disk amplifier and laser. We derive expressions for the cw power extraction, slope efficiencies, and threshold. The manifold rate equations are free from nonlinear terms.

In this paper\textsuperscript{70} we generalize earlier work\textsuperscript{71,72,73,74} on power extraction from cw Yb:YAG lasers by including a multi-pass configuration where the pump makes $M$ bounces and the laser makes $N$ bounces through the gain region.

Specifically, we consider the pumping configuration described in reference\textsuperscript{75} extended to include $N$ laser passes for quasi-three level laser and four-level lasers; the latter is appropriate for Yb:YAG cryogenic temperatures below about 150°K. There is considerable work on the higher temperature Yb:YAG and more recent work on cryogenic Yb:YAG\textsuperscript{76,77}. Our expressions are valid for both lasers.
and amplifiers.

4.5 Beam Quality

Our thin-disk lasers operate at high power in multimode, stable resonators with a moderate beam quality. For our application, the generation of high power is only part of the challenge. It is also necessary to obtain high brightness beam\textsuperscript{78}. As the thin-disk laser output power is scaled it is important to maintain the high beam quality. Beam quality in the current state of the art commercially available thin-disk lasers has not been a major issue since they have achieved satisfactory performance for applications used (mainly welding).

As an estimate of the beam quality we calculate $M^2$ for the thin-disk cavity. Our resonant cavity is a two mirror resonator with an outcoupling mirror of radius of curvature $R_1$, and the thin disk mirror of dynamic radius of curvature, $R_2$, induced by heating and stresses. We assume that $M^2$ is proportional to the radius of the pump spot, $r_p$, to the lowest loss Gaussian beam radius at the thin disk, $w_2$.

Thus, we write

$$M^2 = \left( K \frac{r_p}{w_2} \right)^2.$$ \hfill (1)

The constant $K$ describes the pump beam intensity and lasing mode intensity overlap. $K = 1$ is perfect overlap, but it has been estimated to be .85 for thin-disk
laser$^{15}$, which indicates that in practice the multimode Gaussian beam only fills in about 85 percent of the pump spot. For the experiment presented here, the mode filling of the pump spot was nearly complete. These two estimates of $M^2$ are given to provide a representative range of values. At very low pump powers, the thin disk is flat. So that, $R_2 = \infty$. As the thin disk is pumped with increasing pump power, the thin disk thermally bows outward which increases $R_2$. Thermal calculations indicate that $R_2 = 2.5 \text{ m}$ for high pump powers at room temperature. In the cryogenic case, the thin disk does not bow appreciably with pump power. Table 7 summarizes the beam quality values for the thin-disk laser.

**Table 7 Beam quality values for the thin-disk laser**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>L</th>
<th>R1</th>
<th>R2</th>
<th>rp</th>
<th>$M^2$, K=1</th>
<th>$M^2$, K=0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room temperature, Low Power</td>
<td>35 cm</td>
<td>2 m</td>
<td>$\infty$</td>
<td>3.5 mm</td>
<td>49</td>
<td>35</td>
</tr>
<tr>
<td>Room temperature, High Power</td>
<td>35 cm</td>
<td>2 m</td>
<td>2.5 m</td>
<td>3.5 mm</td>
<td>31</td>
<td>22</td>
</tr>
<tr>
<td>Cryogenic</td>
<td>50 cm</td>
<td>2 m</td>
<td>$\infty$</td>
<td>3.5+ mm</td>
<td>43</td>
<td>31</td>
</tr>
</tbody>
</table>

At room temperature for the thin disk laser presented here, the $M^2$ value improves as the thin disk heats up and thermally bows. For this particular case, the $M^2$ is about 35 for low power room-temperature cases the beam quality reduces to near 20 for higher powers at room temperature. For the cryogenic case, the beam quality is near 30.
To further improve the beam quality of the thin-disk laser, we need to look at cavity stability and different resonator designs. Here we consider I and V cavity configurations, and determine the regions where the resonator is in a stable and unstable mode.

The stability of a laser cavity in I and V configurations is considered. A sketch of the two configurations is presented in Figure 85. An I cavity consists of two curved mirrors with radii $R_1$ and $R_2$ separated by a space of length $L$. 

Figure 85 I and V cavity configurations
Corresponding ABCD matrices for this configuration are given by the following formulas:

Free space matrix $S_0 = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$

Left Mirror $T_1 = \begin{pmatrix} 1 & 0 \\ -2/R_1 & 1 \end{pmatrix}$

Right Mirror $T_2 = \begin{pmatrix} 1 & 0 \\ -2/R_2 & 1 \end{pmatrix}$

The stability coefficient is computed as the trace of the product of ABCD matrices taken in order chosen by the ray propagation. Following the ray propagation in the I cavity, the stability coefficient is given by

$g_I = tr(S_0 \cdot T_2 \cdot S_0 \cdot T_1) = \left(1 - \frac{2L}{R_1}\right) \left(1 - \frac{2L}{R_2}\right)$

Here, $Tr$ is the trace of the 2X2 matrix. The condition for stability is of I cavity is then $-1 < g_I < 1$.

The stability of a V cavity is computed in a similar fashion. A V cavity consists of three mirrors – a flat one, and two curved mirrors of the radii $R_1$ and $R_2$, separated from the flat mirror by the intervals of lengths $L_1$ and $L_2$, correspondingly. Light ray will trace a letter “V”, hence the name of the cavity. The corresponding ABCD matrices are given by:

Flat mirror: $S_0 = \begin{pmatrix} 1 & 2L_1 \\ 0 & 1 \end{pmatrix}$
Free space from flat to curved mirror 1: \( S_1 = \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \)

Free space from flat to curved mirror 2: \( S_2 = \begin{pmatrix} 1 & L_2 \\ 0 & 1 \end{pmatrix} \)

Curved mirror 1: \( T_1 = \begin{pmatrix} 1 & 0 \\ -2/R_1 & 1 \end{pmatrix} \)

Curved mirror 2: \( T_2 = \begin{pmatrix} 1 & 0 \\ -2/R_2 & 1 \end{pmatrix} \)

The stability coefficient for the V cavity is then

\[ g_V = \text{tr}(S_2 \cdot T_2 \cdot S_2 \cdot T_1 \cdot S_0 \cdot T_1) \]

We chose not to present the expression for \( g_V \) here, as it cumbersome and difficult to analyze. Instead, we multiply the corresponding ABCD matrices directly in MATLAB in order to obtain numerical expression for the stability. Again, the V cavity is stable if \(-1 < g_V < 1\).

In Figure 86 we plot \( g_I \) (blue line) and \( g_V \) (red line) as a function of \( R_2 \), holding the other parameters fixed. The limits of stability (\( g_I = 1 \) and \( g_V = 1 \)) are plotted with dashed lines.
In order to compute the beam divergence, we define the complex beam parameter $q(z)$ as

$$\frac{1}{q(z)} = \frac{1}{R(z)} - i \frac{\lambda}{\pi w(z)^2}$$
where $R(z)$ is the radius of curvature of the wavefront, and $w(z)$ is the waist size of the beam at the distance $z$ along the optical axis.

In this calculation, we additionally incorporate the lens thickness by introducing the matrices

$$F_1 = \begin{pmatrix} 1 & n_l \end{pmatrix} \quad \text{and} \quad F_2 = \begin{pmatrix} 1 & n_l \end{pmatrix},$$

where $l_1$ and $l_2$ are the thicknesses of the first and second lens, correspondingly. We also introduce the matrix of free propagation in space distance $z$ away from the second lens as

$$F(z) = \begin{pmatrix} 1 & z \end{pmatrix} \begin{pmatrix} 0 & 1 \end{pmatrix}$$

Let us define ABCD matrices for the I cavity as

$$\begin{pmatrix} A(z) & B(z) \\ C(z) & D(z) \end{pmatrix} = S_0 \cdot T_2 \cdot F_2 \cdot S_0 \cdot T_1 \cdot F_1 \cdot F(z)$$
using the ABCD matrices for l cavity defined before. The waist of the laser beam after distance z can be computed from the equation for the complex beam parameter:

\[
\frac{1}{q(z)} = \frac{A(z) + B(z)/q_0}{C(z) + D(z)/q_0} = \frac{1}{R(z)} - i\frac{\lambda}{\pi w(z)^2}
\]

where \( q_0 = q(0) \) is the value of the complex beam parameter at \( z=0 \). Again, we do not present analytic formulas for \( q(z) \) as they are cumbersome, although they can be obtained using a symbolic calculation package like Mathematica. Instead, we simply program the matrix multiplication in MATLAB and compute ABCD matrix for a range of \( z \). For the initial conditions, we take flat front \( R_0 = \infty \) and \( w_0 = 9 \text{mm} \) (radius of the beam being equal to the radius of the disk), where \( R(z) \) is the radius of curvature of the wavefront, and \( w(z) \) is the waist size of the beam at the distance \( z \). Then, \( q_0 = -i\lambda / (\pi w_0^2) \), which allows to compute \( q(z) \) for an arbitrary \( z \).

The radius of the wave front and beam waist are computed from the equations

\[
\frac{1}{R(z)} = \text{Re}\left(\frac{1}{q(z)}\right) \quad \text{and} \quad \frac{\lambda}{\pi w(z)^2} = -\text{Im}\left(\frac{1}{q(z)}\right).
\]

The results of these computations are presented below. The divergence of the beam is estimated to be about 5-10% of the original thickness at the distances of 100m. We also did calculations for the super Gaussian beam propagation and the results were almost identical.
4.8 Summary

In Chapter 4 we presented theoretical modeling of thin-disk configurations we tested experimentally. We described the COMSOL finite element model for large test platform, including assemblies with and without heat sinks, and with and without anti-ASE YAG caps. Then, we described models for the small thin-disk test platform, operating at room and cryogenic temperatures.

The idealized model scenario only exists when the material, optical coatings, and attachment techniques are perfected. These are engineering challenges that can be overcome. The more fundamental problem to attack lies
with the inevitable ASE production in the Yb:YAG. This is difficult to theoretically predict. We developed a theoretical model to quantify the ASE in high power thin disk operation, as well a model generalizing thin-disk laser for M number of pump passes and N number of bounces through the gain region. This modeling takes into account both quasi-three level system, as well as four level system laser.

Finally, we focused on beam quality improvements, and discuss cavity stability and a resonator characteristics. Each one of these efforts explained thin-disk performance and helps pave the path to a high power, high brightness thin-disk laser required for defense applications.
Chapter 5 Conclusion

The long-term objective of Air Force Research Laboratory thin-disk laser research is to build a high beam quality, high efficiency, high power laser. We built the highest power, most efficient ceramic thin-disk laser in the world. In order to further improve and optimize this system, our research turned towards investigating and resolving thermal and stress related problems. Thus, we studied capped and uncapped disks, various substrates and bonding materials and techniques. All this was done at high pump powers near room temperature and cryogenic temperature. We tested thin-disks on four separate test platforms.

Mitigating thermal and stress related issues leads to a minimization of disk deformation, improvement in overall efficiency, and ultimately increases in the total laser power. A further necessary step in this direction pertains to understanding all aspects of thin disk lasers. We conducted physics-based research regarding small signal gain, amplified spontaneous emission, and thermal issues. Furthermore, in the course of building and performing our experiments many opto-mechanical engineering problems were encountered, improved and resolved.
The large thin-disk test platform experiments showed that the use of the intermediary heat sink improves the beam quality, since the thermal lensing imprint is effectively removed. We were also able to test assemblies with and without the anti-ASE caps. The difference in performance between the uncapped and capped thin-disk lasers was huge. Uncapped disks heated approximately 30% more than the disks with the anti-ASE caps. These experiments prompted us to consider other solutions to the ASE problem, such as using thin-disks without the anti-ASE cap but with beveled edges, or with diffused surfaces outside the pump beam diameter. Furthermore, we made initial collaborative efforts to use a novel copper-diamond material in our assemblies for improved thermal conductivity, and elasticity of our mounts.

We collaborated with different vendors. RINI developed two new cooling systems: R-134a and LN$_2$, both with the same, interchangeable, mounting cap design. The results of cooling with R-134a system proved to be comparable to water jet impingement on the small test platform. A further improvement is that the vendor (RINI Technologies) already has a multiple nozzle two-phase boiling cooling systems for cooling larger surfaces. This means that they could design a special multi-nozzle cooling system to be used instead of water jet-impingement on the large platform. The main advantage of a RINI two-phase boiling design, besides the better heat removal capacity, is that system can be used for cooling at both room and cryogenic temperatures.
Precision Photonics and Enerdyne worked under AFRL direction to develop a void-free Indium soldering mounting process for thin-disk assemblies. Improper bonding negates any benefits gained from using materials with improved thermal conductivity, so it was critical to develop a repeatable process to mount our thin-disks to a RINI designed cap. In a new proprietary concept, Precision Photonics provided Yb:YAG samples that were bonded using CADB, thus completely eliminating the Indium solder layer to bond the thin-disk to the mounting cap.

Our raw ceramics material came from Konoshima, Japan, but we also tested material manufactured in USA by Raytheon. Spectroscopic results show that Raytheon material is of good optical quality and that it would be possible to fabricate the thin-disk entirely in USA. Furthermore, we demonstrated that it is possible to use the fiber-coupled diode in our small setup to make system more robust and compact. Thus, the requirements for clean environment are reduced as well, for a contained, fiber coupled system.

Novel cooling setups were built for room temperature and cryogenic temperature testing. First RINI system that we built uses R-134a refrigerant, and second system uses liquid Nitrogen to remove heat from the back of the thin-disk. We tested different assemblies on both test platforms. The tests showed that the heat removal capability, and the laser output results of the new R-134a system are comparable to that of the small platform setup with water jet
impingement cooling. We also looked at the wavefront deformation of the laser output beam with this setup.

Finally, we built the cryogenic test platform. The advantages of using the cryogenic setup as compared to room temperature were: diode absorption is higher, optical cross-section increases by 4x, extraction efficiency is significantly higher due to reduced scattering losses and higher gains, thermal conductivity is 4-5X higher, coefficient of thermal expansion is 3X smaller and index of refraction change with temperature is \( \frac{1}{4} \) as large. Consequently, overall efficiency was improved, intra-cavity flux was lower, as well as thermal loading.

In summary, we demonstrated that cooling a 0.2mm thick, 14mm diameter, 9% Yb-doped ceramic Yb:YAG thin-disk from 278°C down to 77°C results in a laser threshold drop from 155W to near 10W. The threshold at the room temperature operation was between 150-160W. The cryogenic slope efficiency reached 63%, and the laser generated 277W from a 500W pump. A novel two-phase spray cooling method mitigates the heat produced within the Yb:YAG. In the cryogenic case LN\(_2\) overflow cooled the optics and prevented condensation. Yb:YAG disks were Indium mounted to CuW caps that are interchangeable between the two systems. Hence the same disk was tested with cooling at 268 to 288°C (R-134a) and also at 77°C (LN\(_2\)). Material damage due to cycling the temperature from room to 77°C was not observed. This is ostensibly due to the soft and thick Indium layer that buffers the tensile strain of the cap on the disk. The cryogenic results can be readily improved with wavelength
stabilized pump diodes, minor refinements to the pump coupling, and optimization of the material characteristics.

A realistic path towards the ultimate high power thin-disk laser would commence with wavelength-stabilized fiber laser pump delivery (robust and compact with improved beam quality). The resonator design can be improved with superior composite materials that combine diamond-like thermal conductivity with designed expansion coefficients. New gain media material such as Lutetia, Yb:Lu2O3, are an advancement over YAG. And complex resonator cavities can operate in the unstable mode for better beam quality as well. Any and all of these topics create a wealth of possibilities for innovative future research.
Appendices

A Fused silica rod specifications

Regarding: Quotation fused silica rod

Specifications homogenizing rod

- Material: fused silica with lowest absorption at 940 nm (lowest OH and water content) e.g. Heraeus Suprasil F300, Infrasil 301
- Quantity 2
- End faces polished for laser applications with surface planity of lambda
- Cylindrical shell and facets free of grooves
- Perpendicular end face with AR coating at 0° +/- 16° R<0.1%
- Tilted end face (60°) with AR coating from 27° to 75° R<0.1% (all angles with respect to surface normal)

Thank you and best regards,

Christian Stolzenburg
VersaDisc line produces output powers from 10 to 100 W and targets industrial and research applications. The company claims its laser has a perfect Gaussian beam intensity distribution and that higher power levels are possible by changing pump sources. Its novel pumping geometry directs the pump beam 24 times through the crystal, providing a long effective absorption length without the negative effects associated with conventional rod-based solid-state lasers.

ELS planned to launch a frequency-doubled version in October, according to CEO Günter Hummelt. "This emits more than 5-W output power at 515 nm, and applications for the laser include spectroscopy, interferometry, printing and holography." He added that it is ideally suited to pump Ti:sapphire lasers because the emission wavelength fits perfectly with the absorption of the Ti:sapphire crystal.

The company’s mode-locked version could be available by spring. The fundamental line at 1030 nm generates subpicosecond pulses with expected peak powers up to 50 MW. ELS aims mainly for research markets, where it has sold several systems. The area where Yb:YAG lasers have the most potential, however, is the thin-disc Yb:YAG laser.

## How Thin-Disc Yb:YAG Lasers Work

The thin-disc Yb:YAG laser combines two ideas into one powerful laser: thin-disc geometry, which gives high beam quality at high powers, and Yb:YAG crystal, which can be pumped with 940-nm diodes. Yb:YAG crystals also have a longer upper-state lifetime than their neodymium-doped counterparts. As their name suggests, thin-disc lasers use crystals shaped into discs that are typically 200 μm thick and 10 mm in diameter. A diode laser quasi-end-pumps the disc on one of its faces while a heat sink on its other face provides cooling. A compact mirror system passes light through the crystal many times to generate high absorption. The coated back side of the crystal acts as an end mirror in the laser resonator.

One advantage of the disc geometry is that cooling runs parallel to the direction in which the laser beam spreads (i.e., in an axial direction). This gives only a small radial temperature gradient and prevents much of the beam distortion from which most other solid-state lasers suffer. The geometry also means that the laser has a large ratio of surface area to volume, allowing efficient cooling.
List of References


41 ProcedureThinDisk.doc


43 A. Giesen Private communication


http://www.epotek.com/


http://www.rinitech.com/

http://www.precisionphotonics.com/

http://www.enerdynesolutions.com/


61 Dmitrii Kouznetsov, Jean-François Bisson, Jun Dong, and Ken-ichi Ueda,


26, 26-35 (2009).


