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CRYOGENIC Yb: YAG THINN-DISK LASER

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Cryogenic Yb:YAG Thin-Disk Laser

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ABSTRACT

At cryogenic temperatures, Yb:YAG behaves as a 4-level laser. Its absorption and emission cross-sections increase, and its thermal conductivity improves. Yb:YAG thin disk laser performance at room and cryogenic (80°K) temperatures will be presented. The Yb:YAG gain media is cooled using either a pressurized R134A refrigerant system or by a two-phase liquid nitrogen spray boiler. Interchangeable mounting caps allow the same Yb:YAG media to be switched between the two systems. This allows direct comparison of lasing, amplified spontaneous emission, and temperature performance between 20°C and -200°C.

1. INTRODUCTION

In this manuscript we report the improvement in power extraction, lasing threshold, and thermal distortion of a cryogenic ceramic Yb:YAG thin disk laser operating at a initial temperatures near 77K, as compared to the same system operating near 280K. These correspond to LN2 and R-134 coolants. We show that for the same resonator the threshold drops dramatically by a factor of 50 while the slope efficiency changes from 54% (280°K) to 63% (77°K). These changes are all, for the most part, manifestations of the differences between quasi-three levels and four level Yb:YAG.

Cryogenic solid-state laser materials offer many improvements in thermo/optical, structural, and lasing properties. And a number of Yb:YAG lasers have been investigated for cryogenic operation [1-11]. 85% slope efficiency has been achieved [1] and later on the same laser configuration produced 300W with an optical-to-optical efficiency of 60% [2]. Later the same group increased the power to. Yb:YAG disks have produced optical-to-optical efficiency of 42.2% with an output of 963W [6]. In 1999 Kasamatsu et al. [11] studied low power (<2.5W) Yb:YAG lasers as a function of temperature from 313°K to 77°K. Cooling was via a liquid-nitrogen dewar.

2. EXPERIMENTAL SETUP

Figure 1(a) shows a 2-D cross section of the experimental setup. The Evaporative Spray Cooling (ESC) nozzle unit (S) directs coolant into the interior of the copper-tungsten (CuW-90) cooling cap (C). Yb:YAG thin-disk material is attached to the cap using a void-free thin layer of Indium solder. Since the cap will be cooled to 80 °K, the layer of indium is thicker than that which would be necessary for room temperature operation. This is to alleviate stresses from the large difference in expansion between the cap and Yb:YAG. Samples averaged an indium thickness of 20 µm. 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

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to the Yb:YAG and the output coupler (OC R=95-99%) on the other. The resonator at room temperature was 35cm long. In the cryogenic case it is 50cm long. The pump spot size is approximately 7mm at room temperature with a nearly supergaussian. In the cryogenic case the profile is not an ideal flat top with a spot size slightly greater than 7mm. An image of the pump on the disk is shown in Fig. 1(b) for the cryogenic case. Bright spots are scattering sites. The white circle denotes the edge of the disk. The difference in pumping between the room and cryogenic case is due the lens train (L in Fig. 1). For cryogenic lasing there is a need to pass the pump through a sapphire port in the vacuum chamber, see below. As a consequence the pump spot is not perfectly circular and top-hat.

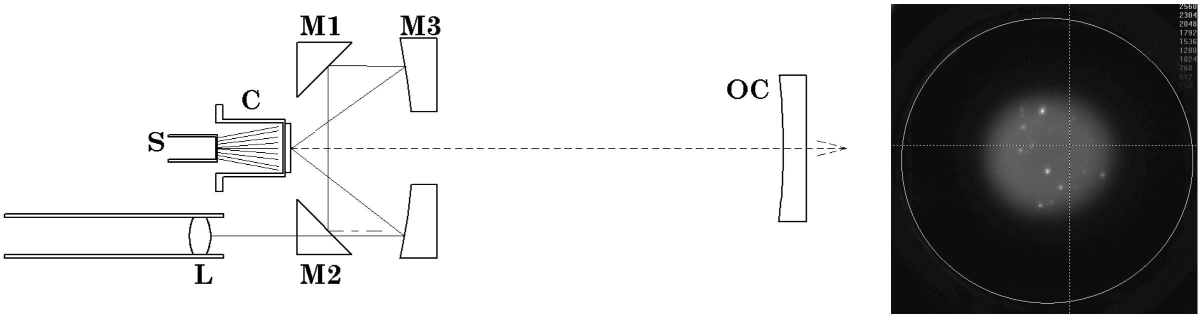

Figure 1. (a) Experimental Setup. (b) Pump beam imaged on thin-disk.

To manage the high heat loads an advanced two-phase Evaporative Spray Cooling (ESC) technique, developed by the RINI Corporation (Orlando, FL), is utilized. Two versions were constructed. R134A refrigerant is the coolant in one. This system can maintain the disk temperature near 290 $^{\circ}$K with a convective heat transfer coefficient of 80,000 W/m^{2}K. A second system uses liquid nitrogen, LN_2. Traditional LN_2 cryostats are limited to fluxes on the order of 20-25W/cm^2. The two-phase technique consistently removes heat fluxes of 100W/cm^2 and has even removed heat fluxes as high as 160W/cm^2. This cooling system utilizes an open cycle design comprised of a nozzle located at the bottom of a stainless steel reservoir mounted on a base. The reservoir is designed to vent excess bubbles generated by an ambient heat leak, thus enabling a consistent spray. Heat generated by the thin disk is removed by the liquid droplets impinging on the inner surface of the interface cap and vaporizing which cools the crystal through a two-phase heat transfer process. The generated vapor and any remaining liquid exit an exhaust fitting on the base section of the reservoir/nozzle assembly. The measured convective heat transfer coefficient across the cap is 123,000W/m^{2}K.

RINI's LN_2 spray cooling system utilizes an open cycle design, and is comprised of a stainless steel reservoir, a nozzle assembly located at the bottom of the reservoir, and a base with a dovetail feature that facilitates mounting of the cooling hardware to the translation stage in the laser cavity. RINI's LN_2 ESC prototype system was designed to interface with AFRL's 14 mm diameter thin disk laser amplifier geometry which operated in a vacuum chamber to minimize ambient heat leaks and to avoid moisture forming on the laser cavity components. The LN_2 is supplied from a standard non pressure building LN_2 Dewar tank that is pressurized to the desired supply pressure with a Gaseous Nitrogen (GN_2) tank. The reservoir is designed to vent any excess bubbles generate due to ambient heat leak into the system as depicted in Fig. 2; enabling consistent spray cooling conditions. As heat is generated by the thin disk laser assembly the heat is removed by when the liquid droplets impinging the inner surface of the interface cap vaporize and effectively cool the laser crystal through a two-phase heat transfer process. The vapor generated during cooling along with any remaining liquid exit out an exhaust fitting on the base section of the reservoir / nozzle assembly. RINI demonstrated the ability to remove 120 watts of waste heat per cm^2 using the LN_2 spray cooling system which is many times greater than can be achieved by traditional cryostat pool boiling methods. When used with R134A refrigerant, the Yb:YAG and cap is identical but there is no dewar and the spray nozzle assembly is different.

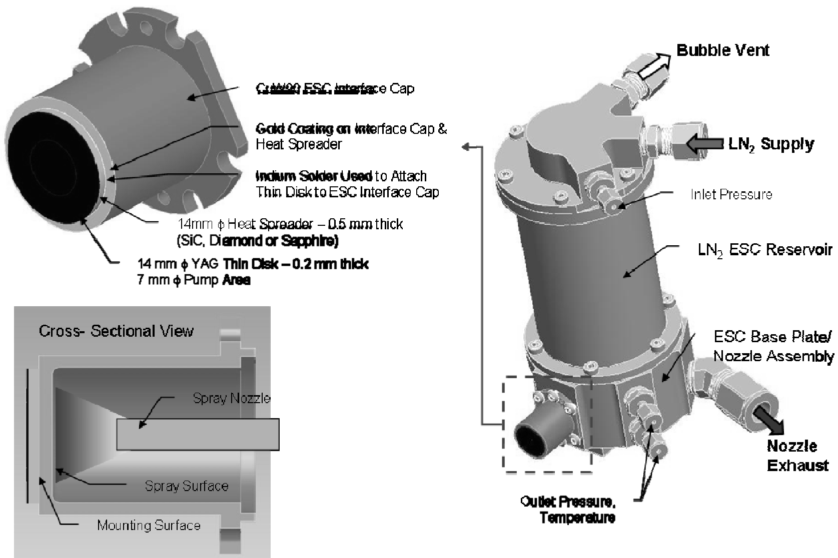

Figure 2. LN2 Spray Cooling System and Interface Cap

In the laboratory experiments, the difference in the two systems is the environment. For cryogenic operation, the entire thin-disk laser is placed within a vacuum chamber so as 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 in through a port. This necessitated a different set of optics to effectively collimate and launch the pump light into the thin-disk resonator. And this resulted in a modest degradation in the cumulative beam that is incident on the disk surface. In either case, the laser pump power is increased slowly so as to allow a thermopile detector time to settle. For room temperature operation (R134A) a thermal camera is imaged onto the disk surface to track the surface temperature increase. The camera was not calibrated at cryogenic temperatures and not used when the disk was LN_2 cooled.

The spray system requires that the thin-disk is attached to the mounting cap over its entire area. Flux-less Indium soldering process was developed by Precision Photonics (Boulder, CO) and Enerdyne Solutions (North Bend, WA). The mounting worked well for both cryogenic and room temperature operation. Both capped and uncapped ceramic Yb:YAG thin-disk gain material was tested. The uncapped gain media is 200µm thick, 9.8% Yb-doped, 14mm diameter provided by Konoshima Corporation (Japan). The gain media is coated with a high reflective coating on one end. Capped thin-disks have the gain media bonded to undoped and antireflection coated for 940/1030nm YAG. Precision Photonics bonds them using the chemically activated direct bonding (CADB) technique.

We modeled our cryogenic disk/mount structure using the FEM software COMSOL. This shows that as the temperature is reduced from room to cryogenic to 77°K the sides of our mount cave inward such that the top of the mount drops about 9µm, but remains flat. If a heat load of 65W is applied as a 9th order supergaussian with a spot size of 7mm the capped surface has a temperature rise from 77 to 89°K, which is true of the bottom of the doped region as well. The deformation of the top surface is quadratic with a 2µm sag over the spot size. The Indium solder layer plays its role by reducing the stresses on the boundaries.

3. MEASUREMENTS

3.1 Power and Optical Spectra

Figure 3(a) shows the lasing power versus the incident pump power at room temperature, 20°C, using R134A refrigerant and 80°K using liquid nitrogen. In both cases, the laser cavity incorporates a 98% reflective output coupler with a 2m radius of curvature. The room temperature lowest lasing threshold is 155W at which point the disk surface temperature is 308°K. The slope efficiency is 54%, and the slope remained linear throughout the 500W pump range. At 510W the power reached 184W.

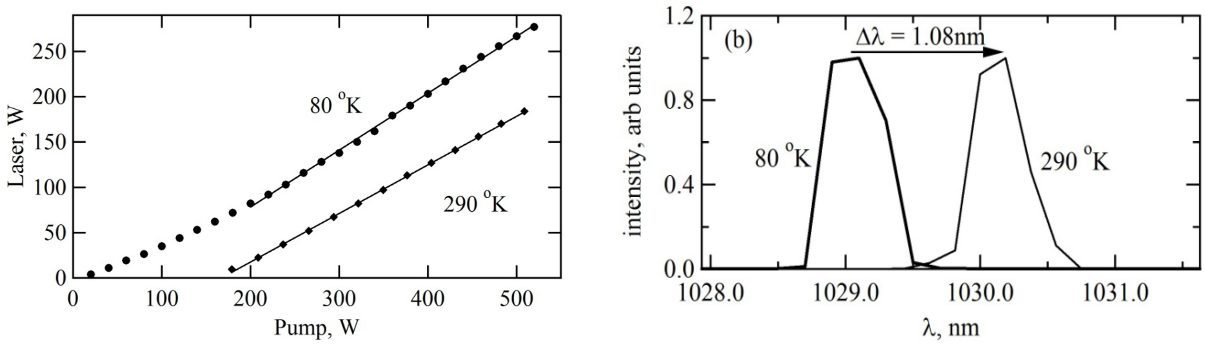

Figure 3. (a) Lasing power at 290°K and 80°K (b) Laser emission at 290°K and 80°K.

In stark contrast to the R134 results the cryogenic laser threshold plummets to near 10W. This is an emphatic demonstration of the superiority of a near 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. 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 only a 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.

Figure 3(b) shows the lasing line at the two temperatures when the laser power for both is nearly equal. The wavelength red shifts 1.08nm over the 210°K range. The shift is due to the population increasing in the lower manifold as can be computed using the Boltzmann distribution.

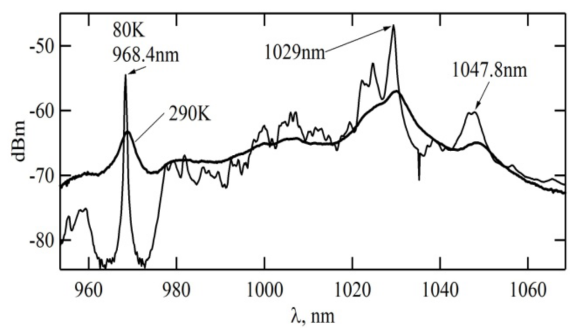

Figure 4. Amplified Spontaneous Emission spectra at 77°K and 280°K.

Figure 4 shows the amplified spontaneous emission (ASE) on axis when thin-disk is pumped with a low power, 25W, and 915nm pump source. No output coupler optic is in place in order to eliminate lasing. A 50μm multimode fiber is placed near the surface so as to capture emission emitted vertically from the disk face. Captured light is launched into to an Agilent 86146B Optical Spectrum Analyzer. The material is ceramic Yb:YAG. The disk is subsequently cooled to 80 °K 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. Interestingly, there is a strong dip in the cryogenic emission spectra around the 968nm zero phonon line. This dip is due to the collapse of homogeneous broadening since $k_bT = 55$ cm^{-1} at 80°K. The width of this dip is 8.2nm on both sides of the line.

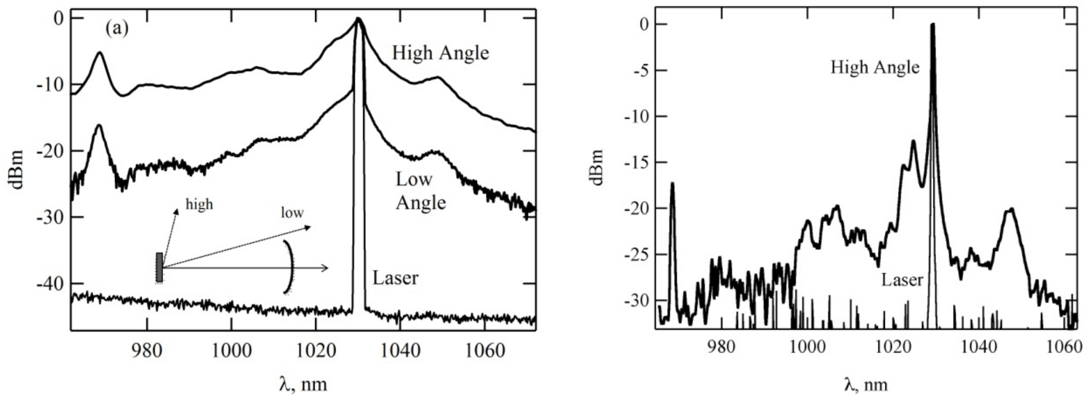

Figure 5. Emission spectra at (a) 280°K (b) and 77°K and emitted from high and low angles from the disk face.

In the lasing situation, amplified spontaneous emission (ASE) emitted at a high angle (~80^o) and a low angle (~12 ^{o}) from the optical axis of the disk was measured. This spectrum is shown in Fig. 5. The cartoon inset in Fig. 5(a) shows the emission angles. Here the output coupler is in place and the laser is operating with a pump of 180W. The laser power is 72W at77°K and 7W at 290°K. A direct comparison between ASE spectra in room and cryogenic cases is difficult due to different experimental arrangements, and power levels. 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.

In Fig. 5(a), the room temperature spectrum at a large angle shows a very broad spectral signature peaked at the 1030nm lasing line. The 969nm and 1048.8nm peaks are only 4.4dBm and 8.2dBm less than the laser peak intensity. This emission leads to an increase in heat in the disk and a siphoning of the available gain in the media. Great effort has been spent on suppressing the ASE in the radial direction (undoped caps or beveled edges for example). At the low angle, the emission is much more strongly peaked at the lasing line. The on-axis laser spectrum only shows the main emission. At cryogenic temperatures, Fig 5(b), There is a much stronger reduction in ASE away from the main emission line. The zero-phonon 969nm line is 17.1dBm less than the 1029nm peak while the peak at 1048.8nm is 20.2dBm lower. There is a strong reduction in spurious ASE generated when Yb:YAG is behaving as a 4-level laser.

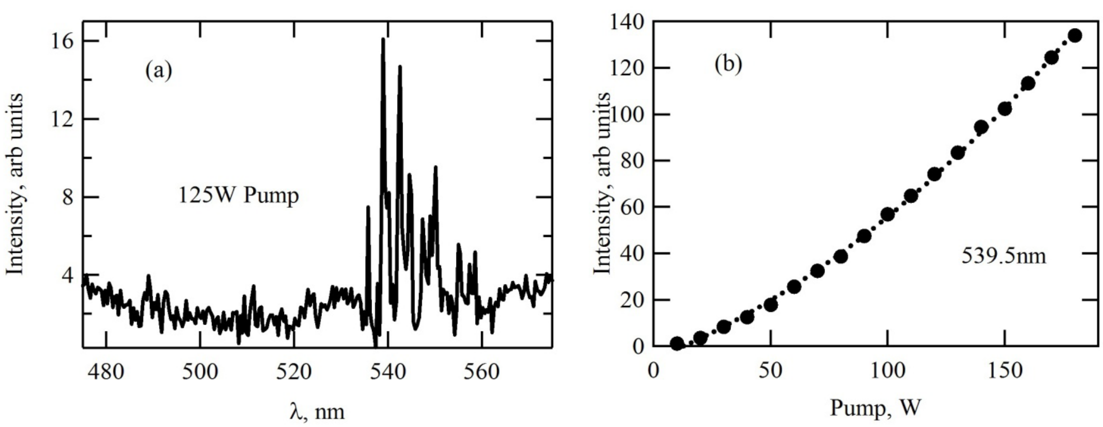

Figure 6. Up-converted light. (a) Spectra at 125W pumping. (b) Power versus incident pump.

3.2 Up-Converted light in Yb:YAG

An intriguing question with respect to Yb-based lasers (Yb-silica fiber lasers as well as Yb:YAG) concerns the significance of up-converted light. Yb is a simple ion with only 2 manifolds. Yet when pumped, light in the range of 500 to 550nm is easily observed. This greenish colored glow is often considered to be due to ytterbium clustering. Using an Acton Research 2m monochromator to disperse the light the up-converted signal was studied. For this room temperature experiment the 940nm pump light was chopped and focused onto the Yb:YAG ceramic disk in a simple 2-pass arrangement. A pair of 650nm shortwave pass filters blocked scattered pump and the ASE around 1µm. The signal was detected with a cooled photomultiplier tube and SRS 850 Lock-In amplifier. Figure 6(a) shows the spectral signature. Emission ranges from 535mn to 560nm, and the peak intensity is near 540nm. The spiked nature of the signal is likely due to the existence of Fabry-Perot modes in the Yb:YAG. Figure 6(b) shows the intensity of the up-converted signal at 539.5nm as a function of the incident pump power. It does show some evidence of superlinear behavior. However the signal is very weak. Hence we do not feel that up-converted light is a significant issue in thin-disk Yb:YAG lasers. However, it may be useful as a diagnostic for Yb:YAG. It has been suggested that in ceramic materials doped with Ytterbium, Yb ions may migrate and cluster on the grain boundaries. If this is the case, then the up-converted signal may be stronger in ceramic media than in single crystal Yb:YAG where Yb should be fixed in the lattice.

3.3 Beam Quality, M^2, for a Thin Disk Laser

As a measure of beam quality, the term M^2 has developed out of the theory of Gaussian modes. The properties of the Gaussian modes are discussed in Siegman [12]. In the thin disk case, the resonant cavity is usually 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. The two mirrors are separated by the mirror separation, L. The higher order radial Gaussian modes and a Gaussian multimode beam grow in size as a function of the radial mode index. The higher order modes follow a similar quadratic profile with the beam radius scaled everywhere in z by the scaling factor M. The beam divergence is also scaled by a factor of M. The M^2 value or the mode quality [13] is determined by calculating the quadratic envelope or measuring the quadratic envelope of an actual laser beam and determining the fit parameters for a quadratic curve. Determining the M^2 value depends on what particular measurement scheme is used and what choices are made for values within the fitting process. In the thin disk laser two mirror cavity, the multimode Gaussian beam also has a quadratic shape. M^2 is based upon the comparison of the multimode beam to an ideal TEM_{00} beam. A convenient place to accomplish the comparison for thin disk lasers is at thin disk. The lowest loss Gaussian beam radius, w_2, at the thin disk is given by Siegman in Ref 1. The M^2 is given as the ratio of the radius of the pump spot, r_p, to the lowest loss Gaussian beam radius at the thin disk, w_2. The theoretical M^2 for the thin disk laser is given by

$$M^2 = \left(\frac{r_p}{w_2} \right)^2 \quad , \quad M_G^2 = \left(0.85 \frac{r_p}{w_2} \right)^2 \quad . \quad (1)$$

The second expression, M_G^2 comes from Adolph Giesen [14] who indicates that in practice for thin disk lasers 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, $R_2 = \infty$ and $g_2 = 1$. As the thin disk is pumped with increasing pump power, the thin disk thermally bows outward which increases R_2. Thermal calculations indicate that $R_2 \approx 2.5$ m for high pump powers at room temperature. Note that our experimental wavefront sensor measurements indicated a value of 2.66m radius of curvature at a 250W laser power for the room temperature case. In the cryogenic case, the thin disk does not bow appreciably with pump power.

Parameter	L	R_1	R_2	r_p	M^2	M_G^2
Room temperature, Low Power	35 cm	2 m	∞	3.5 mm	49	35
Room temperature, High Power	35 cm	2 m	2.5 m	3.5 mm	31	22
Cryogenic	50 cm	2 m	∞	3.5+ mm	43	31

Table 1. Beam Quality Values for the Thin Disk Laser

At room temperature for the thin disk laser presented here, the M^2 value improves as the thin disk heats up and thermally bows. In other thin disk experiments, the bowing became so severe that the resonant cavity was driven to be unstable [15]. 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. At low power the M^2 can be reduced when only a few transverse modes are above threshold. For the cryogenic case, the beam quality is near 30.

4. SUMMARY

In summary we demonstrated that cooling a 0.2mm thick, 14mm diameter, 9% Yb-doped Yb:YAG thin-disk from 5°C down to -195°C results in a laser threshold drop from 155W to near 10W. In concert, the 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. Two systems, one using R134A and LN2 for the other, were built. Yb:YAG disks are Indium mounted to CuW caps that are interchangeable between the two systems. Hence the same disk can be tested with cooling at -5 to 15°C (R134A) and also at -195°C (LN2). Material damage due to cycling the temperature from room to -195°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. These initial cryogenic results can be readily improved with wavelength stabilized pump diodes, minor refinements to the pump coupling, and optimization of the material characteristics. The beam quality is poor, which is due to the large pump spot on the surface of the thin-disk that excites many lasing modes.

It is quite likely that substantial improvements can be gained using this form of cryogenic cooling. The 98% output coupler optic and 0.2mm disk thickness are optimal for R134A or water cooling methods. They were used here for direct comparison. Brown [16] 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 [17] 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.

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