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Laser Material Processing Final Report CRADA No. TC-321-92

L. Hackel, R. Walker

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Laser Material Processing

Final Report

CRADA No. TC-321-92

Date: November 27, 1996

TACT: Microelectronics and Photonics

Revision:

A. Parties

The project is a relationship between the Lawrence Livermore National Laboratory (LLNL) and Rofin-Sinar, Inc.

University of California
Lawrence Livermore National Laboratory
7000 East Avenue, L-XXX
Livermore, CA 94550

Rofin-Sinar, Inc.
45701 Mast Street
Plymouth, MI 58170

B. Project Scope

Current commercial cw flashlamp pumped solid-state laser systems employed in laser machining operate at multi-hundred watt to kilowatt levels and produce 30-100 times diffraction limited beam quality. Developing similar power lasers but with a beam quality 5-10 times better is an important advancement in the laser machining industry especially precision laser machining. For example, fiber delivery of > 30 times diffraction limited systems require large diameter (> 600 μm) and large numerical aperture ($\text{NA} > 0.2$) fibers. The primary disadvantages of such fiber delivery systems are poor depth of focus, short work piece standoff, and large focal diameter. The advances demonstrated as part of this CRADA would permit small diameter (200-400 μm) and low numerical aperture ($\text{NA} = 0.12-0.2$) fiber delivery systems to be used for much higher precision laser machining than currently possible. In addition, the systems developed here could also be employed in high intensity (W/sr) pulsed applications, for example, precision cutting and drilling of ceramics and other difficult materials

Rofin-Sinar's goal is building a high power (> 1 kW), small diameter (200-400 μm), low numerical aperture ($\text{NA} = 0.12-0.2$) fiber delivery system. LLNL's goal is to demonstrate a high power cw diode-pumped solid-state laser (DPSSL) system producing high beam quality output with high extraction efficiency. Specifically, LLNL's initial focus is to demonstrate moderate cw power (50-500 W) with high beam quality (1-20 times diffraction limited) from a diode-pumped laser system. Our strategy for meeting this goal is discussed in detail below, but can be summarized by several important design criteria:

1. Minimize the rod diameter.
2. Maximize the gain.
3. Produce uniform gain across the rod diameter.
4. Employ high cross section laser material.
5. Employ a diode-side-pump geometry.
6. Keep the thermal lens focal larger than the rod length.

An additional goal of this program is to credibly scale such lasers to kilowatt levels.

CRADA Milestones

As part of this CRADA we achieved the following milestones:

1. Demonstrated 275 W cw with < 15 times diffraction limited output from two diode-pumped Nd:YAG rods.
2. Demonstrated 160 W with ~ 3 times diffraction limited output from a single diode-pumped Nd:YAG rod.
3. Demonstrated 60 W cw TEM₀₀ (1.2 times diffraction limited) from single diode-pumped Nd:YAG rod.
4. Demonstrated primarily spherical and correctable rod aberrations under high power diode pumping. This is important for credibly scaling systems to higher average power.
5. Demonstrated birefringence compensation under high power diode pumping. This is important for high power short pulsed (< 40 ns) laser machining requiring EO q-switching and intracavity polarizer.
6. Fully characterized energetic and thermal performance of diode-side-pumped Nd:YAG DPSSL.
7. Fully characterized resonator performance.
8. Developed a full suite of cw energetic and thermal laser performance models and resonator design codes and validate them through laser experiments.

C. Technical

Program Strategy

The primary limitation of current commercial flashlamp pumped cw laser systems for producing high beam quality is the large number of transverse modes supported by typical stable resonators employed in these systems. Since flashlamp pumping deposits considerable heat into the rod per unit of stored power, a large rod (typically 6-7 mm diameter) is used to keep the thermal lensing manageable. Usually, the design criterion is to keep the rod thermal lens focal length greater than the rod length. Since the rod is the mode limiting aperture and is much larger than the cavity mode diameter (typically ~ 1 mm), a large number of transverse modes have sufficient gain to reach threshold, resulting in poor beam quality. An alternative method for reducing the number of transverse modes is to employ an unstable resonator. In order to produce high beam quality and minimize sensitivity to alignment or gain fluctuations, a high magnification ($M > 2$) unstable resonator is required. Unfortunately, a cw flashlamp pumped system has insufficient gain to operate at high magnification, which is, again, due to the large rod diameter.

LLNL's original goal of the Rofin-Sinar CRADA was to produce 250-500 W cw from a DPSSL system with less than 20 times diffraction limited beam quality. An additional goal was to credibly scale such systems to > 1 kW with similar high beam quality. To meet these goals we performed various design tradeoffs, including: laser material choices, diode pump configurations, and laser system options.

One option initially proposed was to simply replace the flashlamp pump source with diodes and keep the same rod diameter. Since the thermal loading of a flashlamp pumped system is 2-3 times larger than with diode pumping, the thermal aberrations of diode-pumped laser rods will be much lower. However, this scheme does not produce high beam quality, a requirement of this program. Here the resonator cavity's aperture (i.e. the rod diameter) is still much larger than the stable mode diameter and will produce large number of transverse modes and poor beam quality. An unstable resonator is still not feasible due to the low gain of the large diameter rod.

Our strategy for producing high average power simultaneously with high beam quality and high extraction efficiency is based on several design criteria and trade-offs:

1. We analyzed alternative laser materials, specifically Nd:YAG and Yb:YAG. The primary advantages of Yb:YAG are lower heat deposition due to a lower quantum defect (ratio of the pump to laser wavelength) and Aluminum free diode laser pump sources. Aluminum free diode material in principle has better reliability and performance, however recent advances in diodes for Nd:YAG with Aluminum free active regions should reduce or eliminate this advantage. The main disadvantage of Yb:YAG is its low absorption and emission cross section. This limits diode pump geometry to end pumping the rod. The low emission cross section produces low gain reducing extraction efficiency and eliminating an unstable resonator as a possible design option. In contrast, the advantages of Nd:YAG are its high emission and absorption cross section. The large emission cross section permits higher gain operation. The large absorption cross section permits a variety of diode pump geometries.
2. Instead of employing a large diameter rod with low thermal lens, our design decreases the rod diameter and length by a factor of 2-3 and supplies the same diode pump power. The length can be reduced because the rod is operated at a lower percent of its fracture limit. Although, this strategy maintains the same thermal loading as the flashlamp pumped system, it results in a quadratic (G^2) to cubic (G^3) increase in gain (i.e. amplification). Basically, we are trading reduced thermal loading for high gain. This scheme has several important advantages.
 - 2.1. For moderate power systems (< 500 W) a small diameter (< 3 mm) rod and a suitably designed stable cavity having a transverse mode size of ~ 1 mm would produce a low number of transverse modes (< 5-10) with high extraction efficiency.
 - 2.2. The higher gain results in higher extraction efficiency and the use of lower reflectivity output couplers to reduce intra cavity power loading.
 - 2.3. The quadratic to cubic increase in gain permits a high magnification unstable resonator to be employed to produce high beam quality in high power (larger rod diameter) systems. The advantages of a high magnification ($M > 2-3$) unstable resonator are lower sensitivity to alignment and gain fluctuations.
3. The stable resonator cavity is designed to operate at the edge of stability by making the cavity longer. Here higher order modes will have significant loss and will not get above threshold. In principle, near the stability limit only the TEM₀₀ mode will have sufficient gain to lase. This will result in high extraction efficiency and high beam quality. **This was demonstrated as part of this CRADA.**
4. Both side-pumped and end-pumped rod systems were analyzed. Although there are advantages to end-pumping (primarily low absorption cross section or 3-level laser materials), our analysis indicated that since Nd:YAG is the optimal laser material a diode-side-pumped geometry has several advantages.
 - 4.1. A properly design side-pumped geometry produces better gain uniformity across the rod aperture. (This advantage is discussed below). **This was demonstrated as part of this CRADA.**
 - 4.2. The diode pumping is confined to the central portion of the rod. Compared to end-pumped systems, this approach eliminates:
 - 4.2.1. The need for high damage threshold dichroic coatings (808 and 1064 nm) operating at high diode pump powers.
 - 4.2.2. Diode pump power loading on the rod o-ring seals. (Recent advances in end-pump designs have reduced this problem).
 - 4.2.3. Pumping at the uncooled end of the rod. (Recent advances in end-pump designs have reduced this problem).
 - 4.3. Nonuniform heat deposition along the length of the rod due to Beer's law absorption. The end pumped rod operates at a higher percent of the fracture limit compared to a uniformly pumped rod of same length.
 - 4.4. Multiple rods can be employed in a cavity, increasing output power. Since the rod lensing can be compensated via intra cavity lenses, several rods could be employed.

- 4.5. Birefringence depolarization can be compensated for by employing two rods and a 90° rotator between heads. This is important for high power short pulsed (< 40 ns) laser machining requiring EO q-switching and intracavity polarizer. **This was demonstrated as part of this CRADA.**
- 4.6. A side-pumped head permits a symmetric cavity with the rod(s) placed in the center, and identical curved mirrors at the cavity ends. This maximizes the cavity mode diameter at the rod center, which is also the mode limiting aperture. This simultaneously produces high beam quality (low number of modes) and high extraction efficiency. **This was demonstrated as part of this CRADA.**
5. An important design criterion was Uniform diode pumping across the rod diameter. Uniform pumping will produce primarily spherical aberrations, which can be corrected with concave lenses or convex cavity mirrors. **This was demonstrated as part of this CRADA.** Alternatively, the cavity design can take advantage of the spherical lensing to produce a stable resonator. This goal is also important for high a beam quality unstable resonator because the output will not be diffraction limited if the components in the cavity have wavefront distortions of higher order than spherical.

An important aspect of this strategy is scaling to higher powers is straight forward. If satisfactory performance has been demonstrated at moderate powers, then scaling to higher powers requires linearly scaling the rod length or number of rods (because of fracture limit), the diode pump power and the rod aperture (area). The resulting rod thermal focal length and gain of the higher power system will be identical to the lower power system. Since satisfactory performance (i.e. beam quality, alignment sensitivity, gain fluctuations, etc.) have already demonstrated at these operating points, similar performance will be expected from the higher power system. For example if we demonstrate satisfactory performance of an unstable resonator at 400 W using two 3 mm x 50 mm rods and 40 diode packages then two 4.75 mm x 100 mm or four 4.75 mm x 50 mm rods and 80 packages should produce 1 kW.

DPSSL Laser Hardware

We used the above design strategy to develop and build two diode side-pumped rod heads for this CRADA. Each head contains forty microchannel cooled diode packages (two 9 mm bars per package) pumping a 3 mm x 110 mm Nd:YAG rod. In addition to the Rofin-Sinar laser these heads have subsequently been employed in a variety of LLNL programs including: the EUVL laser master oscillator, in preliminary AVLIS laser experiments, in the CALIOPE pump laser amplifier module used in the FY 96 NTS field experiments, and the FY 97 CALIOPE power oscillator testbed.

We based our initial performance goals on two important parameters: high power cw diode performance and a set of thermo-mechanical parameters for YAG. Since we had already quantified the efficiency of diode output to stored power using pulsed diodes, we were confident that two heads could produce 500 W cw based on projected reliable (i.e. safe) cw diode performance of 60 W cw per 2-bar diode package. In addition, our design strategy is based on operating small diameter rods at the thermal lensing limit. We estimated that 500 W could be produced from two 3 mm rods keeping the rod's thermal lens focal length greater than the rod length. This was based on thermal lens estimates using published thermo-mechanical parameters for YAG. However, the actual laser system output to date has been lower than anticipated due to three issues: (1) rod o-ring damage, (2) lower "safe" operating point for cw diode packages (40-50 W instead of 60 W), and (3) larger thermal lensing than originally modeled (1.6 times shorter focal length).

The first problem has a potential solution, which would increase output power to 300-325 W. However, the maximum safe diode operating point and thermal lensing with a 3 mm rod would now be the major limitation. Currently, the o-rings that seal the rod operate at significant intra cavity power loading, since the rod (and o-ring) are the mode limiting aperture. A solution to this

problem is to fabricate a rod that has a larger diameter at the rod ends (at the o-ring seal) and has a 3 mm diameter central pump region. This removes the o-ring from the active mode volume. Additional diode development focusing on Aluminum free active regions would improve diode output to ~ 60-70 W per 2-bar package, but that is beyond the scope of this CRADA. The third issue has no solution i.e. we have to live with the actual thermal lensing of the 3 mm rod diameter. Since our strategy is to operate at the point where the rod's lens focal length is equal to the rod length, the larger than expected thermal lensing will lower output power from a given diameter rod. High output power can be obtained by increasing the rod area, length, and diode pump power linearly. A more detailed discussion of the thermal performance of laser rods and issues with YAG thermo-mechanical parameters will be discussed below.

The head is constructed from 4 rings. Each ring contains 10 packages arrayed around the rod in a five fold symmetry (see Fig. 1). Each ring is rotated 36° from the previous to produce good pump uniformity. A fully assembled head is shown in Fig. 2.

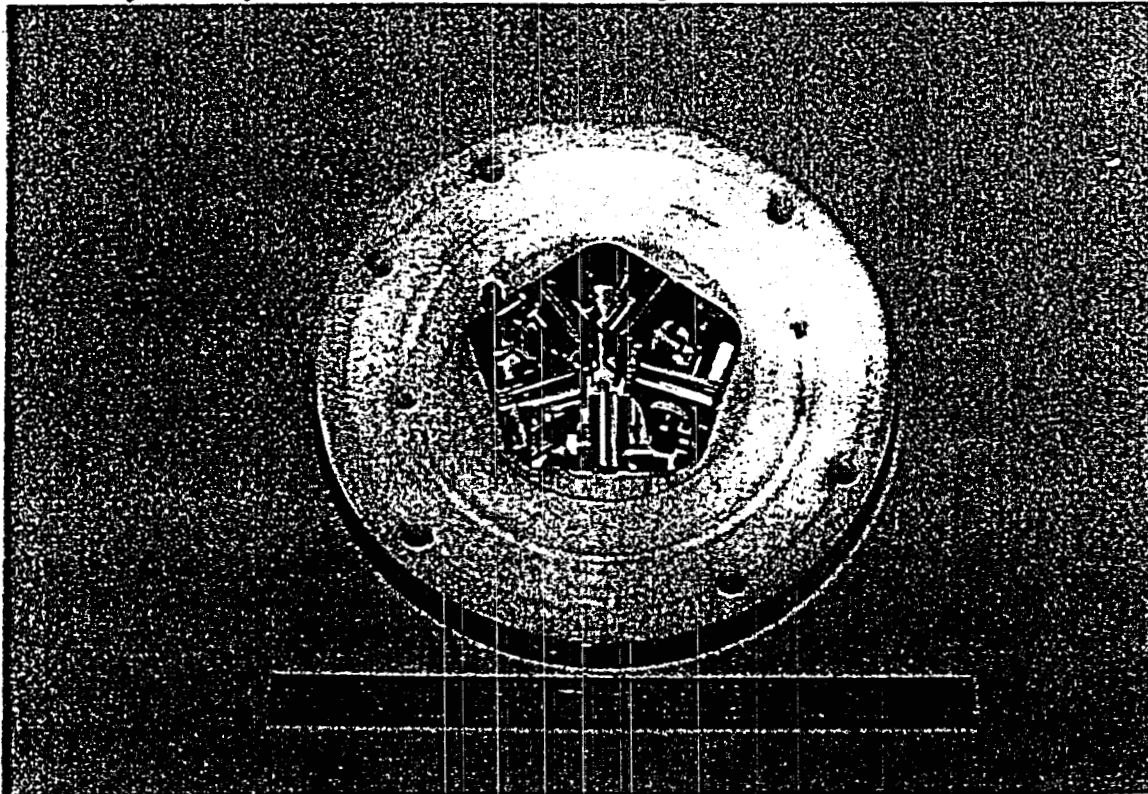


Figure 1. Photo of diode-side-pumped ring containing 10 packages. The rod and water jacket (not shown) are positioned at the ring center.

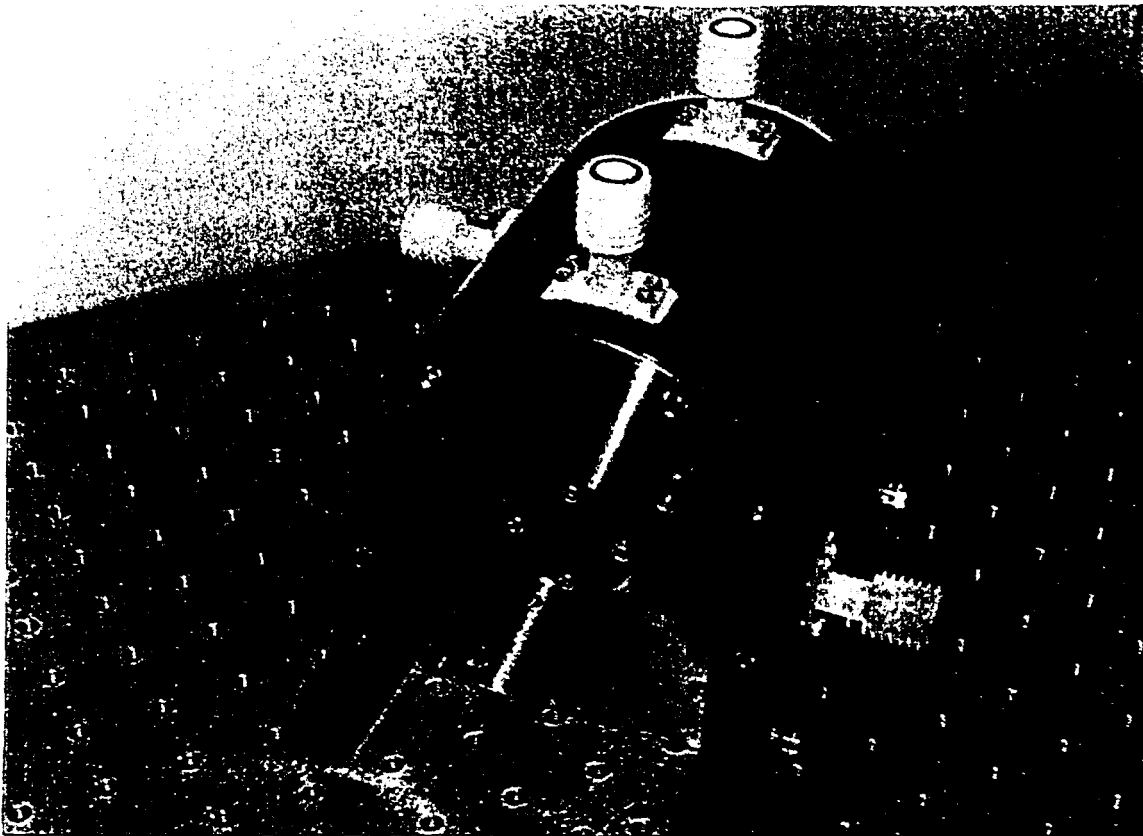


Figure 2. Photo of assembled diode-side-pumped head.

Characterization of Laser Thermal Performance

We have fully characterized the DPSSL rod thermal and energetic performance. One important design criterion we set and accomplished was uniform diode-pumping of the rod. The measured gain profile for the head is uniform as seen in Fig. 3. The gain profile was obtained by dividing the profile of the probe beam with gain by the probe beam without gain. In principle a flat gain profile should produce primarily spherical wavefront distortion under thermal load. Interferometry on the rod under thermal load demonstrates that the wavefront distortion of the rod is primarily spherical and can be compensated with a concave spherical lens. Fig. 4 is the interferometer profile of a thermally loaded rod and concave compensating lens. The diode current was adjusted to produce parallel fringes demonstrating that the rods thermal aberrations are primarily spherical and can be corrected with a simple concave lens. There are small higher order aberrations due to different radial and tangential focal lengths caused by thermal stress in the rod.

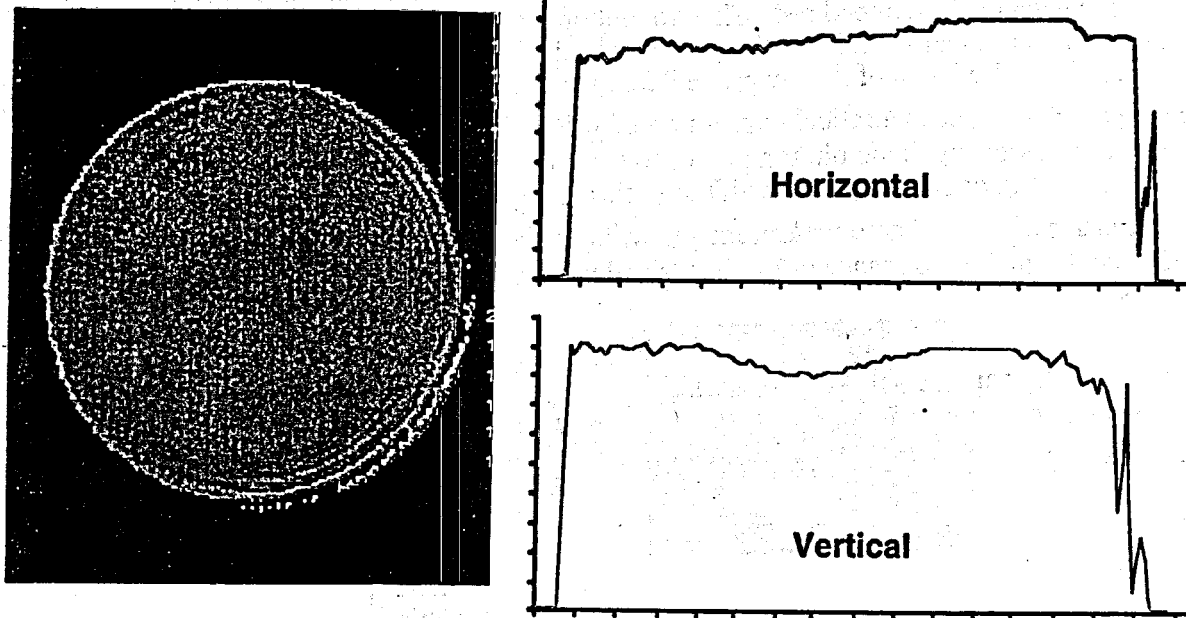


Figure 3. Gain profile of 3 mm diode-side-pumped rod. Also displayed are horizontal and vertical profiles through center. The structure at rod's edge is due to diffraction of probe beam.

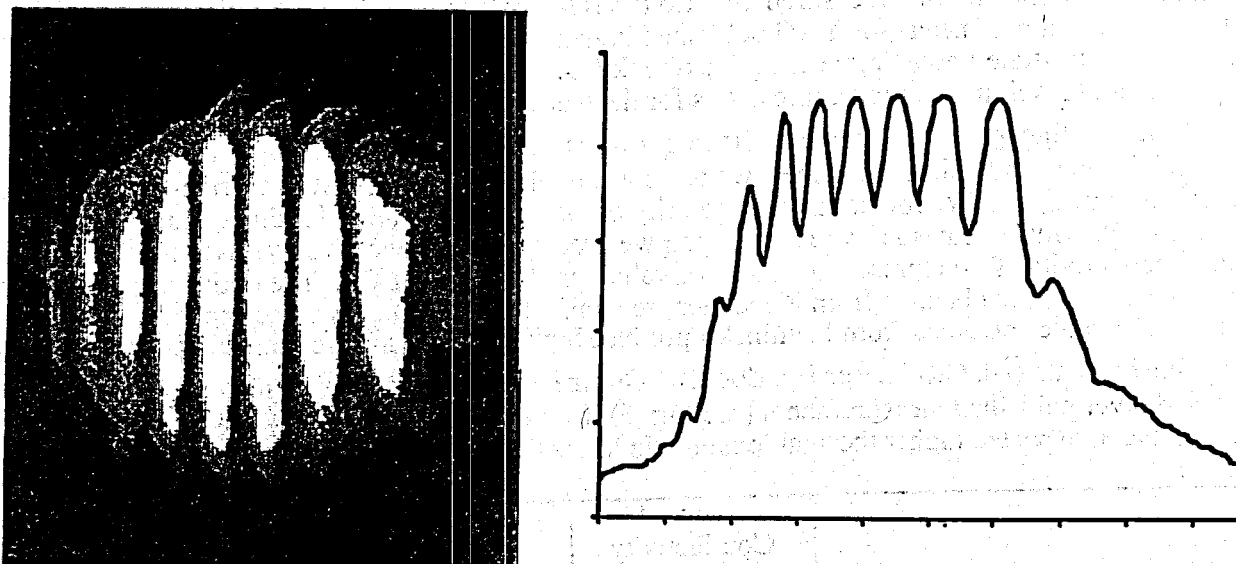


Figure 4. Interferometer profile of thermally loaded rod and 20 cm concave lens. The diode pump power was adjusted to produce nearly uniform fringes. Also displayed is a fringe profile through beams center.

To validate our modeling of thermal performance of these heads, we measured χ the ratio of heat deposited into the rod to the stored power. Although these experiments were performed using pulsed operation the results can be scaled to cw operation. The uniform diode pumping provides "textbook" expressions for the rod's thermal lensing and birefringence. Using an experimental layout shown in Fig. 5 we simultaneously measured gain and rod thermal lensing. Thermal lensing estimates were obtained by first focusing a probe laser onto a camera without a concave lens and no diode pumping, we then inserted various focal length concave lenses and increased the

repetition rate and diode current until best focus was again obtained. An ABCD matrix analysis of the concave lens and the rod thermal lens (treated as a spherical waveguide) provided estimates of the thermal lensing of the pumped rod. The amount of heat deposited into the rod is calculated using the rod's thermal lens focal length and "supposedly" well known YAG thermo-mechanical parameters. The pulsed gain of the cw probe beam measured with a photodiode provided estimates of the stored power. The theoretical expression of χ depends only on energetics i.e. energy pathways for transferring diode photon power to laser stored power. In addition, published measurements are in good agreement with theoretical expressions. Consequently, our ability to extract estimates of χ from these measurements will demonstrate our ability to correctly predict the energetic and thermal performance of our heads and validate YAG's thermo-mechanical parameters.

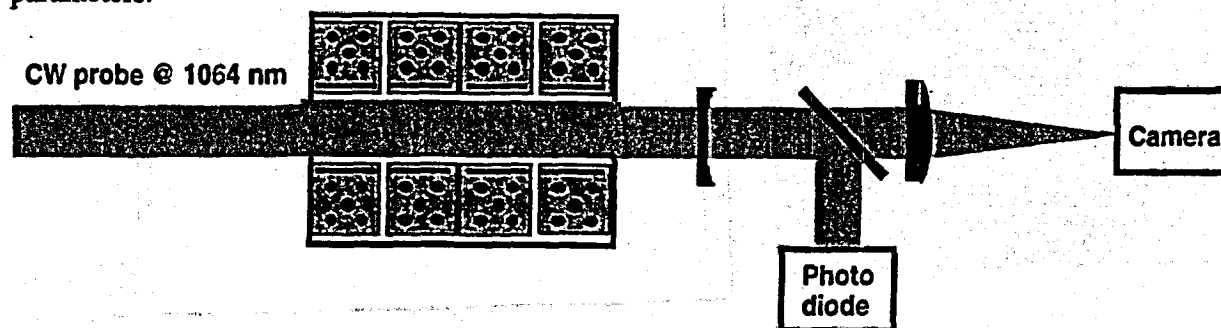


Figure 5. Experimental layout employed to measure χ by simultaneously measure stored power (from gain) and heat deposited (from thermal lensing).

The amount of thermal lensing measured was 1.6 times larger than we originally anticipated using thermo-mechanical parameters for YAG published in most vendors product literature and in Koechner's "solid-state Laser Engineering" textbook (see reference in Table 1). Since uniform rod pumping should result in textbook expressions for the thermal lensing, the 1.6 times larger thermal lensing and resulting χ was unexpected. Since our measured χ was 1.6 times larger than the theoretical estimate and published values, we reviewed published data of YAG's thermo-mechanical parameters. We found that the majority of most reported values for dn/dt and coefficient of thermal expansion were larger than we used and were lower than we used for the thermal conductivity. Two representative sets of values are listed in Table 1. The optimistic (lower thermal lensing) values obtained from Koechner are similar to those listed in some vendors catalogs. The values obtained from Kaminskii produce higher lensing and are representative of other published data (i.e. CRC Laser Handbook). Our measured estimates of χ now agree with theory and other published measurements (see Fig. 6) if we employ Kaminskii's parameters. However, the unexpected higher thermal lensing did lower the laser performance from our original goal.

	Thermal Conductivity $W\ cm^{-1}\ K^{-1}$	Thermal Expansion K^{-1}	dn/dt
From W. Koechner, "Solid-State Laser Engineering" 3rd Edition, Springer Ser. Opt. Sci., Page 51	.13	7.5×10^{-6}	7.3×10^{-6}
From A.A. Kaminskii, "Laser Crystals: Their Physics and Properties" 2nd Edition, Springer Ser. Opt. Sci., Page 51	.11	6.96×10^{-6}	9.86×10^{-6}

Table 1. YAG thermo-mechanical parameters used in original analysis (Koechner) and less optimistic parameters but more representative of existing published data (Kaminskii) used to correctly model experimental χ measurements.

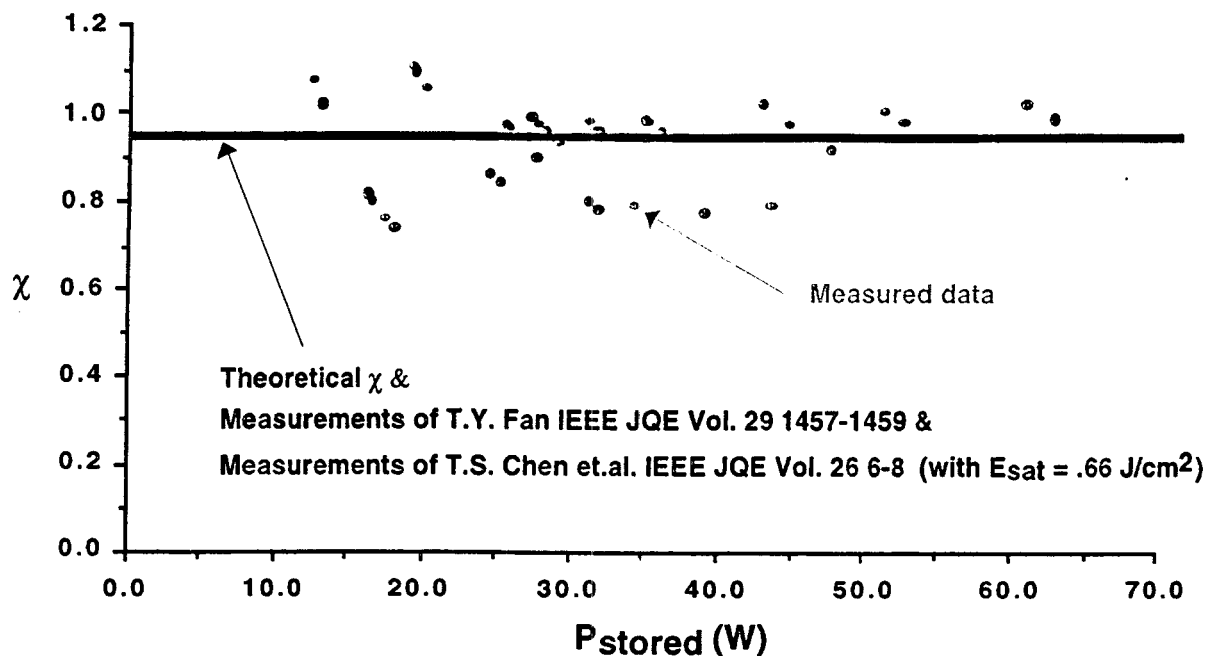


Figure 6. Measured values of χ obtained at various repetition rates (400, 600, 800, & 1000 Hz), diode currents (adjusted to produce best focus at camera), and concave focal lengths lenses (15.5, 20, 25, 34, 40, 46, 51, 61 & 102 cm). The pump time is 200 ms. Theoretical expressions for χ were obtained from T.Y. Fan and agree with his measured results (modifying the pump time to match our experiment) and with independent measurements of T.S. Chen but modifying his results to use the "correct" cross section for Nd:YAG (i.e. the same value we used).

Another measure of the heat deposited into the rod is the birefringence depolarization produced by the rod. In Fig. 7 (top) the profile of a probe beam propagating through the thermally loaded rod followed by a polarizer is displayed. The polarizer reflects the depolarized portions of the beam resulting in the null spots at the edges of the profile. The heat deposited into the rod was estimated at 90-100 W from thermal lensing measurements using Kaminskii's thermo-mechanical YAG parameters. Corresponding calculations (using Kaminskii's parameters) of birefringence at 100 W agree with the measured profile as seen in Fig. 7. This further demonstrates our capability to properly model thermal effects in diode-pumped YAG rod laser systems and our choice of published thermo-mechanical parameters.

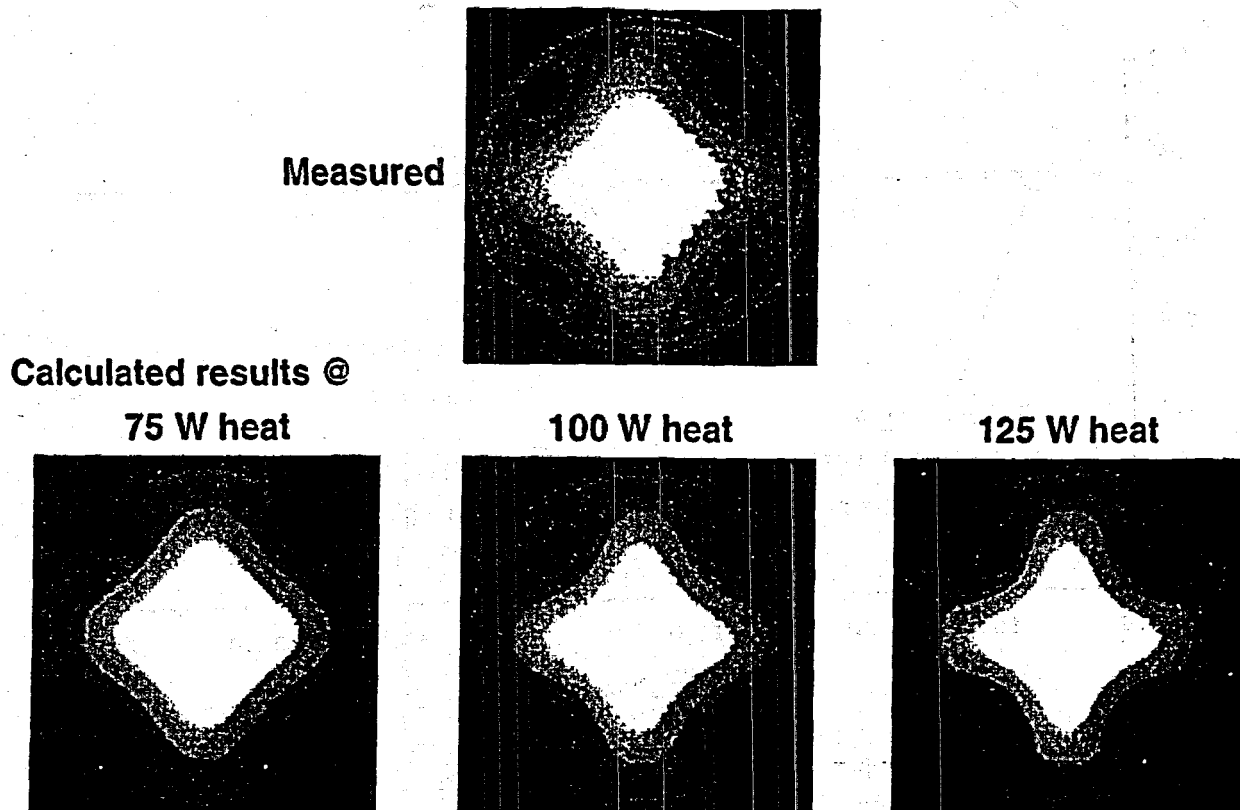
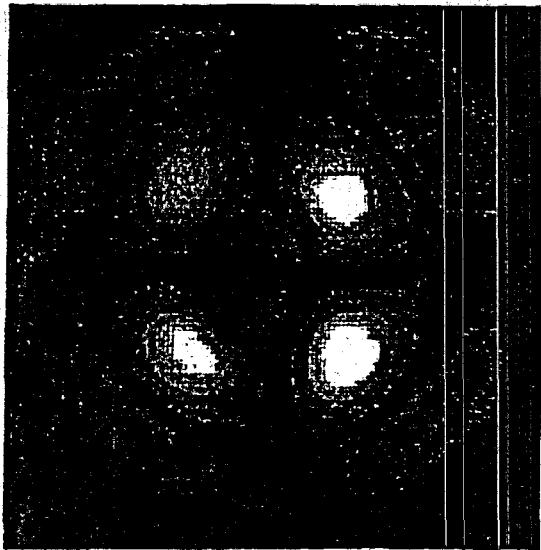
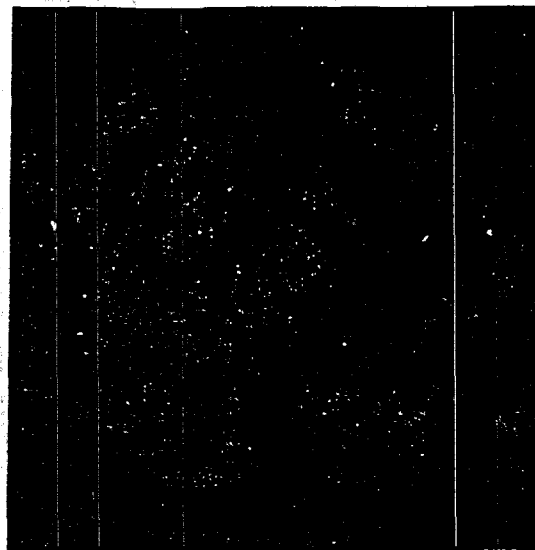


Figure 7. Measured and calculated beam profiles of birefringence loss. The measured results were taken at diode pump levels corresponding to 90-100 W heat deposition estimated from thermal lensing measurements.

One advantage of a diode-side-pumped rod architecture is that two identically pumped rods with a 90° rotator between them will in principle compensate birefringence depolarization. Compensating birefringence is important when an intra cavity polarizing component is present, for example: a high power q-switch power oscillator with intra cavity polarizer or cw intra-cavity (Type I) doubler. In addition, birefringence compensation will be required if polarized output is required for external cavity frequency conversion. As part of this CRADA we demonstrated depolarization compensation. In Fig. 8 are displayed the depolarized beam profiles of a $1 \mu\text{m}$ probe beam propagating through 2 of our DPSSL rods with 100 W heat deposited per rod followed by a polarizer with and without a 90° rotator between the heads. As can be seen there is significantly less depolarized light with the 90° rotator. A laser containing an intracavity polarizer would see ~ 8 times less loss per round trip with 2 diode-side-pumped rods and a 90° rotator.



No compensation



90° rotator between rods

Figure 8. Profile of beam through two diode-side-pumped rods (100 W heat per rod) and polarizer. The same ND filters were used for both profiles. If the rods were unpumped then the polarizer would completely reflect the probe beam resulting in a null image.

Laser Performance

As mentioned previously, our strategy for producing high beam quality at moderate power was to design appropriate stable resonator cavities to maximize the mode waist size. In addition, we employed a symmetric cavity to maximize the mode diameter at the center of the cavity where the rod is located. If the mode waist is slightly smaller (2-3x) than the rod diameter then only low order modes (i.e. high beam quality) will be produced. We combined thermal lensing codes and stable resonator models to optimize the cavity length and choice of end mirror curvatures at a given operating point (i.e. thermal loading). We performed this analysis and corresponding experiments for a single rod producing 60 W and 160 W and for 2 rods producing 275 W. The 160 W (for 1 rod) and 275 W (for 2 rods) were the high power limit for o-ring burning in cavities producing high beam quality. The experiments involved increasing the cavity length monitoring the beam quality. We found that when the cavity length became close to the stability limit predicted from our codes the beam quality improved dramatically. If we increased the cavity length further the cavity became unstable. Unfortunately, operating near the stability limit also produced the largest o-ring power loading. The o-ring burning limited our ability to produce TEM₀₀ output at 160 W and 275 W. Comparison between modeling and experiment were excellent. The typical cavity length producing the best beam quality was within 10% of that predicted. In addition, the cavity length where the resonator became unstable was also in accord with modeling.

60 W, TEM₀₀ Performance

At 60 W cw output we were able to obtain TEM₀₀ output from a single diode-side-pumped rod in a symmetric cavity. The near and far field profiles are displayed in Fig. 9. The cavity was 86 cm long and employed 100 cm convex curved end mirrors. A beam quality analysis indicated an M^2 of 1.1-1.2. The brightness of this laser (to my knowledge) is unique, comparable to a 1.8-6 kW laser with 30-100 times diffraction limited output (typical of commercial flashlamp pumped systems). When the cavity length was increased it became unstable. Reducing the cavity length decreased the beam quality ($M^2 > 20$) but did not decrease the output power considerably (65-70 W compared to 60 W).

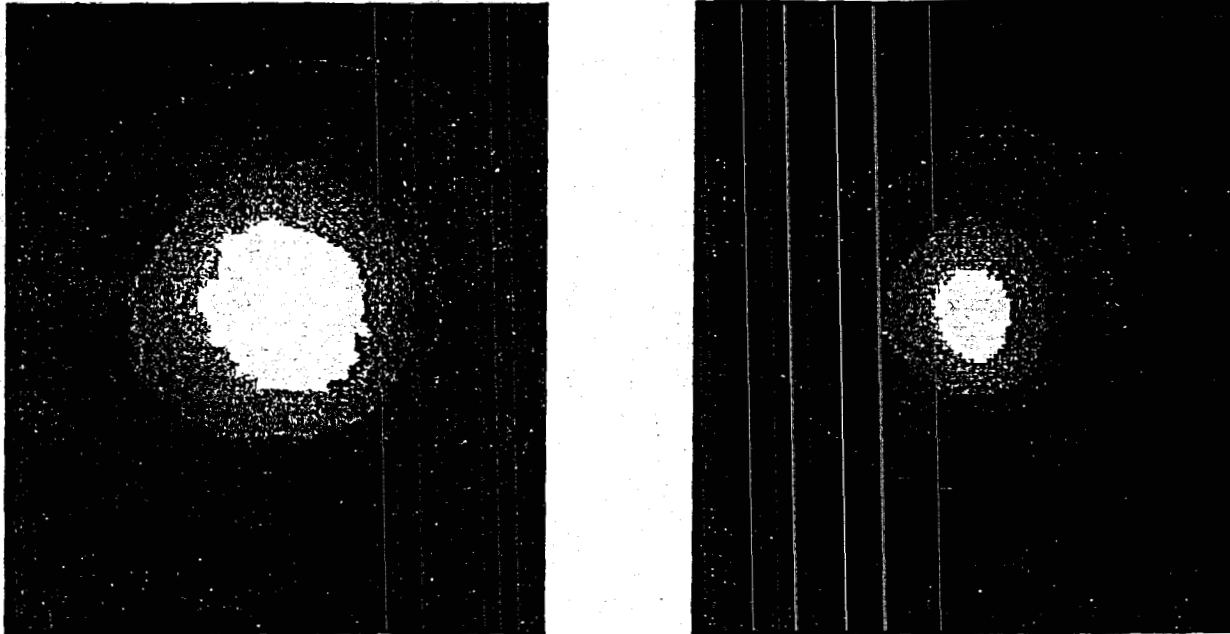


Figure 9. TEM₀₀ near (left) and far (right) field profiles at 60 W cw. The beam quality was measured to have an M^2 of 1.1-1.2.

160 W, 3 Times Diffraction Limited Performance

We increased the output power to 160 W but found that single mode operation was not feasible due to o-ring burning. At 160 W output we were able to produce a 3.2 mm near field beam with a far field divergence corresponded to ~ 3 times the diffraction limit of a 3.2 mm round flat-top aperture. The beam diameter was measured at a camera ~ 30 cm from the rod and has a larger diameter than the rod due to the expanding beam wavefront produced by the cavity. Again the laser brightness from this single diode pumped system is unique, equivalent to a 5 kW 100 times diffraction limited laser. The near and far field beam profile at 160 W are displayed in Fig. 10. The 40 cm long symmetric cavity employed two 100 cm convex end mirrors. A 60% output coupler optimized the output power.

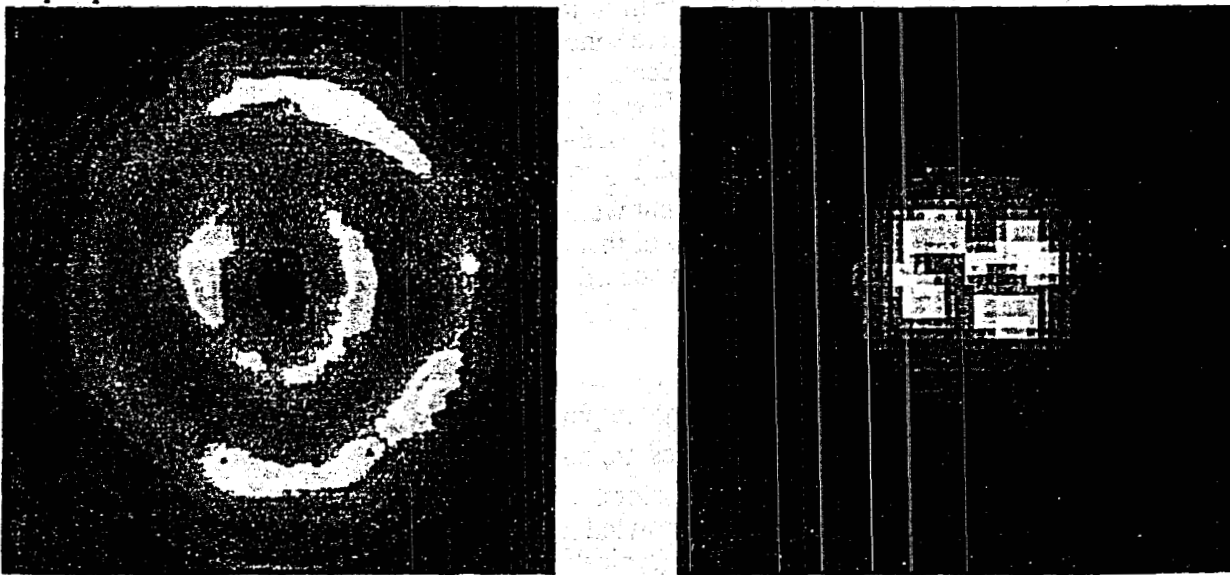


Figure 10. Near (left) and far (right) field profiles at 160 W cw. The size of the far field frame is $4.2 \times 4.2 \text{ mrad}^2$ or ~ 5 times the diffraction limit of a 3.2 mm aperture ($2.44\lambda/D$).

The beam quality of the of the cw laser was determined by measuring percent power contained in various focal apertures. We measured this by increasing the resolution² of a CCD camera from 8-bits to effectively ~ 15-bits by removing calibrated ND filters. This improves resolution of power contained at higher divergence angles of the far field not resolved in Fig. 10. In Fig. 11 are four far field profiles of the 160 W beam with different levels of attenuation (136, 21, 6, and 0). Each figure also has a circular aperture corresponding to 2-, 3-, 4-, and 6.5-times the diffraction limit of a 3.2 mm aperture, which encloses all saturated pixels. We calculate the total power and the power outside the various apertures using 15-bits resolution, which provides estimates on the percent power contained in each aperture (also displayed in Fig. 11). Based on this analysis the beam quality was estimated to be 3 times diffraction limited.

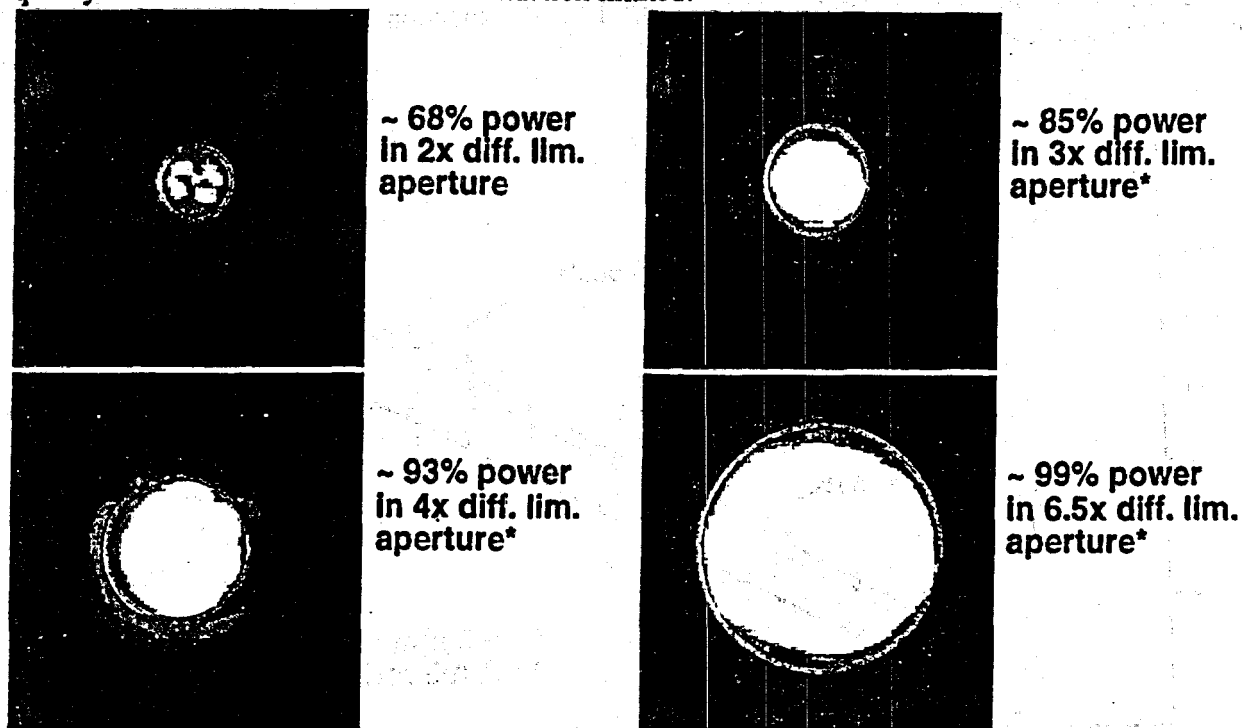


Figure 11. Far field beam profiles for different levels of attenuation obtained by removing calibrated ND filters. The attenuation from left-to-right and top-to-bottom is 136, 21, 6, and 0.

² Determining far field divergence or beam quality (i.e. times diffraction limited) from a CCD camera beam profile is limited by the camera's 8-bit (0-255) resolution. It is impossible to determine the power contained at higher divergence angles not resolved by the 8-bit profile. Measurements of power through different aperture diameters positioned at best focus are usually employed to accurately determine beam quality (i.e. "power -in-the-bucket"). A simpler method is to employ a CCD camera but increase its resolution by removing calibrated ND filters. Since a CCD camera can be saturated by approximately 128 before bleaching occurs, previously unresolved high divergence information can be displayed by removing calibrated ND filters. By storing different beam profiles at different levels of attenuation (ideally 0x, 2x, 4x, ..., 128x) a 15-bit profile can be constructed by combining the different attenuated profiles. Assuming the 128x attenuated profile has no saturation, the saturated pixels of the 64x profile is replaced with the 128x profile, scaling the 128x profile by 2. This procedure is repeated for each successive level of less attenuation until a 15-bit resolved beam profile is constructed.

The circles are 2-, 3-, 4-, and 6.5-times the diffraction limit of a 3.2 mm aperture. [* There are no saturated pixels outside aperture]

The slope efficiency (diode pump power to output power) for the single rod was measured to be ~ 15%. The slope efficiency corresponding to absorbed power to output power was estimated to be 30-40%. Early in the program we purposely traded high diode-power-to-absorbed power efficiency for uniform diode pumping. We are currently developing an improved design to increase the diode transfer efficiency by 65%. This should increase our slope efficiency from 15% to 25%. The experimental data for a 50%, 60% and 70% output coupler is shown in Fig 12. The slope efficiency does decrease slightly as the diode power increases above 1.1 kW, as is displayed in Fig. 12. This change corresponds to pump levels where the mode quality changes from > 30 to ~ 3 times diffraction limited. As is evident from Fig. 12 high extraction efficiency and high beam quality can be achieved simultaneously.

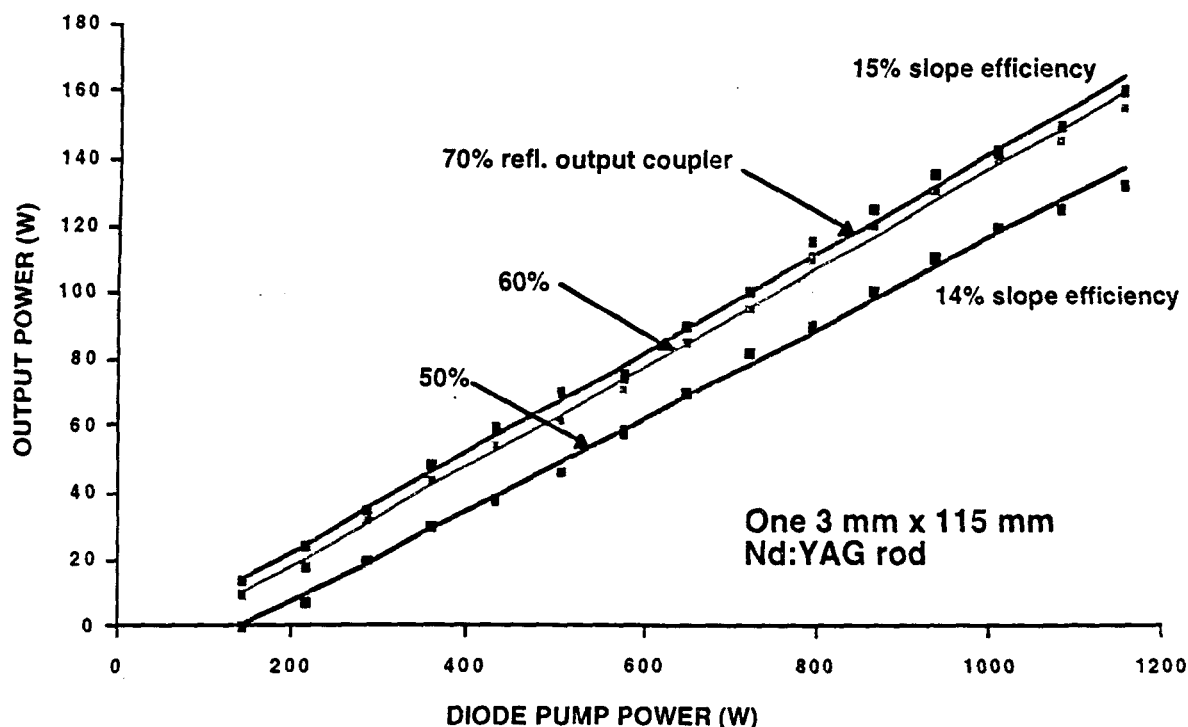


Figure 12. Diode pump power to output power slope efficiency for single diode-side-pumped rod.

275 W, 15 Times Diffraction Limited Performance

Increasing the power to > 160 W required adding an additional DPSSL rod. We were able to produce 275 W with reasonable beam quality from two diode-side-pumped rods without o-ring damage. However, increasing the power beyond 275 W or increasing the cavity length to produce better beam quality did result in o-ring burning. Our strategy for producing high beam quality by increasing the cavity length was limited much more by the o-ring problem than at 160 W. Our best output at this power level was produced from a 42 cm long symmetric cavity with 60 cm convex end mirrors. The near and far field profiles are displayed in Fig. 13. A photo of the laser is displayed in Fig. 14. The near field beam size is 3.6 mm diameter and the far field divergence was estimated to be ~ 11 mrad corresponding to 15 times the diffraction limit of a 3.6 mm aperture. We measured (using ~ 14 -bits resolution) > 90% of the power is contained in a far field aperture (also displayed in Fig. 13) corresponding to 15 times diffraction limited

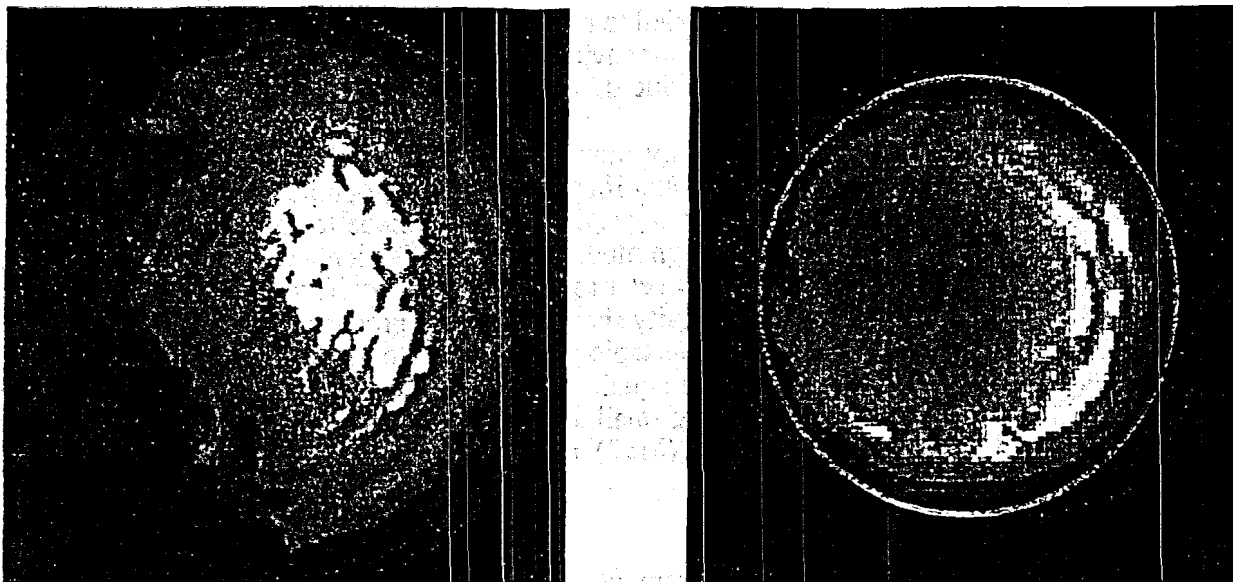


Figure 13. Near (left) and far (right) field profiles at 275 W cw. 90% of the power is contained in the aperture (displayed) corresponding to 11 mrad or 15 times diffraction limited.

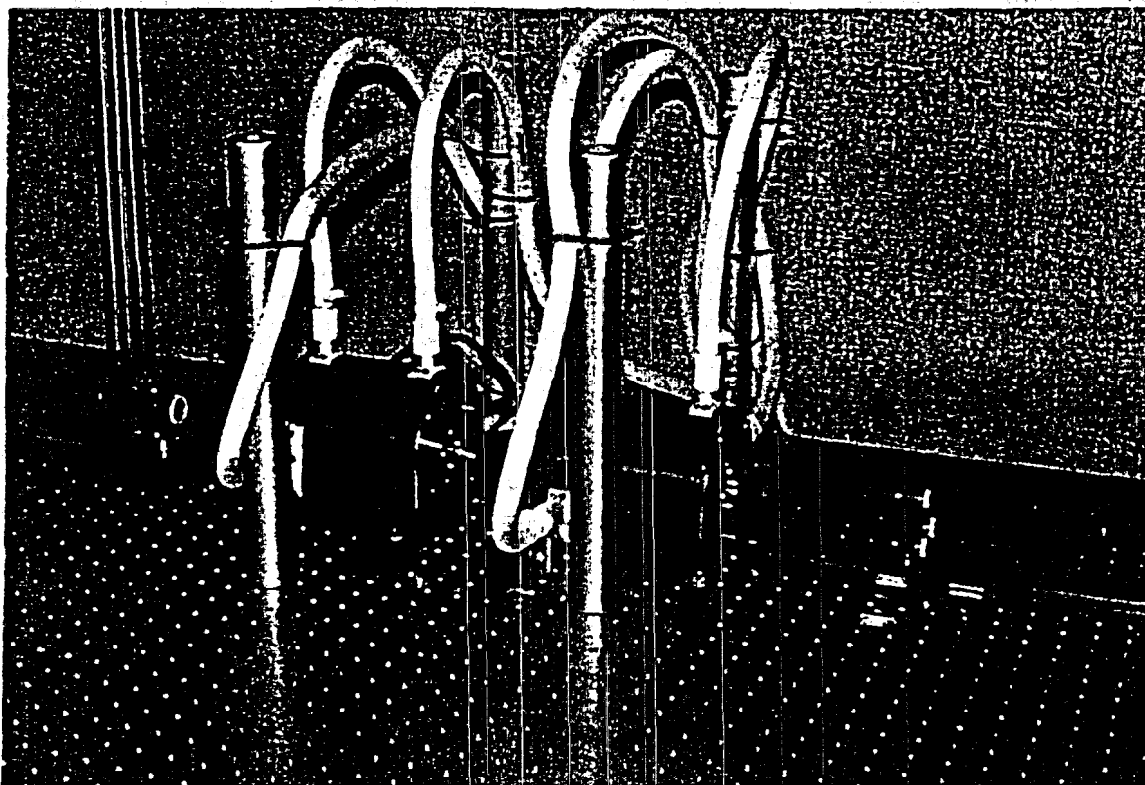


Figure 14. Photo of 275 W cw two rod DPSSL system.

Current System Limitations and Solutions to Produce Higher Output Power

The primary limitation of our current DPSSL head is burning of o-ring seals around the Nd:YAG rod. Since our current design strategy for producing high beam quality with good extraction efficiency is to use the rod as the mode limiting aperture, significant power loading on the o-rings is produced. A low cost solution to this problem is machine a YAG rod with larger diameter endfaces (where the o-ring contacts the rod) and a smaller diameter central pump region. This will remove the o-ring seals from the active mode volume. Similar techniques have been employed in

high power Ruby lasers (glass sleeves epoxied to rod ends) and in other LLNL DPSSL systems. This modification would allow stable resonator cavity configurations which produce higher beam quality than our 2 head system currently produces.

The output power can further be increased by employing larger diameter rods. Currently, we use 3 mm but could increase to 3.5 mm without modification to the diode-pumped head. This modification would decrease the thermal lensing and increase the diode-to-absorbed power efficiency. Based on our validated laser design models, this modification would increase output power to 350-400 W. Although a larger diameter rod would increase the number of modes (the rod is the mode limiting aperture) a stable cavity should be able to produce ~ 400 W in ~15-20 times diffraction limited beam quality. An unstable resonator employing high power Gaussian reflective mirrors would produce higher beam quality. Since our laser material Nd:YAG has a high emission cross section and we are employing small diameter rods, the gain of our two head system would be sufficient for a high magnification ($M > 2$) unstable resonator.

Scaling to > 1 kW

One of the important milestones of this program was demonstrating that (1) uniform-flat gain across the rod diameter could be obtained with diode-side-pump geometry and (2) the resulting rod thermal aberrations were primarily spherical and correctable with concave lenses. Demonstrating this permits scaling the system design to higher average powers by increasing the rod diameter and employing an unstable resonator. Since the aberration of our systems are primarily spherical, the unstable resonator output beam's wavefront can be corrected. Remember the output beam quality of an unstable resonator will not be diffraction limited if the resonator cavity contains aberration higher than spherical order.

Scaling our present system is straight forward. Since the thermal lensing and gain are proportional to the absorbed diode power per unit rod area (aperture), the present system can be scaled by linearly increasing the area, the diode pump power, and the length of the rod or number of rods. For example, our present 3 mm rod head, which produces ~ 160 W, could be scaled to 6 mm and produce ~ 640 W with the same thermal lensing. To limit rod fracture to < 30% the rod length would be increased to 15 cm (our current 10 cm rod operates at ~ 10% fracture). The rod thermal lens focal length would be approximately the same as the rod length. A two rod system would produce > 1 kW

High beam quality output from a larger diameter rod would now require an unstable resonator employing a Gaussian reflector output coupler. A unreasonably long stable resonator cavity would be required to produce a mode diameter of ~ 2-3 mm. An important point here is that since Nd:YAG has a high emission cross section, sufficient gain can be achieved with diode pumping to make a high magnification unstable resonator feasible. A high magnification (> 2) unstable resonator is much more efficient and less sensitive to operating point fluctuations (gain, alignment, etc.) than an unstable resonator with a low magnification near 1. The gain for a 1 kW laser from two 6 mm rods would be ~ 14 per pass permitting a high magnification ($M < 14$) unstable resonator.

An alternative design approach to higher average power maintaining high beam quality was to amplify the 200-300 W high beam quality output produced from our diode-side-pumped rod laser with a zig-zag slab amplifier. The advantage here is the zig-zag averaging of the slab thermal aberrations and the scaling of the slab to multi-kilowatt power levels. This would be the preferred pathway for scaling to > 3 kW levels. A wedge slab with 30 mm by 4 mm aperture could store as much as 8-10 kW. Unfortunately, due to lack of cw diode packages early in the program and high diode package cost, much of our work on slab systems has been restricted to pulsed applications. In addition, our first generation slab amplifier design suffered from larger than expected thermal distortions, making high beam quality output impractical without wavefront correction. This was due to poor design engineering and to use of overly optimistic thermo-mechanical YAG

parameters. In principle some of these deficiencies can be corrected via better slab design and modeling.

Delivery of DPSSL Laser Components to Rofin-Sinar

Rofin-Sinar has expressed interest in beginning precision laser machining application development using one of our DPSSL systems. For a modest cost we could deliver a DPSSL system to Rofin-Sinar in a short period of time (<6 months) with unique brightness performance. The system would employ a single DPSSL head with previously described rod modification to prevent o-ring damage discussed above. This system would produce 150-200 W with 3-5 times diffraction limited beam quality. The performance of this system is to my knowledge unique. The brightness of this source is roughly equivalent to a 1.5-5 kW cw system with 30-100 times diffraction limited output but with much smaller beam area.

D. Partner Contribution

Rofin-Sinar technical contribution to this CRADA focused on developing a high power fiber delivery system. Specifically, Rofin-Sinar built and delivered a high power fiber delivery system employing a 400 μm fiber with a 0.2 numerical aperture. This system has ~ 2 times better performance than typical 600 μm , .24 NA fibers. Specifically, this would increase work piece stand-off produce smaller focal spot size and have a larger depth of focus. This system coupled with a high beam quality laser would greatly impact the precision laser machining industry. In addition, they have worked on further reducing the fiber diameter to 200 μm with a 0.12 NA. This fiber would require a laser producing < 20 times diffraction limited beam quality and produce a 6x improvement over current commercial systems. The major issue here is high power loading of the fiber input and output face. A photo of the Rofin-Sinar fiber delivery system is displayed in Fig. 15.

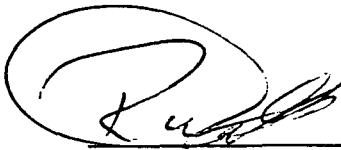


Figure 15. The 400 mm, 0.2 numerical aperture fiber delivery system.

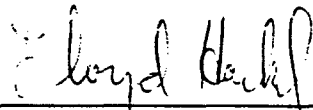
F. Acknowledgment

Participant's signature of the final report indicates the following:

- 1) The Participant has reviewed the final report and concurs with the statements made therein.
- 2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
- 3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures attributable to the project have been disclosed or are included on a list attached to this report.
- 4) The Participant certifies that if real property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
- 5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.


Richard Walker
Rofin-Sinar

2/26/97
Date


Lloyd Hackel
Lawrence Livermore National Laboratory

3/24/97
Date

Laser Material Processing

Attachment I Abstract CRADA No. TC-0321-92

Date: 11/27/96

Revision:

Current commercial cw flashlamp pumped solid-state laser systems employed in laser machining operate at multi-hundred watt to kilowatt levels and produce 30-100 times diffraction limited beam quality. Developing similar power lasers but with a beam quality 5-10 times better is an important advancement in the laser machining industry especially precision laser machining. For example, fiber delivery of > 30 times diffraction limited systems require large diameter (> 600 μm) and large numerical aperture ($\text{NA} > 0.2$) fibers. The primary disadvantages of such fiber delivery systems are poor depth of focus, short work piece standoff, and large focal diameter. The advances demonstrated as part of this CRADA would permit small diameter (200-400 μm) and low numerical aperture ($\text{NA} = 0.12-0.2$) fiber delivery systems to be used for much higher precision laser machining than currently possible. In addition, the systems developed here could also be employed in high intensity (W/sr) pulsed applications, for example, precision cutting and drilling of ceramics and other difficult materials.

Rofin-Sinar's goal is building a high power (> 1 kW), small diameter (200-400 μm), low numerical aperture ($\text{NA} = 0.12-0.2$) fiber delivery system. LLNL's goal is to demonstrate a high power cw diode-pumped solid-state laser (DPSSL) system producing high beam quality output with high extraction efficiency. Specifically, LLNL's initial focus is to demonstrate moderate cw power (50-500 W) with high beam quality (1-20 times diffraction limited) from a diode-pumped laser system.

Laser Material Processing

Project Accomplishments Summary (Attachment II) CRADA No. TC-0321-92

Date: 11/96

Revision: 1

A. Parties

The project is a relationship between the Lawrence Livermore National Laboratory (LLNL) and Rofin-Sinar, Inc.

University of California
Lawrence Livermore National Laboratory
7000 East Avenue, L-795
Livermore, CA 94550

Rofin-Sinar, Inc.
45701 Mast Street
Plymouth, MI 58170

B. Background

Current commercial cw flashlamp pumped solid-state laser systems employed in laser machining operate at multi-hundred watt to kilowatt levels and produce 30-100 times diffraction limited beam quality. Developing similar power lasers but with a beam quality 5-10 times better is an important advancement in the laser machining industry especially precision laser machining. For example, fiber delivery of > 30 times diffraction limited systems require large diameter (> 600 μm) and large numerical aperture ($\text{NA} > 0.2$) fibers. The primary disadvantages of such fiber delivery systems are poor depth of focus, short work piece standoff, and large focal diameter. The advances demonstrated as part of this CRADA would permit small diameter (200-400 μm) and low numerical aperture ($\text{NA} = 0.12-0.2$) fiber delivery systems to be used for much higher precision laser machining than currently possible. In addition, the systems developed here could also be employed in high intensity (W/sr) pulsed applications, for example, precision cutting and drilling of ceramics and other difficult materials.

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C. Description

Rofin-Sinar has expressed interest in beginning precision laser machining application development using one of our diode-pumped solid state laser (DPSSL) systems. For a modest cost we could deliver a DPSSL system to Rofin-Sinar in a short period of time (<6 months) with unique brightness performance. The system would employ a single DPSSL head with previously described rod modification to prevent o-ring damage discussed above. This system would produce

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D. Expected Economic Impact

This new laser machining system will enable advancements in machining capability for U.S. industry. Higher quality and more rapid cutting, drilling, and welding will enable new classes of techniques and products.

E. Benefits to DOE

LLNL has acted as a center of expertise in laser system engineering for the DOE, other government agencies, and U.S. industry for more than 20 years. The project is consistent with that role and will allow LLNL to maintain its technical base in an area critical to both DOE and U.S. industry.

F. Industry Area

This project will advance the laser machining industry, especially precision laser machining. The machine tools have applications in welding, drilling, cutting, marking, surface modification, and reflow soldering.

G. LLNL Point of Contact for Project Information

For more information on this project, please contact Lloyd A. Hackel, Laser Programs, L-487, Lawrence Livermore National Laboratory, 7000 East Ave., Livermore Ca 94550. Phone: (510) 422-9009; Fax: (510) 422-9554; Email: hackel1@llnl.gov.

H. Company Size and Point(s) of Contact

Rofin-Sinar is one of the world's largest industrial laser manufacturers. Contact at Rofin-Sinar is Richard Walker, vice president, Rofin-Sinar Inc., 45701 Mast St., Plymouth, MI 48170. Phone: (313) 455-5400; Fax: (313) 455-2741.

I. Project Examples

To achieve our goal, we had to accomplish the following design criteria:

1. Minimize the rod diameter.
2. Maximize the gain.
3. Produce uniform gain across the rod diameter.
4. Employ high cross section laser material.
5. Employ a diode-side-pump geometry.
6. Keep the thermal lens focal larger than the rod length.

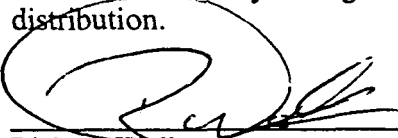
An additional goal of this program is to credibly scale such lasers to kilowatt levels.

As part of this CRADA we achieved the following milestones:

1. Demonstrated 275 W cw with < 15 times diffraction limited output from two diode-pumped Nd:YAG rods.
2. Demonstrated 160 W with ~ 3 times diffraction limited output from a single diode-pumped Nd:YAG rod.
3. Demonstrated 60 W cw TEM₀₀ (1.2 times diffraction limited) from single diode-pumped Nd:YAG rod.
4. Demonstrated primarily spherical and correctable rod aberrations under high power diode pumping. This is important for credibly scaling systems to higher average power.
5. Demonstrated birefringence compensation under high power diode pumping. This is important for high power short pulsed (< 40 ns) laser machining requiring EO q-switching and intracavity polarizer.
6. Fully characterized energetic and thermal performance of diode-side-pumped Nd:YAG DPSSL.
7. Fully characterized resonator performance.
8. Developed a full suite of cw energetic and thermal laser performance models and resonator design codes and validate them through laser experiments.

RELEASE OF INFORMATION

I have reviewed the attached Project Accomplishment Summary prepared by Lawrence Livermore National Laboratory and agree that the information about our CRADA may be released for external distribution.

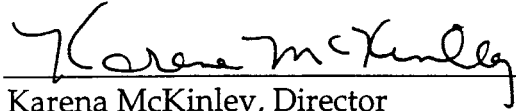


Richard Walker
Rofin-Sinar, Inc.

2/26/97
Date

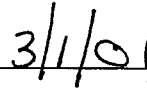
RELEASE OF INFORMATION

I certify that all information contained in this report is accurate and releasable to the best of my knowledge.



Karena McKinley, Director

Industrial Partnerships and Commercialization



Date