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Observation of Enhanced Thermal Lensing Due to Near-Gaussian Pump Energy Deposition in a Laser-Diode Side-Pumped Nd:YAG Laser

David Welford, *Member, IEEE,* David M. Rines, *Member, IEEE,* Bradley J. Dinerman, and Robert Martinsen

Abstract—**We report operation of a laser-diode side-pumped Nd:YAG laser with a novel pumping geometry that ensures efficient conversion of pump energy into the TEM$_{00}$ mode. Significant enhancement of thermally induced lensing due to the near-Gaussian energy deposition profile of the pump radiation was observed and is reported for the first time. An induced lens of approximately 3.2 m focal length was measured at average incident pump powers of only 3.2 W (corresponding to a 0.6 W heat load).**

INTRODUCTION

LASER-DIODE-PUMPED solid-state lasers with high TEM$_{00}$-mode conversion efficiencies have been demonstrated using both end-pumped [1]-[3] and side-pumped [4]-[7] geometries. However, these systems are not suitable for all applications. The end-pumped lasers typically operate at low average power because of the limited pump power that can be focused onto the end of the laser rod. The side-pumped systems, on the other hand, have no difficulty generating high powers using CW [6], [7] or quasi-CW [4], [5] pump sources. Their shortcoming is that the TEM$_{00}$-mode quality is obtained with pumping geometries optimized for high-average power operation and require the use of either expensive, high-power CW [6], [7] or several quasi-CW [4], [5] laser-diode arrays. This renders these geometries difficult to implement as cost effective low-average power systems.

In the case of pulsed systems, given the high cost of quasi-CW laser-diode arrays, side-pumped lasers operating at the tens of millijoule level are cost effective only when pumped by as small a laser-diode array as possible. Previous work [8]-[11] with single laser-diode array pump sources (up to 5 bars per array) in side-pumped geometries has been unable to demonstrate efficient operation in the TEM$_{00}$-mode.

The subject of this paper is a novel side-pumped geometry [12] with efficient TEM$_{00}$-mode conversion using a single 5-bar quasi-CW laser-diode array pump source and the thermal lens properties resulting from this geometry. The noteworthy feature of our present paper is the intentional use of near-Gaussian pump energy deposition profile to efficiently extract energy in the TEM$_{00}$ mode of operation even in the presence of the associated thermal lens, because the spherical nature of the lens does not degrade the TEM$_{00}$-mode profile other than to change its diameter. It should also be noted that the nonuniform pump deposition profile provides the dominant driving term for the thermal diffusion process and thereby enhances the thermally induced lens.

TEM$_{00}$ LASER PERFORMANCE

In this paper, the laser rod was a 12 mm long, semicircular cross section (*D*-shaped) crystal of 1% Nd-doped YAG. The curved face was antireflection coated at the pump wavelength and had a 3 mm radius of curvature. This face of the rod acted as a cylindrical lens to focus the highly divergent output from the diode array, which was placed parallel to the rod axis facing the curved surface. Unabsorbed pump light was reflected from the highly reflecting, flat, rear surface. The path length of this double pass was approximately one absorption length of the material that leads to 65% absorption of the incident pump energy. The rod also had Brewster-angled end-faces oriented such that the electric field axis was parallel to the flat, rear surface. The flat, rear surface of the laser rod was mounted on a convection-cooled heatsink.

The laser-diode array used was a Spectra Diode Laboratories SDL3230 quasi-CW device composed of five 1 cm long laser-diode bars stacked vertically with 0.3 mm center-to-center spacing. The laser array was temperature tuned to operate at 808 nm center wavelength with a spectral width (FWHM) of approximately 3 nm.

Prior to conducting laser experiments, we evaluated the absorbed-energy profile (which corresponds to the deposited heat load) in the laser rod by imaging the fluorescence from the center of the array-pumped rod onto a CCD detector array, which was interfaced with a frame grabber

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D. Welford, D. M. Rines, and B. J. Dinerman are with Schwartz Electro-Optics Inc., Concord, MA 01742.

R. Martinsen is with Lightwave Atmospherics, Marblehead, MA 01945.

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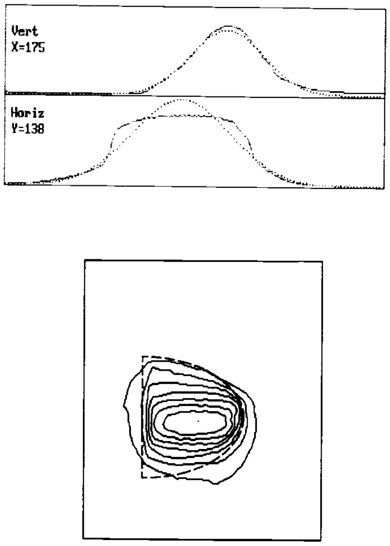


Fig. 1. Fluorescence image of the laser rod with absorbed energy profiles parallel (horizontal) and perpendicular (vertical) to the flat rear surface of the rod. The rod cross-section is shown as a dashed line forming a semi-ellipse.

and computer (Montana Laser Corp, Multicam System). As shown in Fig. 1, the excited-state density in the horizontal direction was nearly uniform over most of the rod aperture, while in the vertical direction a close approximation to a Gaussian distribution was obtained.

We chose to use a planoconcave resonator (Fig. 2) with a 50 cm radius-of-curvature, high-reflector placed 3.6 cm from one Brewster face of the laser rod and a flat, output coupler placed 35 cm from the other Brewster face. The calculated TEM_{00} mode diameter at the laser rod was approximately 1 mm (1 mm × 1.8 mm inside due to the Brewster orientation). This resonator design results in less than 1% loss for the TEM_{00} mode while preventing laser oscillation of higher-order modes and provides good overlap with the pump profile.

Long-pulse laser operation (200 μs at 50 Hz) was investigated with a 20% output coupler (eq. (3.59) of [13] predicts 19% as the optimum output-coupling). 11.8 mJ of 1064 nm output was obtained with 64 mJ from the pump laser. Fig. 3 shows the output energy as a function of the pump energy incident on the laser rod (approximately 65% of the pump energy was absorbed). The 23% slope efficiency was comparable to that obtained in multimode operation with earlier pump geometries [4], [5], and also far exceeds their potential TEM_{00} mode performance. Using the multimode resonator shown in Fig. 4 we obtained output energies of 20 mJ with a slope efficiency of 33%, which corresponds to 50% slope efficiency relative to the absorbed pump energy.

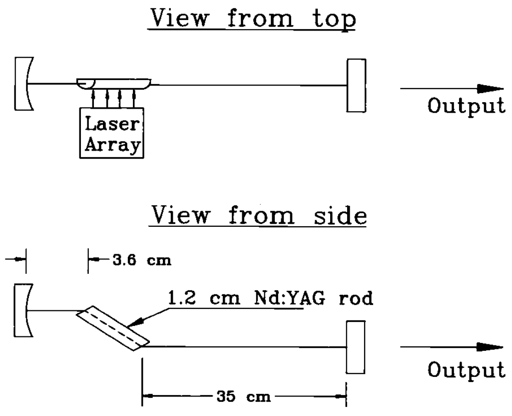


Fig. 2. Schematic layout to the TEM_{00} laser resonator.

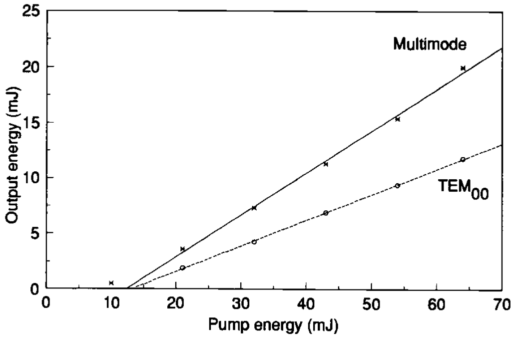


Fig. 3. Multimode and TEM_{00}-mode energies as a function of incident pump energy.

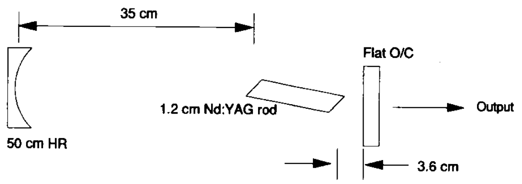
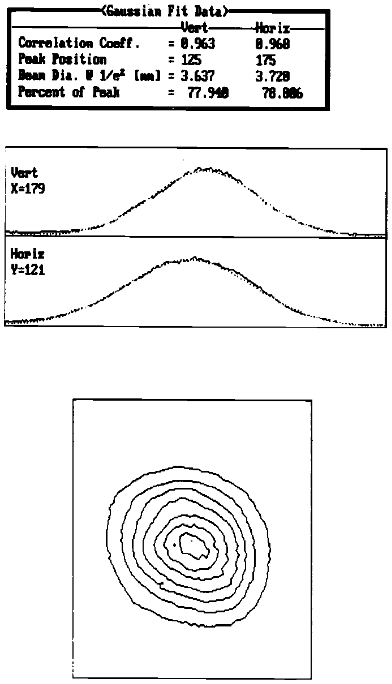


Fig. 4. Multimode laser resonator.

The output beam profile (at 64 mJ pump energy) shown in Fig. 5 shows greater than a 0.96 correlation with a least-squares fit to a Gaussian beam profile and less than 3% deviation from circular symmetry. The mean beam diameter of 3.7 mm, approximately 1 m from the output coupler, was larger than expected from calculation of the "cold" resonator beam divergence. The presence of thermal lensing in the laser rod provides an explanation for the increased beam divergence.

THERMALLY INDUCED LENSING OF THE LASER ROD

We investigated the presence of thermally induced lensing in the laser rod using the optical probe technique shown in Fig. 6. A He–Ne laser operating at 632.8 nm probed the laser rod after passing through a 54.7 cm



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───────────<Gaussian Fit Data>───────────
                          ─Vert────────Horiz──
Correlation Coeff.      = 0.963     0.968
Peak Position           = 125       175
Beam Dia. @ 1/e² [mm]   = 3.637     3.720
Percent of Peak         =  77.940    78.086
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Fig. 5. Contour plot and beam profiles for the TEM_{00}-mode output beam.

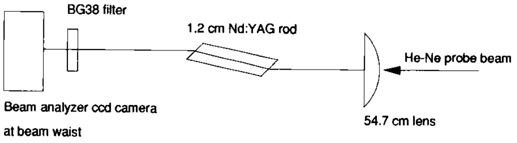


Fig. 6. Experimental arrangement for the thermally induced lens measurements.

planoconvex lens. The measurement technique was based on analyzing changes to the Gaussian beam waist as a result of the thermally induced lens in the pumped laser rod. The thermal lens focal length can be determined from eq. (67) of [14]. We used a beam profile analyzer (Spiricon Model LBA-100) to determine the position and diameter of the initial beam waist from the center of the unpumped laser rod and the diameters of the beam waists obtained at different pump-laser energies.

Fig. 7 shows the focal lengths of the thermally induced lens as a function of average pump power incident on the laser rod. The functional form was similar to the inverse-power dependence commonly seen in lamp-pumped, circular cross section rods in which a radial refractive index distribution (i.e., lens) is the result of a radial heat flow in the rod cooling system. Yet, the present system has a more complex heatflow pattern that is strongly influenced by both the nonuniform pump deposition and the asymmetric cooling geometry.

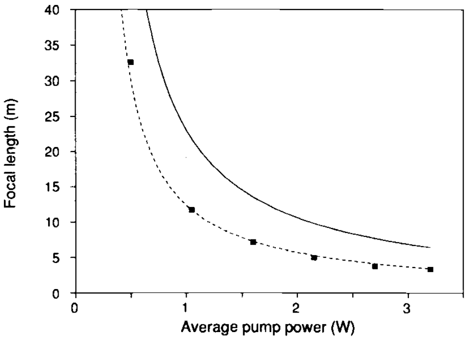


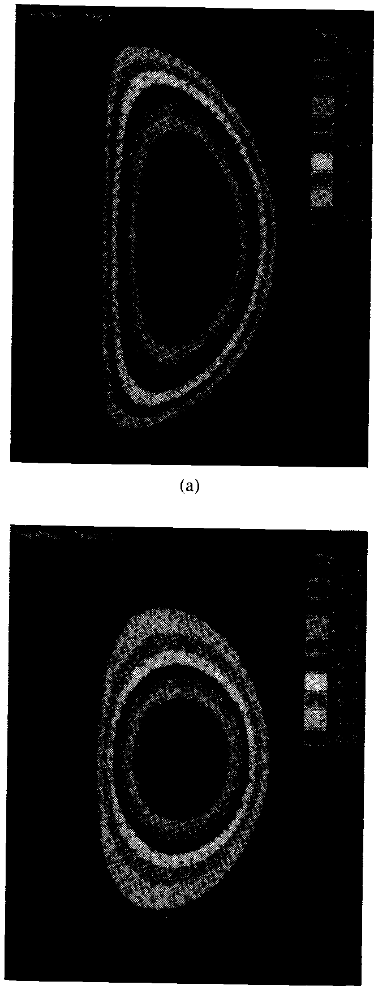
Fig. 7. Thermally induced lensing as a function of the average incident pump power. Solid line is the calculated lensing using eq. 13 of [7]. Dashed line is a least squares fit to the function $f = M/P$, where $M = 1.05 \times 10^3$ Wcm.

In addition to the thermally induced lensing, significant angular deflection of He–Ne laser probe beam was also observed. The magnitude of this beam deflection was as large as 0.3 mrad or approximately 0.1 mrad/W of incident pump power.

The thermal lens data represents the mean focal length, f, for the laser rod at each average pump power level P assuming ideal circular symmetry of the induced index profile. This assumption allowed us to operate the beam profile analyzer in a "real-time" mode and determine the beam waist position by observing the digital readout of the beam diameter ($1/e^2$ diameter of the peak). Even though the deposited energy profiles in the laser rod were not circularly symmetric the probe beam profiles showed no evidence of either strong asymmetry or the existence of separate beam waists (indicative of different lens focal lengths in the vertical and horizontal directions).

The work of Innocenzi *et al.* [15] treats thermal lensing in a laser rod with a Gaussian pump deposition profile and is similar to the more conventional radial diffusion analysis of uniformly pumped lamp-based systems [13], except that the rod area is replaced by the area of the pump deposition profile. This analysis [15] closely matches our pump geometry (but not our cooling geometry) and was used to generate the solid curve of Fig. 7 that is of the form $f = M/P$, where M is a constant equal to 1.96×10^3 W-cm. A least squares fit of the same functional form to the experimental data gave a value of 1.05×10^3 W-cm and is shown as the dashed line in Fig. 7.

The poor agreement of the analytical model [15] led us to numerically model the steady-state temperature distributions in the laser rod for different heat load distributions and boundary conditions. The modeling was performed using a finite-element software package (COSMOS/M, Structural Research and Analysis Corp.) designed for mechanical engineering and was therefore unable to directly predict the thermal lens parameters. However, we were able to interpret the temperature distributions obtained



(a)

(b)

Fig. 8. Temperature profiles for laser rods with 20°C isothermal boundary conditions and 0.6 W heat load with (a) uniform heat deposition and (b) the near-Gaussian heat deposition corresponding to the actual pumping geometry.

from the modeling with the aid of the analytical model [15].

Fig. 8 shows two temperature distributions for 20°C isothermal boundary conditions and 0.6 W total heat loading. The first case, Fig. 8(a), has a uniform heat load distribution and is equivalent to conventional lamp pumped laser rods (except for the semicircular rod cross-section). The temperature distribution is almost elliptical in profile and could be optically described as a spherical lens with an additional cylindrical lens. This is in contrast to the circular symmetry obtained in lamp pumped rods. The second case, Fig. 8(b), has the near-Gaussian heat load distribution of the diode-laser pumped system. The heat load was derived from the fluorescence image data shown in Fig. 1. The near-Gaussian heat load distribution generated a circularily symmetric temperature distribution with three times the peak temperature rise obtained with the uniform heat load distribution and hence the generation of a stronger thermal lens.

Fig. 9. Temperature profile for a laser rod with near-Gaussian deposition of 0.6 W heat load and experimentally measured boundary conditions of a 30.5°C isothermal on the flat heatsink surface and convection cooling of the curved face at an ambient air temperature of 23.8°C.

These two cases illustrate the effect of nonuniform pump deposition in the presence of isothermal boundary conditions. Yet, in our laser the curved surface of the rod was not isothermal since clear optical access must be maintained. Therefore, a third case was modeled, which simulated the laser rod boundary conditions more accurately with 30.5°C isothermal heatsinking at the flat surface and convection cooling to ambient air at 23.8° C over the curved surface. The resulting temperature distribution shown in Fig. 9 has a stronger thermal lens than for the isothermal boundary conditions [see Fig. 8(b)] and is decentered by approximately 0.5 mm. This decentering of the thermally induced lens leads to a beam deflection that we estimate to be 0.16 mrad for the measured focal length of 3.2 m, while the measured beam deflection was 0.3 mrad.

The analytical result obtained earlier by applying eq. (7) of [15] assumed isothermal boundary conditions, which in our numerical model underestimated the maximum temperature rise by a factor of two (2°C in Fig. 8(b) instead of 4°C in Fig. 9) compared to the real boundary conditions. Hence, the analytical estimate of the lens focal length is also underestimated by this factor of two. A suitable correction to the analytical model is to reduce the thermal lens coefficient from 1.96×10^3 W-cm to 0.98×10^3 W-cm, which is in close agreement with the value of 1.05×10^3 W-cm obtained from a least squares fit to the focal length data shown in Fig. 7.

The measured thermal-lens data was used in resonator calculations to determine the TEM_{00} mode beam diver-

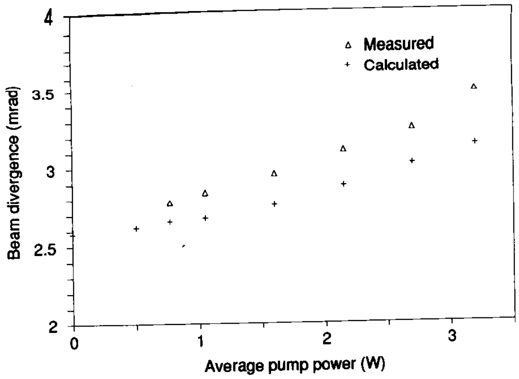


Fig. 10. Comparison of measured and calculated resonator beam divergences as a function of the average incident pump power.

gence. The beam divergence was estimated experimentally by focusing the beam with a 1 m focal length, plano-convex lens and by measuring the beam waist diameter (at $1/e^2$) with the Multicam System (described earlier). The calculated and measured beam-divergence data shown in Fig. 10 are in close agreement, thereby supporting the thermal lens data.

In addition, we also looked for evidence of thermal birefringence by adding an analyzing polarizer to our linearly polarized He-Ne laser-based probe arrangement. We saw no evidence of thermally or otherwise induced birefringence.

SUMMARY

In summary, we have demonstrated 23% slope efficiency and 11.8 mJ output energy for a TEM_{00} mode, 1064 nm Nd : YAG laser side pumped by a 64 mJ, 5 bar stack of quasi-CW laser diode arrays using a novel pumping geometry. We have observed a 3.2 m thermally induced lens in the laser rod at 3.2 W of average pump power (0.6 W heat load). Computer modeling of the thermal diffusion process confirms that the thermally induced lensing is significantly enhanced due to the near-Gaussian pump deposition profile. This effect is somewhat unique to laser pumped solid state media and must be carefully considered when designing these lasers to operate efficiently in the TEM_{00} mode.

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David Welford (S'79–M'80) was born in Whitby, North Yorkshire, England, on March 17, 1956. He received the B.Sc. degree in 1977, and the Ph.D. and D.I.C. degrees in 1980, all in physics, from the Imperial College of Science and Technology, University of London, England. His thesis research was on CW mode-locked dye lasers and their application in picosecond kinetics studies of organic molecules.

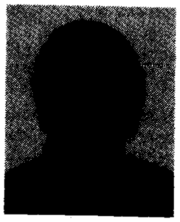
He was with the Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, from 1980 to 1987, where he investigated the emission linewidth and modulation properties of semiconductor diode lasers and the application of diode lasers to optical communications. Since April 1987 he has been with Schwartz Electro-Optics Inc., Concord, MA. His primary research interests are tunable solid state laser materials and semiconductor diode pumped lasers.

Dr. Welford is a member of the Optical Society of America.

David M. Rines (A'88–M'91) was born in Rochester, NH, on July 19, 1966. He received the B.S. degrees in physics and mathematics from Gordon College, Wenham, MA, in 1988.

He was a summer staff member at Schwartz Electro-Optics Inc., Research Division, Concord, MA, in 1987 and became a full-time staff member in 1988. Since that time he has contributed to the development of both pulsed and CW solid-state lasers operating in the visible and near-infrared wavelength regions. Most recently he has been investigating a cadmium selenide optical parametric oscillator (OPO), pumped by a *Q*-switched erbium laser, as a tunable source in the 4 μm wavelength region.

Mr. Rines is a member of the Optical Society of America.



Bradley J. Dinerman was born in Salem, MA, on November 23, 1965. He received the B.A. degree in physics from Connecticut College, New London, in 1987 and the M.S. degree in physics from Boston College, MA, in 1991, where he is currently pursuing the Ph.D. degree in physics with a concentration in rare earth solid-state spectroscopy.

In 1990, he conducted his Master's degree research at NASA, Langley Research Center, Hampton, VA, on the spectroscopy and nature of energy transfer in Tm, Ho:YAG. In January 1991, he joined Schwartz Electro-Optics Inc., Research Division, Concord, MA, where he has since been investigating diode-pumped 2.8 μm laser systems.

Robert Martinsen was born in New York City, NY, on June 11, 1961. He received the B.S. degree in marine engineering from New York Maritime College in 1983, and the M.S. degree in mechanical and aerospace engineering from the University of Virginia, Charlottesville, in 1986.

He is currently pursuing Ph.D. research at the Massachusetts Institute of Technology, Cambridge, in optical remote sensing of oceanic wave spectra. Since 1983, he has been actively involved in the analysis and development of optical sensors for marine and aerospace applications. In March 1991, he founded Lightwave Atmospherics Inc. to investigate lidar remote sensing instruments for wind shear detection and pollution monitoring, and he has been working in cooperation with Schwartz Electro-Optics Inc., Research Division, to advance the performance of diode-pumped solid-state laser sources.

Mr. Martinsen is a member of the International Society for Optical Engineering (SPIE) and the Optical Society of America.