Highly efficient 60-W TEM_{00} cw diode-end-pumped Nd:YAG laser

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We have demonstrated a diode-end-pumped Nd:YAG laser that produces an output power of 60 W in a near-diffraction-limited beam (i.e., $M^2 < 1.3$). In multimode operation, the laser produces an output power of 92 W. The optical-to-optical efficiency (i.e., the ratio of laser power to diode power) is 26% for TEM_{00} operation and 44% for multimode operation.

We have previously reported on a scalable end-pumped laser that used four 10-W cw laser diode bars to pump a laser that produced a multimode output power of 15 W.[1] This laser architecture has significant economic advantages resulting from highly efficient operation and the use of diode bars [which are the least-expensive source of diode power in terms of cost per watt (Ref. 2)]. In the present study we use this power-scaling approach to extend the multimode output power of cw diode-pumped lasers to 92 W. In addition, thermal distortion and stress-induced birefringence are corrected. The result is a near-diffraction-limited output of 60 W with an optical-to-optical efficiency of 26%. This is to our knowledge the first demonstration that the effects of higher-order thermal nonuniformities inherent to end-pumped lasers can be overcome without sacrificing efficiency.

The output power of end-pumped lasers can be scaled by increasing the pump power delivered to a single end[3,4] and by combining multiple ends within a single cavity.[5] In cw lasers, it is important to minimize losses to provide high extraction efficiency. Thus, in a multiple-end laser each end should be pumped with the highest possible power in order to minimize the number of surfaces contributing to internal loss. The ultimate power-scaling limit for a single end is determined by the thermal fracture strength of the laser material.[6] Thermal distortion and stress-induced birefringence can significantly degrade performance at powers well below the thermal fracture limit.[7,8] Nd:YLF exhibits negligible thermal distortion and stress-induced birefringence, but many ends would be needed to produce high output powers owing to the low fracture strength.[9] In contrast, almost 25 W can be extracted from a single Nd:YAG rod end.[6] Nd:YAG is, therefore, the preferred material for an efficient, high-power cw end-pumped laser. Because Nd:YAG exhibits strong thermal distortion and birefringence it is essential to correct these effects in order to achieve good beam quality, high polarization purity, high power, and high efficiency simultaneously.

We use an angularly multiplexed pump geometry

15-W laser diode bars (Spectra Diode Laboratories SDL-3450-S) are arrayed around both ends of each rod as shown in Fig. 1. The two sets of diodes on each rod are clocked 45° with respect to one another to produce a circular gain distribution. The divergence of each diode bar is reduced from ~40° to ~10° in the plane perpendicular to the array by using a 2-mm-diameter quartz rod lens. The diode light is then focused into the rod end by using a 14.2-mm focal-length spherical lens. Unused sections of the spherical lenses are removed to eliminate mechanical interference and additional intracavity apertures. The pump light is incident upon the rod at an angle of 30°. The edge-cooled Nd:YAG rods have a diameter of 6.35 mm, a length of 7.5 mm, and a doping level of 1.0 at.%.

The pumping geometry allows for efficient use of the pump light. Both lenses have antireflection coatings for the pump light, and the rod ends are antireflection coated for both the pump and lasing wavelengths. A passive tuning scheme is used to set the center wavelengths of the diodes to within ±1 nm of the optimum for absorption. The efficiency with which pump light is transferred from the diode and absorbed in the rod is over 80%. Thus approximately 50 W of pump power is absorbed per rod end.

The pump power is concentrated in the central portion of the rod, as shown in Fig. 2. The result is high gain and a distribution that can be extracted

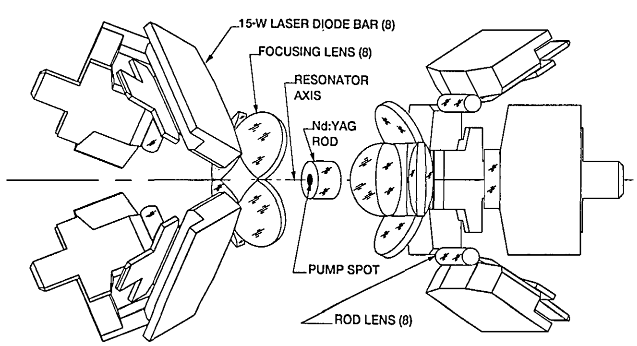

Fig. 1. Angularly multiplexed pump geometry used to focus the power of eight 15-W laser diode bars into each

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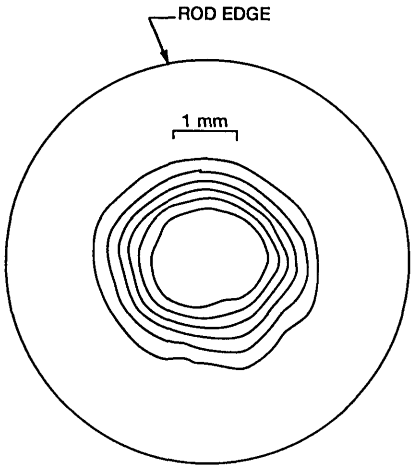

Fig. 2. Fluorescence profile of a 6.35-mm-diameter end-pumped Nd:YAG rod. A total pump power of approximately 100 W is absorbed in the rod, 70 W of which is encircled within the 2.4-mm mode diameter.

efficiently by the fundamental mode.[10] The small-signal gain in the central area of each rod is approximately 0.5.

Multimode extraction tests using a single rod were performed with a 14.3-cm-long resonator formed between two 1.1-m concave mirrors with 3% output coupling. Output powers as high as 24 W are extracted from a rod pumped on a single end, whereas a rod pumped from both ends can produce 49.5 W.

Multimode tests using two rods are performed with a 44-cm cavity formed between a 1.1-m-high reflector and a 90% reflective 1-m output coupler. A multimode output power of 92 W is obtained with a total pump power of 235 W. The threshold for the two-rod oscillator is approximately 24 W, and the slope efficiency is 44% (based on the diode output power). No effort was made to correct thermal distortion or birefringence in the multimode tests. The beam quality of the multimode output ranged from 20 to 30 times diffraction limited.

A resonator that has a symmetry plane between the two rods, as illustrated in Fig. 3, was designed for high-beam-quality extraction tests. The symmetry ensures that the mode is the same size and that rays pass through similar areas in both rods. The resonator is formed by flat-end mirrors separated from the rods by 65 cm. The rods are separated from one another by 20 cm. A −16-cm focal-length lens located at the symmetry plane compensates for first-order thermal focusing. Neglecting aberrations, each rod has a thermal lens focal length of 25.7 cm and a TEM_{00} mode diameter of 2.4 mm ($1/e^2$). The rods form the limiting apertures.

The birefringence is corrected by placing a quartz polarization rotator between the two rods.[11] If the thermally induced stresses and ray paths are identical in the two rods then the depolarization and bifocusing can be cancelled by rotating the polarization of all rays by 90° between rods. We have demonstrated this technique by using two rods pumped with 20 W each. In this proof-of-principle test, the depolarization in a collimated He–Ne laser passing through the two rods was reduced from 6% to less than 0.2% with the use of a quartz rotator.

The thermally induced spherical aberration is corrected by an aspheric surface on the lens at the symmetry plane. The shape of the asphere is derived from calculations that use the measured thermal distortion of the rod to predict the properties of the aberrated mode. The thermal distortion is measured in a Mach–Zehnder interferometer while the rod is being extracted. Efficient extraction decreases the distortion by approximately 25% compared with when the power is lost to fluorescence. This difference is a result of upconversion leading to a lower net quantum efficiency for the fluorescence. The thermal distortion is added to the phase of the desired Gaussian mode at the rod, and the aberrated wave front is propagated to the symmetry plane numerically. The proper asphere shape is simply that which reverses the phase at the symmetry plane, effectively making the asphere a phase conjugator.

Radial profiles for the thermal distortion (measured at the rods) and the correction (imposed by the asphere) are given in Fig. 4. The thermal distortion is the sum of contributions from both rods. The transverse dimensions of the two profiles are different because the mode focuses down from the rod to the asphere. The net effect of the asphere and two thermally distorted rods on the mode phase front is equivalent to pure focus. The CaF_2 asphere is diamond machined and postpolished to reduce scatter losses to less than 0.5%.

A stable output power of 60 W with near-diffraction-limited beam quality is obtained with the flat–flat resonator and a total diode power of 235 W. The beam quality is calculated from measurements of the

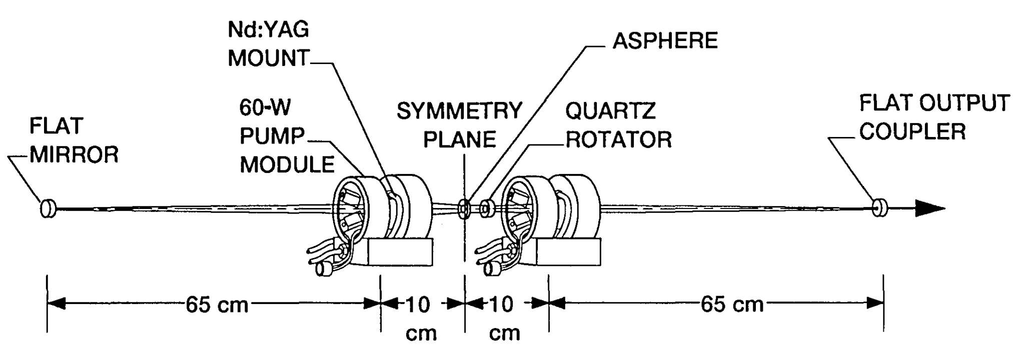

Fig. 3. Symmetrical resonator used in TEM_{00} extraction experiments. Symmetry between the two laser rods allows

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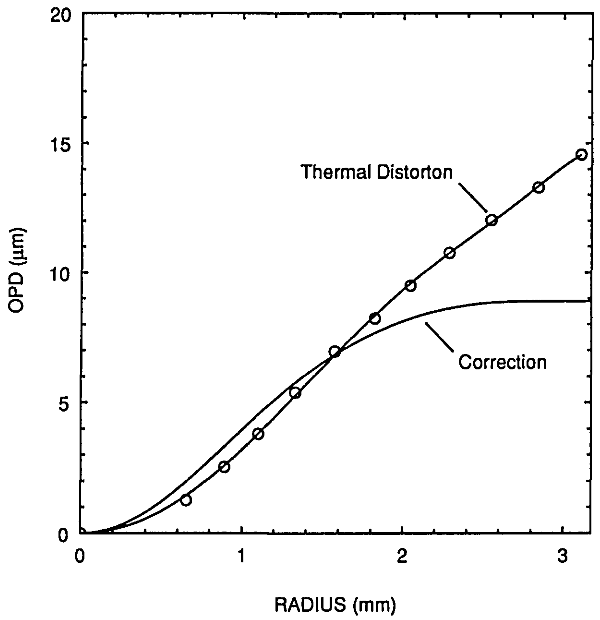

Fig. 4. Radial profiles of the thermal distortion resulting from two pumped rods and the correction imposed by the aspheric lens. The profiles have different transverse scales because the mode size decreases by approximately 1.4 times between the rod and asphere. OPD, optical path difference.

beam size taken at the output coupler and then in the far field. The flat output coupler defines a waist for the mode, which nominally has a radius of 174 μm. Far-field measurements were taken 2 m from the output coupler (the beam Rayleigh range is 9 cm). The beam quality, or M^2 factor, is simply the ratio of the far-field beam size to that calculated for a diffraction-limited beam with the same waist. The beam quality of this laser is 1.3 times diffraction limited.

The output power and beam quality of the laser are sensitive to adjustments in pump power because the resonator Fresnel number changes rapidly as a function of the rod focal length. The sensitivity can be greatly reduced by using convex end mirrors rather than flats.[12] For example, the mode size would be nearly constant for pump power variations of $\pm 5\%$ if the flats were replaced with -30-cm mirrors at the same locations. Flat-end mirrors are used here for experimental convenience. In our case, the resonator length is adjusted so that the Fresnel number approaches unity under full pump power. When properly adjusted, the power is stable, and the mode discrimination is sufficient to assure good beam quality without sacrificing efficiency.

In summary, we have demonstrated a diode-end-pumped cw Nd:YAG laser that produces an output power of 92 W in a multimode beam and 60 W in a near-diffraction-limited beam. The laser uses a total of sixteen 15-W laser diode bars pumping two short rods in an angularly multiplexed pump geometry. A diamond-machined asphere and a quartz polarization rotator are used in a symmetric resonator to correct thermal distortion and the stress-induced birefringence for TEM_{00} extraction. The optical-to-optical efficiencies are 44% and 26% for multimode and TEM_{00} operation, respectively. The high efficiency of the end-pumped oscillator and the use of laser diode bars as pump sources provide significant economic advantage for this design.

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