Efficient TEM_{00}-mode operation of a laser-diode side-pumped Nd:YAG laser

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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. Of the 1064-nm output, 11.8 mJ of energy was obtained in a 200-μs pulse with 64 mJ of pump energy at 808 nm. The overall conversion and slope efficiencies were 18% and 23%, respectively.

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 that they require the use of either expensive, high-power cw[6,7] or several quasi-cw[4,5] laser-diode arrays (see below for a definition of what constitutes a laser-diode array). This renders these geometries difficult to implement as cost-effective, low-average-power systems.

Before proceeding, we define the differences between laser-diode bars and laser-diode arrays in the context of our pumping geometry and the previous research of others. A laser-diode bar is a single-device structure with laser emission over a rectangular area with a large aspect ratio. The emitting-region fill factor and sizes vary among device types, but the standard length is usually 1 cm and the height approximately 1 μm. These bars often have individual emitting regions that form a linear array. Yet, when we use the term laser-diode array, we are not referring to this microscopic structure but to a single, macroscopic, device package that consists of two or more of these 1 cm $\times$ 1 μm laser-diode bars stacked vertically on top of one another. Hence a five-bar stack of quasi-cw laser-diode bars is a five-bar, quasi-cw, laser-diode array. This type of device is considered to be a single laser-diode array irrespective of the number of bars in the stack.

In the case of pulsed systems, given the high cost of quasi-cw laser-diode arrays, side-pumped lasers operating at the energy level of tens of millijoules are cost effective only when pumped by as small a laser-diode array as possible. Previous research[8-11] with single laser-diode array pump sources (as much as five bars per array) in side-pumped geometries has been unable to demonstrate efficient operation in the TEM_{00} mode. We will describe a novel side-pumped geometry with efficient TEM_{00}-mode conversion using a single, five-bar, quasi-cw, laser-diode array as the pump source.

The major difference between our pumping geometry and that of previous side-pumped schemes is the achievement of a near-Gaussian pump deposition profile while using only a single laser-diode array as the pump source. Earlier side-pumping geometries fall into two broad categories. In the first category are those schemes that employ quasi-end-pumped geometries[7] or radially pumped geometries with spatial overlap/averaging of multiple pump sources[6] to achieve high TEM_{00}-mode conversion efficiency. The second category includes those schemes that employ a single laser-diode-array pump source and operate multimode.[8-11] Our research utilizes a pumping geometry whose geometry falls in the second category while achieving TEM_{00}-mode conversion efficiencies more typical of the first category.

Our laser rod is a 12-mm-long, semicircular-cross-section (D-shaped) piece of 1% Nd-doped YAG. The curved surface is antireflection coated at the pump wavelength and has a 1.5-mm radius of curvature. This surface of the rod acts as a cylindrical lens to focus the highly divergent output from the diode array, which is placed parallel to the rod axis facing the curved surface. Unabsorbed pump light is reflected from the highly reflecting, flat, rear surface. The path length of this double pass is approximately one absorption length of the material and leads to 65% absorption of the incident pump energy. The rod also has Brewster-angled end faces oriented such that the electric field axis is parallel to the flat, rear surface.

This rod is designed to perform the following specific functions: (1) The cylindrical lens action transforms the highly divergent diode array output into a Gaussian absorbed energy profile in the vertical direction. (2) The double pass of the pump beam over a total path equal to one absorption length provides a uniform absorbed energy profile in

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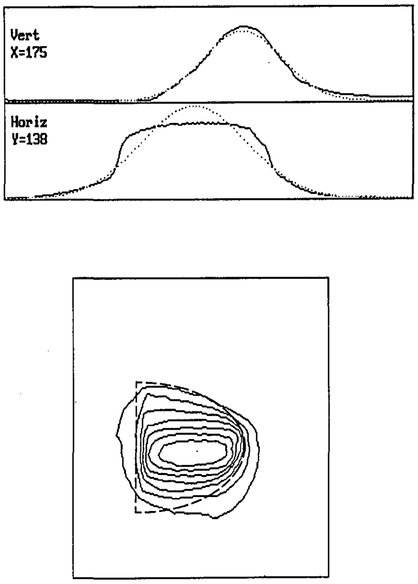

Fig. 1. Fluorescence image of the laser rod with absorbed energy profiles parallel (horizontal) and perpendicular (vertical) to the flat rear surface of the rod. The rod cross section is shown as the dotted curve that forms a semiellipse.

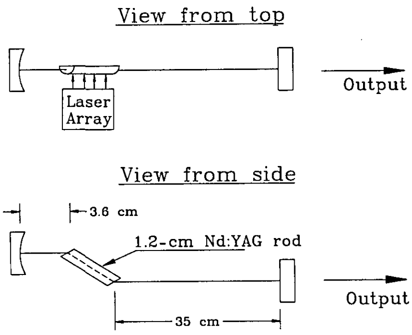

Fig. 2. Schematic layout of the laser resonator.

the horizontal direction. A shorter path would significantly reduce the total absorbed energy, and a longer path would significantly reduce the mean inverted population density. (3) The use of Brewster end faces on the rod expands the TEM_{00} cavity mode in the vertical direction to match the pumped volume in the rod. (4) The rod acts as the TEM_{00}-mode aperture for the resonator. (5) The flat rear face provides a mounting and heat-sinking surface.

Before conducting laser experiments, we evaluated the absorbed energy profile in the laser rod by imaging the fluorescence from the center of the array-pumped rod onto a CCD detector array interfaced to a frame grabber and computer (Montana Laser Corporation Multicam System). The fluorescence image was observed from a point beyond the Brewster end faces and represents the excited-state density as seen by the resonator outside the laser rod. The fluorescence image intensity is directly proportional to the excited-state density of Nd ions, and hence absorbed energy, in the laser rod.

The data shown in Fig. 1 were taken with the five-bar laser-diode array spaced 0.5 mm from the nearest point on the curved surface of the rod. This spacing gives the optimum energy conversion for TEM_{00}-mode laser operation as determined experimentally. Data taken for array-to-rod spacings of as much as 2 mm show that the pumped volume becomes more diffuse as the spacing increases. 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 a 0.3-mm center-to-center spacing.

The fluorescence image shows that the excited-state density in the horizontal direction is almost uniform over most of the rod aperture, while in the vertical direction a close approximation to a Gaussian is obtained. A suitable resonator design for efficient energy conversion to the TEM_{00} mode must maximize the overlap integral of the resonator TEM_{00} mode and the pump profile while simultaneously utilizing the rod to apodize higher-order spatial modes.

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

Long-pulse (200 μs at 50 Hz) laser operation was investigated with output-coupling transmission in the range of 2% to 25%. Optimum energy conversion was obtained with a 20% output coupler with 11.8 mJ of output at 1064 nm for 64 mJ from the 808-nm pump laser (approximately 65% was absorbed in the laser rod). Total intracavity losses were estimated to be 1.2% from a Findlay–Clay analysis of the laser threshold as a function of output coupler transmission. Figure 3 shows the output energy as a function of the pump energy incident upon the laser rod with a 20% transmission output coupler. The TEM_{00}-mode slope efficiency of 23% is comparable with that obtained by the majority of side-pumped geometries operating multimode, using a single quasi-cw laser-diode array,[7–9] and it far exceeds their potential TEM_{00}-mode performance.

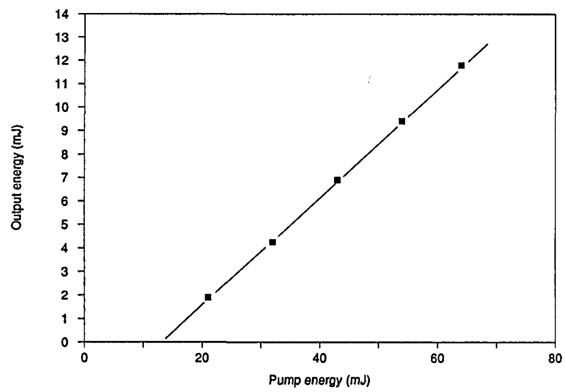

Fig. 3. TEM_{00}-mode energy as a function of the incident pump energy.

⟨Gaussian Fit Data⟩	Vert	Horiz
Correlation Coeff.	= 0.963	0.968
Peak Position	= 125	175
Beam Dia. @ $1/e^2$ [mm]	= 3.637	3.728
Percent of Peak	= 77.940	78.886

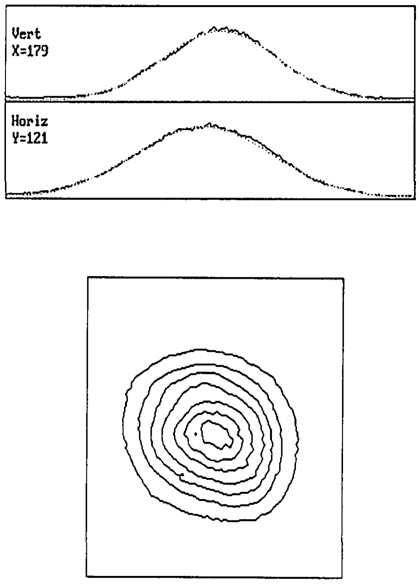

Fig. 4. Contour plot and beam profiles for the TEM_{00}-mode output beam.

The output-beam profile (with 64-mJ pump energy) in Fig. 4 shows a greater than 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 resonator calculations. We therefore measured the beam divergence with the aid of a 1-m focal-length lens and obtained a 3.4-mrad divergence. We then probed the pumped laser rod with a He–Ne laser (632.8 nm) and determined the presence of a thermally induced lens of 3.4-m focal length. Inclusion of such a lens in our resonator calculations yielded a 3.1-mrad beam divergence. This is in good agreement with the experimental value of 3.4 mrad. Given that the heat load (0.6 W) on the laser rod is concentrated in a small volume of material with a near-radial deposition profile, a significant, thermally induced lensing effect is not unexpected, as shown by Innocenzi *et al.*[12]

In summary, we have demonstrated a 23% slope efficiency and 11.8 mJ of energy for a TEM_{00}-mode, Nd:YAG laser side pumped by a 64-mJ, five-bar, quasi-cw, laser-diode array using a novel pumping geometry. Higher output energies may be obtained by scaling the axial length of the system and adjusting the resonator mode size accordingly. This approach should allow efficient generation of TEM_{00}-mode-quality beams at energies of as much as several tens of millijoules.

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