Room-temperature diode-bar-pumped Nd:YAG laser at 946 nm

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Efficient, high-power operation of a diode-bar-pumped Nd:YAG laser on the quasi-three-level transition at 946 nm is reported. Longitudinal pumping of a simple folded cavity by a 20-W diode bar, with a two-mirror beam shaper used to reformat the bar's output, yields a continuous-wave output power at room temperature of ~3 W in a 1.5-times diffraction-limited beam for 13.6 W of incident pump power. The corresponding optical slope efficiency was approximately 33%. © 1996 Optical Society of America

The relatively low cost and wide availability of high-power diode bars has stimulated growing interest in their use as pump sources for solid-state lasers. However, progress in scaling such lasers to multiwatt average power levels has been hindered by the rather inconvenient, highly elongated shape of the diode bar's output, which renders it difficult to focus to the small circular beams required in efficient end-pumped configurations. As a result, efforts to scale end-pumped lasers to the multiwatt level have generally been confined to the highest-gain Nd transitions near 1 μm. However, there are many other laser transitions that have important applications potential if they can be scaled efficiently to high powers but that suffer from unfavorable level schemes, have very low stimulated-emission cross sections, or both.

One important example of such a transition is the 946-nm line in Nd:YAG. This line has attracted attention as a convenient, all-solid-state blue source through frequency doubling, for which numerous potential applications exist. Additionally, a high-power 946-nm Nd:YAG laser with good beam quality is an attractive pump source for Yb-doped materials (e.g., Yb:YAG and Yb:phosphate glass). However, efficient lasing on this transition is considerably more difficult to achieve than on the more familiar 1.064-μm transition. This is partly due to its quasi-three-level nature,[1,2] which results in a significant reabsorption loss, which (at room temperature) is ~0.8%/mm for a 1% Nd-doped YAG rod. The main problem, however, with the 946-nm line is its very small stimulated-emission cross section,[1,2] ~4×10^{-20} cm^2, which is ~9 times smaller than for the 1.064-μm line. As a result the 946-nm Nd:YAG laser has a threshold that is at least a factor of 9 times higher than for a comparable 1.064-μm Nd:YAG laser.

The strategy for coping with the problems of this 946-nm transition has been to use resonators that support a very small laser mode size and to use diode pump laser sources with good enough beam quality to permit tight focusing that matches this mode size. This places stringent demands on the diode beam quality that are in general satisfied only by low-power diodes. To overcome these constraints pulsed high-peak-power diode array have been employed[3] to scale average powers at 946 nm, but, to the best of our knowledge, the maximum cw powers obtained so far at 946 nm have been rather low (<1 W).[4,5]

We describe a 946-nm Nd:YAG laser, end pumped by a single 20-W diode bar that produces cw output at the multiwatt power level. This laser of performance was achieved by use of a simple two-mirror beam-shaping device[6] to reconfigure the highly elongated diode bar output beam into a more convenient form for end pumping. The principle of operation of the two-mirror beam shaper is described in detail in Ref. 6. Here we merely summarize the main features. This beam-shaping technique enables the output beam from a high-power diode bar to be reconfigured with nearly equal M^2 values for orthogonal planes without significant reduction in brightness. Starting with a 20-W cw diode bar (Opto Power Corporation OPC-A020-mmm-CS) and using the beam-shaping technique, we obtained for the focused pump beam the following spot sizes w ($1/e^2$ intensity radius): 170 μm × 155 μm with M^2 values of ~60 and ~95, respectively, for orthogonal planes. The pump power of ~13.6 W at the focus corresponds to an overall transmission of 68% for the pump optics from the diode bar to the laser.

Figure 1 shows schematically the design of the Nd:YAG laser. The Nd:YAG rod with 1.1-at.% doping was 2 mm in diameter by 5 mm in length. It was mounted with an indium foil surround in a water-cooled metal block acting as a heat sink. The lengths of the arms in the simple folded cavity were, respectively, ~70 and 12–13 mm, the latter adjustable with the output mirror mounted upon a translation stage. The input mirror had convex curvature, chosen to give

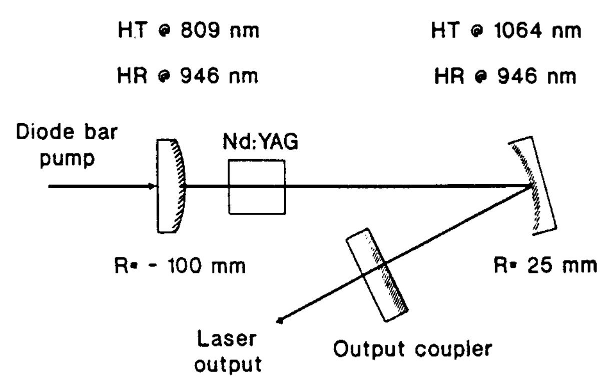

Fig. 1. Schematic diagram of the Nd:YAG laser resonator design: HT, high transmission; HR, high reflecting; R, radius of curvature.

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some compensation for the thermally induced lens in the laser rod, which was measured to have a focal length of ~6 cm at the highest pump powers. The strong lensing is a consequence of the tight focusing of the pump, as the focal length is proportional to the square of the pump beam diameter. This partial compensation, together with the facility to vary the length of the short arm, permitted matching of the mode spot size in the laser rod to ~165 μm, as required. Suppression of oscillation at the much higher gain laser transition near 1.06 μm was achieved with appropriately coated dielectric mirrors. The highest output power was obtained with an output coupler with 7% transmission.

Figure 2 shows the output power as a function of the absorbed pump power for a rod mount temperature of 19 °C (at the highest pump power). The rather high threshold of 2.15 W is, in part, due to the fact that the resonator is optimized for the thermal lensing that corresponds to the highest pump powers. The highest output power at 19 °C is 2.96 W for maximum pump power (13.6 W incident, 11.2 W absorbed). The average slope efficiency with respect to absorbed pump power is ~33%. For pump powers more than four times above threshold the slope efficiency increases to 42% with respect to absorbed pump power (36% with respect to incident pump power). This increase is due mainly to saturation of the reabsorption loss. The circulating intensity I_c in the Nd:YAG rod is of the order of 40 kW/cm^{-2} and thus twice the saturation intensity, I_s, which is ~20 kW/cm^{-2} for this transition. This results in a decrease of the reabsorption loss to ~40% of its value for low circulating intensities [reabsorption loss $\propto I_s/I_c \times \ln(1 + 2I_c/I_s)$, according to Ref. 1]. On the other hand, the unsaturated reabsorption loss is enhanced at high pump powers from its room-temperature value of ~0.8%/mm to more than 1.2%/mm because of the temperature increase in the pumped region, estimated to be ~30 K. Thus the reabsorption loss during operation with the highest pump powers can be estimated to be ~5% per round trip. According to Ref. 7 the slope efficiency with respect to absorbed pump power is

$$\frac{dP_{\text{out}}}{dP_{\text{abs}}} = \frac{T}{L+T}\,\frac{\nu_L}{\nu_P}\,\frac{S}{dF},$$

where T is the output mirror transmission, L is the round-trip loss including reabsorption, dS/dF is the efficiency with which absorbed photons are converted to laser photons, and ν_L/ν_P is the quantum defect with respect to this conversion. The quantity dS/dF considers all the geometrical factors associated with the conversion of the incident pump photons to laser photons, i.e., in particular the mode matching but also the ratio of reabsorption loss to fixed cavity loss and the ratio of pump power to threshold. Using the known and estimated values given above [$T = 7\%$, $L = 6\%$ (5% reabsorption +1% other loss), $\nu_L/\nu_P = 85\%$], we can approximate dS/dF to be 0.85–0.9 in our case. The resulting slope efficiency with respect to absorbed power is ~39%–41%, in reasonable agreement with the measured value. Our calculations and experimental findings indicate that the parameter values chosen, 7% output mirror transmission (of the order of the round-trip loss) and a crystal length of 5 mm, are close to optimum. For instance, as far as the rod length is concerned there is a trade-off between high-pump-power absorption and reabsorption loss, and in practice a laser with a 3-mm-long Nd:YAG crystal (71% absorbed pump power versus 87% for 5-mm length) also performed well but with the output power reduced by ~5%.

A reduction of reabsorption loss without reducing the pump absorption can be achieved by decreasing the temperature. Figure 3 shows the temperature dependence of the output power at the maximum pump power of 13.6 W. The steady (almost linear) increase with decreasing temperature is due to a reduction of the reabsorption of ~0.1%/mm for a 10-K reduction in temperature. For a mount temperature of ~11 °C we obtained 3.04-W output power. It should be noted that an output power of 2.96 W was obtained at ~14 °C, compared with the results presented in Fig. 2 for which this power was obtained at 19 °C. Between the two experiments the rod had been remounted with a new layer of indium foil surround. The slight change in heat transport efficiency is believed to be the source of the difference. Indeed, a number of observations suggest that the performance of this laser is critically dependent on the quality of the heat sink.

The beam quality for powers up to 2 W was very good, with measured M^2 values (with a Coherent Mode-master) of $M_x^2 < 1.2$ and $M_y^2 < 1.2$, and deteriorated somewhat for higher powers ($M_x^2 \sim 1.44$, $M_y^2 \sim 1.49$ for the highest values). The reabsorption loss contributes to the good beam quality by helping to suppress higher-order transverse modes. The output power stability is ~0.5%.

By inserting a thin Brewster plate polarizer into the cavity between the laser rod and the folding mirror, we selected a linear polarized output with a power of 2.0 W and excellent beam quality ($M_x^2, M_y^2 \sim 1.1$). The sum of the linearly polarized output power plus the total power reflected from the Brewster plate (the latter corresponding to a single-pass birefringence loss of 0.25%) was lower than the output power for the unpolarized laser. These results suggest that the polarizer influenced the transverse mode behavior, resulting in reduced power and improved beam quality.

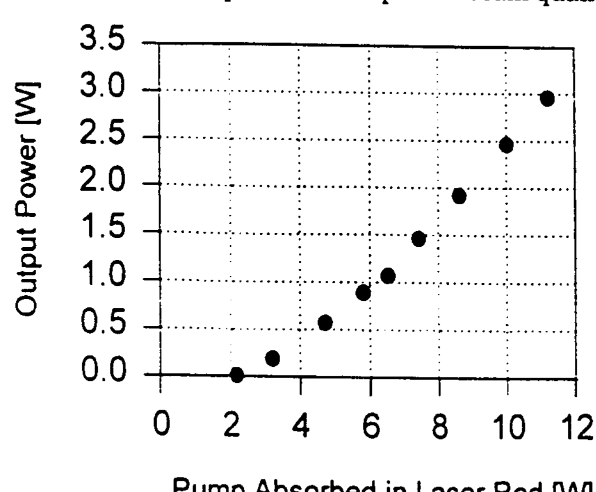

Fig. 2. Output power versus input power absorbed in Nd:YAG at room temperature.

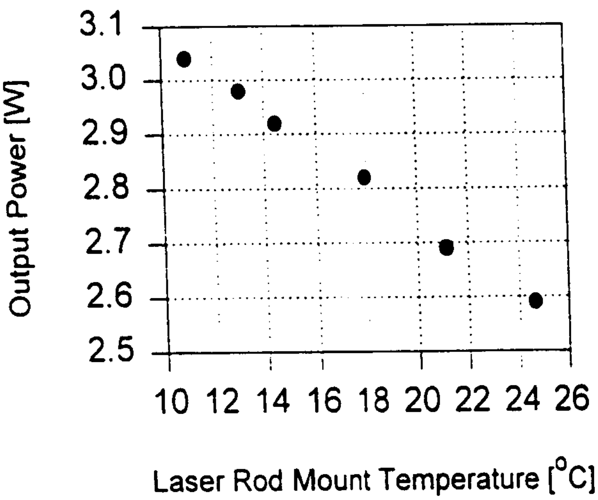

Fig. 3. Output power versus temperature of the laser rod at maximum pump power.

The high power and good beam quality of this polarized output have proved effective in permitting efficient blue-light generation by external frequency doubling in periodically poled lithium niobate.[8]

The laser emission spectrum was investigated with an ANDO AQ-6315A optical spectrum analyzer with an overall spectral resolution of 0.1 nm. It was confirmed that there was no emission on the much higher gain transitions near 1.06 μm. The spectra showed a FWHM of ~0.3 nm with and without the polarizer, with no significant change over the temperature range and the range of powers covered.

In summary, efficient room-temperature operation of a cw Nd:YAG laser at 946 nm is reported; the laser was end pumped with a beam-shaped high-power diode bar. 3 W of unpolarized output with good beam quality ($M^2 < 1.5$) and 2-W linearly polarized output with excellent beam quality ($M^2 \sim 1.1$) were obtained. We believe that this represents the highest cw power demonstrated for a diode-bar-pumped Nd:YAG laser at 946 nm. These results underline the benefits offered by the well-confined pump beam that the beam shaping produces. With further improvements in the pump optics, the resonator design, and the thermal management, we believe that 946-nm cw powers approaching 4 W should be achievable with this 20-W single-bar pump. These initial results suggest considerable potential for Q-switched operation, single-longitudinal-mode operation, and subsequent efficient frequency doubling into the blue.

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