

Efficient, frequency-stable laser-diode-pumped Nd:YAG laser

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We have designed and tested a laser-diode-pumped monolithic Nd:YAG oscillator. The electrical-to-optical slope efficiency was 6.5%. The frequency jitter was less than 10 kHz over a 0.3-sec period, the best frequency stability reported for a Nd:YAG laser to date.

End pumping of a miniature Nd:YAG laser with a gallium-aluminum-arsenide (GaAlAs) laser diode is an attractive means of obtaining a long-lived, efficient cw Nd:YAG laser. For many applications a miniature Nd:YAG laser provides capabilities that the laser diode itself cannot. The spatial and temporal coherence of the Nd:YAG oscillator exceeds that of the laser-diode pump. In addition, the Nd:YAG oscillator output can be amplified by high-gain Nd:YAG amplifiers.

Our goal for laser-diode pumping was to demonstrate a low-power, efficient Nd:YAG laser oscillator for applications in remote coherent Doppler anemometry.¹ Previous work has shown that conventional flashlamp-pumped, water-cooled Nd:YAG oscillators are limited to a frequency stability of 0.2 MHz over 5 msec by flashlamp- and coolant-induced instabilities.² This work shows that laser-diode-pumped Nd:YAG oscillators can be operated at a frequency stability that far exceeds conventionally pumped stabilized Nd:YAG oscillators.

Recently, the efficiency and the output power of GaAlAs laser diodes have improved dramatically. Laser diodes with cw single-mode outputs of 20 mW are commercially available,³ and, with some loss of mode quality, cw laser diodes of 40 and 100 mW are available.⁴ We have used these laser diodes to pump monolithic Nd:YAG rod lasers and have achieved an electrical-to-optical slope efficiency of 6.5%. The observed Nd:YAG oscillation threshold was at 2.3 mW of laser-diode output power, which is a small fraction of the rated output power. Thus the goal of efficient operation at a conservative level of diode power was achieved. The highest Nd:YAG cw output power reached was 4.4 mW at an overall electrical-to-optical efficiency of 1.5%.

The laser-diode-pumped Nd:YAG laser oscillates in a single axial and transverse mode. The laser resonator consists of the Nd:YAG rod itself, which is rigid and thus resistant to acoustic noise. Cooling takes place by conduction and thus is stable. The laser-diode pump source is extremely stable if the diode current and the temperature are stable. Thus extreme frequency stability and long coherence length are possible. We observe a frequency jitter of less than 10 kHz (1 part in 3×10^{10}) in 0.3 sec.

The narrow but strong absorption lines of Nd:YAG make it well suited for narrow-band optical pumping. When the pump beam is collinear with the resonator (end pumping), the overlap between the pumped vol-

ume and the Nd:YAG TEM₀₀ mode can be good and the absorption and coupling efficiency high. A number of workers have built neodymium lasers end pumped with diodes. Light-emitting diodes have been used to end pump Nd:YAG fibers.⁵ Superluminescent diodes have end pumped Nd:YAG rods.⁶ Laser diodes have been used to end pump the stoichiometric neodymium compound LiNdP₄O₁₂ with a 1.5% electrical-to-optical slope efficiency.⁶ This Letter reports the highest efficiency for Nd:YAG to date and contains the first reported measurements of frequency stability.

We fabricated Nd:YAG rods of length 5 mm and diameter 2 mm. Each end had a radius of curvature of 19 mm. One end was coated to be high-reflecting at 1064 nm and high-transmitting at the pump wavelength of 809 nm. The other end had a transmission of 0.3% at 1064 nm and was reflecting at 809 nm. Figure 1 shows a schematic of the end-pumped Nd:YAG oscillator. The output of a constricted double-heterojunction large-optical-cavity (CDH-LOC)⁸ diode laser was collected and focused by a gradient-index lens (Selfoc lens⁹) of 0.25 pitch. A magnification of 20× matched the diode pump beam to the TEM₀₀ mode of the monolithic resonator. The TEM₀₀ mode waist of the Nd:YAG resonator had a radius $w_0 = 39.4 \mu\text{m}$, and the calculated radii for the two axes of the elliptical pump beam were $w = 10.4$ and $w = 37.2 \mu\text{m}$. The pump laser was selected to operate at 806 nm at room temperature. Efficiency data reported here were obtained when the diode temperature was in the range 20–25°C.

Alignment of these small lasers is not difficult. The fabrication tolerance for parallelism between the two mirror faces is determined by the ratio of useful aperture to mirror curvature and in our case was an easily ob-

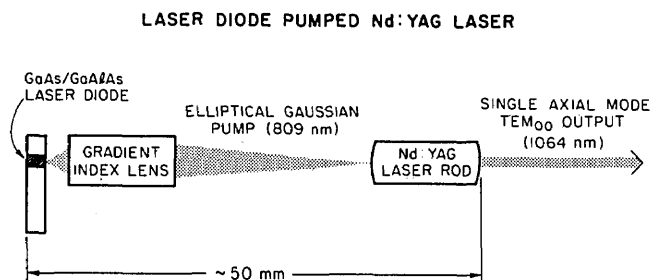


Fig. 1. Schematic of the laser diode, gradient-index lens, and monolithic Nd:YAG oscillator.

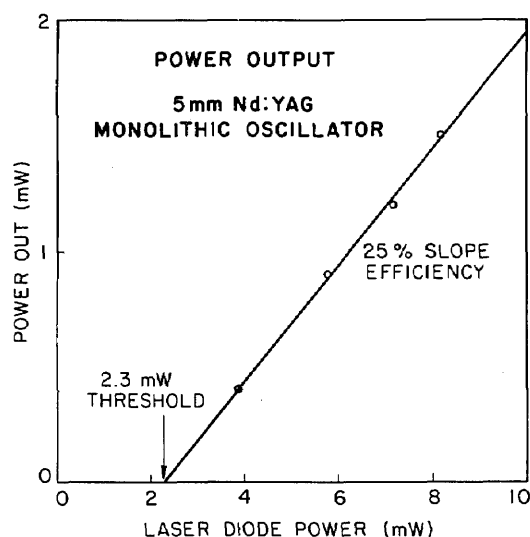


Fig. 2. Power input versus output for the 5-mm Nd:YAG rod end pumped with the CDH-LOC laser, focused by a quarter-pitch Selfoc lens.

tained $\pm 3^\circ$. Alignment of the pump to the resonator was most easily achieved by looking through the output face of the Nd:YAG to see the fluorescence at $1.06 \mu\text{m}$. The pump is reflected at the faces and thus passes through the rod more than once. When all passes overlap, the laser is aligned. The lowest threshold alignment always corresponded to the optimum alignment for TEM_{00} operation. With the CDH-LOC index-guided diode laser, TEM_{00} operation was possible at all pump powers. The threshold of the second axial mode occurred at a Nd:YAG output power of 1.2 mW.

Figure 2 is a plot of output power at 1064 nm as a function of pumping power at 806 nm. Slope efficiency was 25%, and the threshold pump power was 2.3 mW. The electrical-to-optical slope efficiency of the diode was 26%, so the overall electrical-to-optical slope efficiency was 6.5%. Overall efficiency, as opposed to slope efficiency, was low, because the laser diode had been damaged in earlier experiments and had a high threshold.

Similar measurements were made with a Nd:YAG rod of 3-mm length. The slope efficiency was reduced to 17% for the diode-pumped case. With dye-laser pumping at the very strongly absorbed wavelength of 590 nm, efficiency did not depend on rod length. Thus we believe that the 3-mm rod was too short for optimum diode-pumped efficiency. For the 3-mm rod, the threshold of the second axial mode could be reached only with dye-laser pumping and was found to occur at 8 mW of output power.

We tested other laser-diode pump sources and found that the beam quality of the laser-diode pump was important. The gain-guided single-stripe laser produced by Spectra Diode Laboratories had an astigmatic beam. Thus the spot size after a single spherical lens was larger than that of the index-guided CDH-LOC laser. Absorption was lower, because the gain-guided laser oscillated in several axial modes and thus had a linewidth large compared with the width of the Nd:YAG absorption lines. TEM_{00} operation was more difficult to

achieve, and slope efficiency was reduced to 12%. The 40-mW power available from this laser diode, however, resulted in a 4.4-mW output at 1064 nm. The overall electrical-to-optical efficiency was 1.5%.

The polarization of the monolithic lasers was indeterminate unless a small stress was applied transversely to the rod. The 1064-nm polarization was always parallel and never perpendicular to the applied stress.

The laser-diode pump wavelength must be selected to match the absorption of Nd:YAG. Figure 3 is a plot of Nd:YAG optical absorption as a function of wavelength. The dashed horizontal line is at a level corresponding to 50% absorption in 4 mm. The data points in Fig. 3 show the absorption measured by scanning the CDH-LOC diode temperature. Diode temperature control is a convenient way to match the laser-diode output wavelength to the absorption of Nd:YAG and thus to ease the tolerance on diode wavelength. The average temperature-tuning coefficient for the laser diode of Fig. 3 is $0.35 \text{ nm}/^\circ\text{C}$.

A primary goal of this work was to measure the frequency stability of monolithic, laser-diode-pumped Nd:YAG lasers. We pumped two Nd:YAG oscillators with the same laser diode and mixed the output of the two oscillators on the face of a photodiode. The beat signal was observed with a spectrum analyzer. A plastic case was used to isolate the two lasers from fast temperature fluctuations. Other than that, no effort was made to stabilize the lasers. A heater was attached to one laser to permit some tunability. The temperature-tuning coefficient for any monolithic Nd:YAG laser operating at 1064 nm is $3.1 \text{ GHz}/^\circ\text{C}$. The axial mode spacing of the 5-mm rods is 16.5 GHz, so a temperature range of only a few degrees was needed to ensure that the beat signal was within the 1-GHz bandwidth of the detector.

We observed the beat signal for several hours and noted a typical rate of frequency drift of 300 kHz/min.

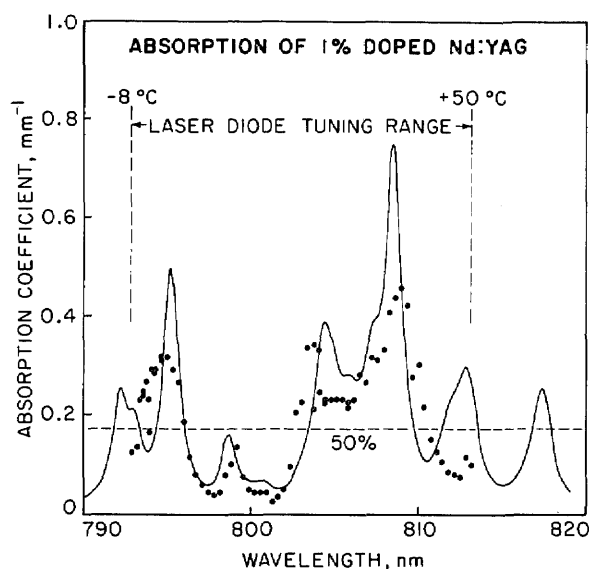


Fig. 3. Bulk absorptivity of Nd:YAG near 810 nm. Absorptivity a is defined by $I(x) = I(0)e^{-ax}$, where $I(x)$ is the optical intensity at a position x . Data points are plotted as a function of diode temperature for a particular diode. The temperature range is indicated.

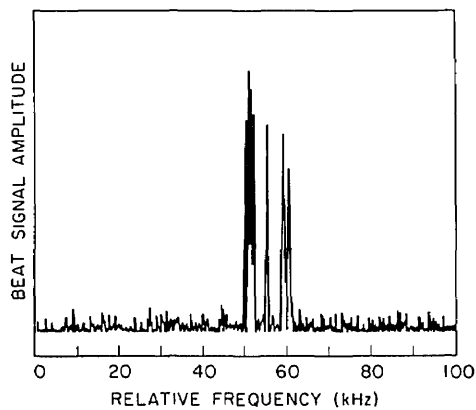


Fig. 4. Spectrum-analyzer trace of beating between independent lasers, recorded over 0.3 sec, shows a frequency jitter of 10 kHz.

There was also jitter of the beat signal, which was observed as random jumping of the signal between traces of the spectrum analyzer. The jitter was measured to be 10 kHz in 0.3 sec. Figure 4 is a spectrogram of the beat signal, recorded over a 0.3-sec period. During short intervals of about 5 msec when there was no jitter, we observed linewidths as low as 300 Hz, perhaps limited by the resolution of the spectrum analyzer.

The frequency drift was due to temperature drift. The jitter was due to relative motion between the laser-diode pump source and the Nd:YAG resonator, which resulted in the pump beam's wandering in the resonator mode volume and causing temperature fluctuations. A temperature-controlled and mechanically rigid mount is being built for further frequency stability studies.

Although we are now limited by frequency jitter of technical origin, it is of interest to find the ultimate frequency-stability limit of these lasers and to compare that limit with what is achievable with the diode laser itself. The fundamental limit to the frequency stability of the Nd:YAG oscillator is the Schawlow-Townes limit, which is given by¹⁰

$$\Delta\nu_{\text{laser}} = h\nu/2\pi t_c^2 P_0, \quad (1)$$

where $h\nu$ is the laser photon energy and P_0 is the output power of the laser. The cold-cavity resonator decay time t_c is equal to $2nl/\delta c$, where n is the index of refraction of the material, l is the length of the laser resonator, c is the speed of light, and δ is the round-trip loss of the resonator, including output coupling. For a monolithic Nd:YAG laser the loss δ is 1% and the length l is 5 mm, whereas for a typical laser diode the loss is greater than 50% and the length is 0.3 mm. Although the other factors in Eq. (1) vary by small factors, the ratio l/δ is nearly 3 orders of magnitude larger for the monolithic Nd:YAG oscillators, as compared with a laser-diode oscillator. Thus the Schawlow-Townes limit is 6 orders of magnitude smaller. In addition, the semiconductor diode laser cannot reach the Schawlow-Townes limit because of an excess linewidth factor that may increase the linewidth by a factor of 30.¹¹ Laser diodes are unlikely to achieve linewidths of less than 1 MHz unless an external resonator is used,

whereas our monolithic Nd:YAG laser at 1-mW output has a theoretical linewidth limit of less than 1 Hz.

The single-axial-mode power from a monolithic rod laser is limited by spatial hole burning. For the 5-mm rod, the threshold of the second axial mode occurs at 1.2 mW of output power. For the 3-mm rod it is 8 mW of output power. The threshold of the second axial mode can be accurately predicted by the theory of Danielmeyer.¹² This theory shows that the single-mode power limit is determined by a number of things but most significantly by cavity length. Shorter cavities offer higher single-mode power. However, since laser-diode absorption is reduced with length, efficiency decreases. The high absorption of stoichiometric neodymium materials⁷ may make possible high single-mode power from a laser-diode-pumped neodymium laser, but at the cost of amplifiability. An alternative approach is to use the recently demonstrated monolithic Nd:YAG ring-laser design (MISER).¹³

Active stabilization of the monolithic Nd:YAG oscillator may be achieved by the control of temperature, pressure, or electric field through the Kerr effect. Applications for the oscillator include metrology, fiber-optic sensing, and very-high-resolution spectroscopy. We expect an oscillator-amplifier combination to provide Fourier-transform-limited output in the multikilowatt range, with pulse lengths ranging from 1 μ sec to 1 msec.

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