Efficient, End-Pumped, 1053-nm Nd:YLF Laser

Diode-pumped lasers offer better stability and higher reliability than flashlamp-pumped laser systems. Most of the diode-pumping schemes can be divided into two major categories: end pumping and side pumping. High efficiency and good beam quality are potential advantages of end-pumped solid-state lasers over side-pumped ones. Practical realization of these advantages depends upon the possibility of reshaping a strongly astigmatic diode-laser beam into a beam with a circular symmetry. Recently, several practical schemes were suggested[1,2] that make it possible to effectively re-image the 1-μm $\times$ 10-mm emitting area of a high-power, cw laser diode bar into a few-hundred-micron spot size. These techniques have been used successfully for direct cw end pumping of solid-state lasers[1] and the efficient coupling of high-power, cw laser-diode radiation into the optical fiber.[2] Using a transport fiber to deliver the pump beam to the end-pumped active medium has a number of practical advantages: (a) the pump beam at the transport fiber output has a high-quality, centrally symmetric energy distribution; (b) the radial size of the pump beam can be easily up- or down-scaled by using simple and virtually lossless optics; (c) a transport fiber provides a simple and transparent interface between the pump source and the active medium, which greatly simplifies the whole diode-pumped laser characterization and maintenance; and (d) both the pumping source and the active medium can be changed simply by reconnecting transport fibers. Therefore, it seems very attractive to couple the high-power, quasi-cw diode laser into the optical fiber and to use this fiber-coupled, quasi-cw, high-power laser diode to end pump a solid-state laser.

In this article we report on an efficient Nd:YLF laser operated at 1053 nm that was end pumped by fiber-coupled, high-power, pulsed diode arrays. Two quasi-cw 100-W linear arrays[3] were used in this experiment. The emitting area of these diodes was 1 μm $\times$ 10 mm with ~100% aperture fill factor. The diode laser's 3.6-nm-wide output spectrum was centered at 805 nm. The output from the laser-diode arrays was coupled into 0.6-mm-diam, 0.22-numerical-aperture step-index fibers in a manner similar to that reported in Ref. 2. Fiber-coupling efficiencies of >50% were measured at the maximum diode-laser output (Fig. 74.53). At the transport fiber output the laser-diode radiation was re-imaged with 1.6$\times$ magnification into the Nd:YLF rod through a beam splitter that was HR coated for 1053 nm (R > 99%) and AR coated for 805 nm (R < 1.5%). In the course of our experiments we investigated a Nd:YLF rod pumped from one side by a single diode array and pumped from both sides by two arrays simultaneously. The pump energy that reached each of the Nd:YLF rod surfaces was ≥25 mJ for the 0.5-ms pump duration. This represents ~50% transport efficiency from the emitting surface of the laser diode to the input surface of the Nd:YLF active element. The active laser element was a 5-mm-diam, 20-mm-long Nd:YLF rod with 1.1 atm% of Nd and AR coated for 805 nm and 1053 nm on both sides. The focused pump beam formed a circularly symmetric spot on the input faces of the Nd:YLF rod with a pump beam cross section of ≤1.3-mm FWHM over the entire 20-mm length of the laser crystal (Fig. 74.54). More than 95% of the pump energy was absorbed in the Nd:YLF crystal. We found that for this pumping scheme the Nd:YLF lasing threshold at 1053 nm is insensitive to pump-wavelength variation within at least ±2 nm. We attribute this to the fact that Nd:YLF has a broad and almost–polarization-insensitive absorption

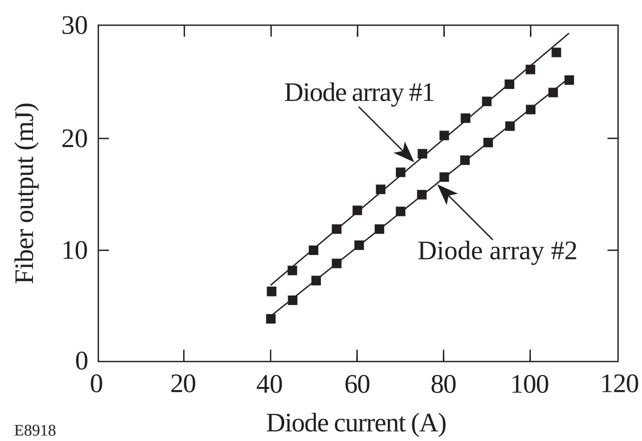


Figure 74.53
Fiber-coupled, 100-W, quasi-cw diode-array output versus diode current. Data presented are for the 0.6-mm-diam, 0.22-NA step-index fiber.

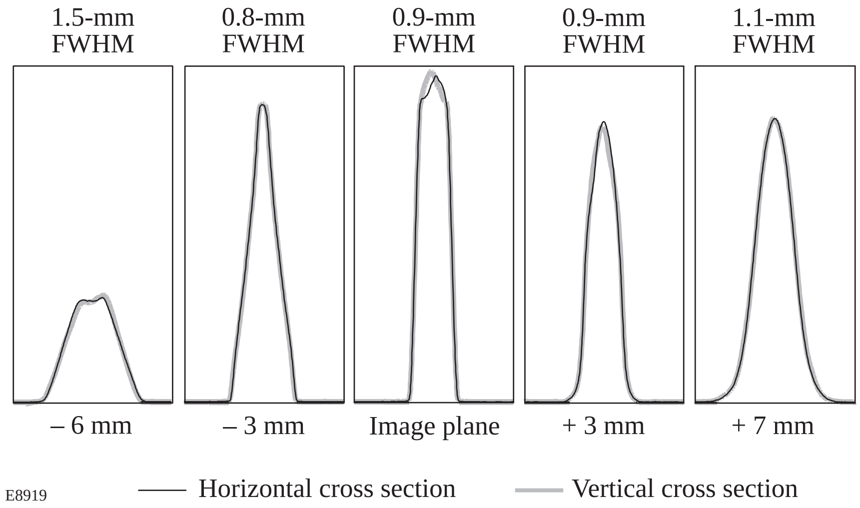


Figure 74.54
Pump-beam cross section along the axis of the active medium.

peak around 805 nm, which eliminates the need for the laser diode to be precisely wavelength tuned and externally cooled when the laser repetition rate is below 5 Hz. It should be pointed out that although all data presented here were taken at a 5-Hz repetition rate, we believe that a higher repetition rate can easily be achieved with proper heat removal from the diode laser and the active element.

The gain of the end-pumped rod was determined using a cw mode-locked Nd:YLF laser operated at 1053 nm that was collimated and apertured so that the probe beam used was ~1 mm in diameter. The single-pass, small-signal gain G_{ss} for the probe beam was observed with an analog oscilloscope[4] and measured with a digital oscilloscope.[5] The measured small-signal, single-pass gain for the ~1-mm beam at 1053 nm was 2.2 for pumping from one side and 4.2 for pumping from both sides (Fig. 74.55).

For the end-pumped Nd:YLF laser demonstration and characterization the following setup was used (Fig. 74.56): The cavity was 3.78 m in length and used a flat output coupler and a high reflector with a 5-m radius of curvature. Output couplers with reflectivity R = 85%, 70%, and 50% were tested. The 1053-nm wavelength for the Nd:YLF lasing was insured by the intracavity thin-film polarizer and appropriate Nd:YLF rod orientation in respect to this polarizer. The polarization of the output laser radiation was monitored by the extra-cavity Glan–Taylor polarizer. At the maximum one-sided pumping energy of ~27 mJ, the free-running output was 8.8 mJ in the multilongitudinal, fundamental TEM_{00} mode, which is 33% of the pump energy delivered to the Nd:YLF rod surface. At the maximum two-sided pump energy of 50 mJ, the free-running output was 20 mJ in the multilongitudinal fundamental TEM_{00} mode, which is 40% of the pump energy delivered to the Nd:YLF rod surface (Fig. 74.57). We believe that this is the highest TEM_{00} energy output reported to date for an end-pumped Nd:YLF laser operated at 1053 nm. The measured optical-to-optical differential efficiency was 54%. The spatial profile for the output beam was measured with a scientific-grade, cooled CCD camera.[6] The highly symmetric output beam has an intensity distribution very close to the intensity distribution calculated for our laser resonator parameters at 6.4-mJ output energy for the one-side pumping scheme (see Fig. 74.58). It should be emphasized that we observed the TEM_{00} output beam without any transverse mode control aperture in the cavity for the entire range of the pumping energies up to six times the threshold. We believe that this is attributed to the fact that the end-pumped volume cross section was smaller than the fundamental-mode cross section.[7]

The Q-switched mode of operation was also tested. To convert the Nd:YLF laser from the free-running mode to the Q-switching mode, a standard combination of the quarter-wave plate and Pockels cell was introduced into the laser cavity between the thin-film polarizer and the end mirror (Fig. 74.56). The reflectivity of the output coupler used for the Q-switched-mode operation was R = 70%. A high-voltage, step-function pulse was applied to the Pockels cell at the end of the pumping cycle to initiate the Nd:YLF laser Q-switching. The amplitude of this high-voltage pulse adjusted for maximum output energy at the highest pumping level (both ends pumping) was found to be 4.5 kV. The measured output energy in the Q-switched mode was 13.6 mJ (Fig. 74.59), and the Q-switched output pulse has a TEM_{00}-mode profile. The measured temporal FWHM of the Q-switched output pulse was 140 ns, which is less than six laser-resonator-cavity round-trips (Fig. 74.60).

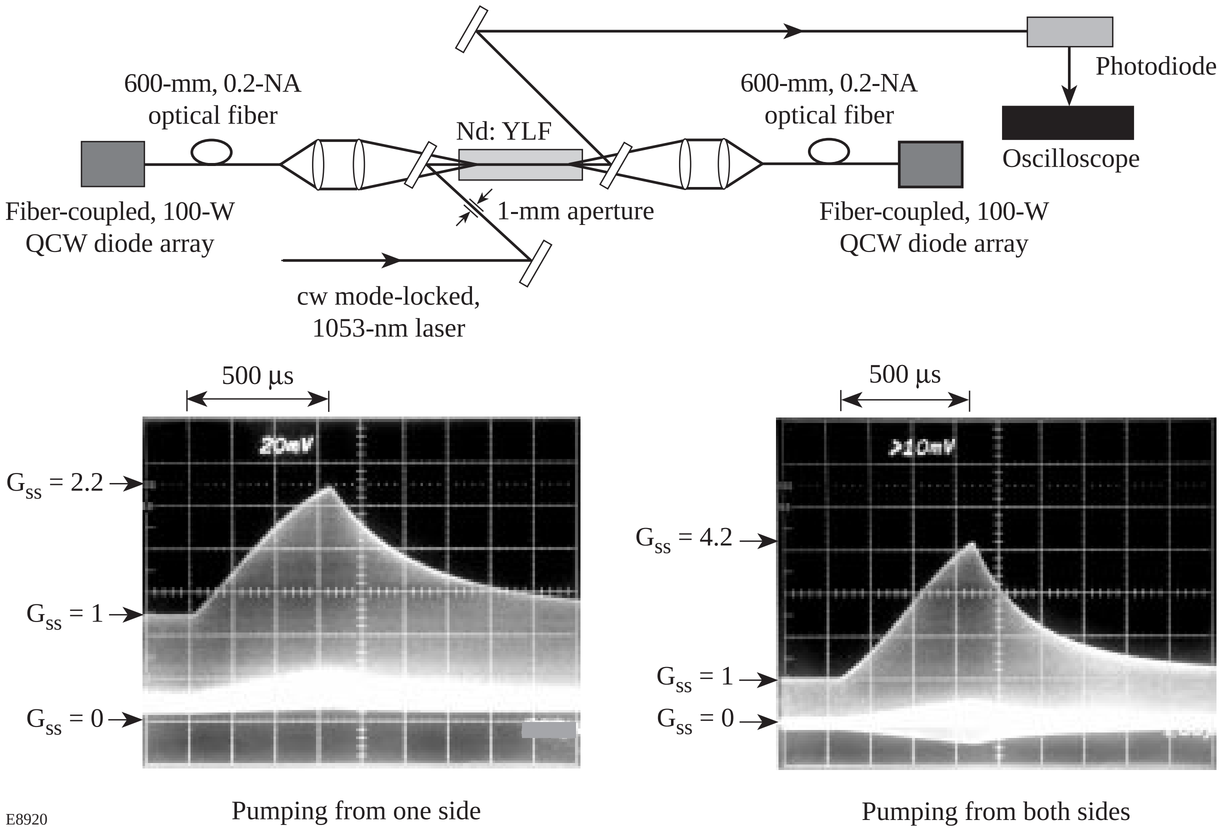


Figure 74.55
Small-signal-gain measurements: setup and experimental results.

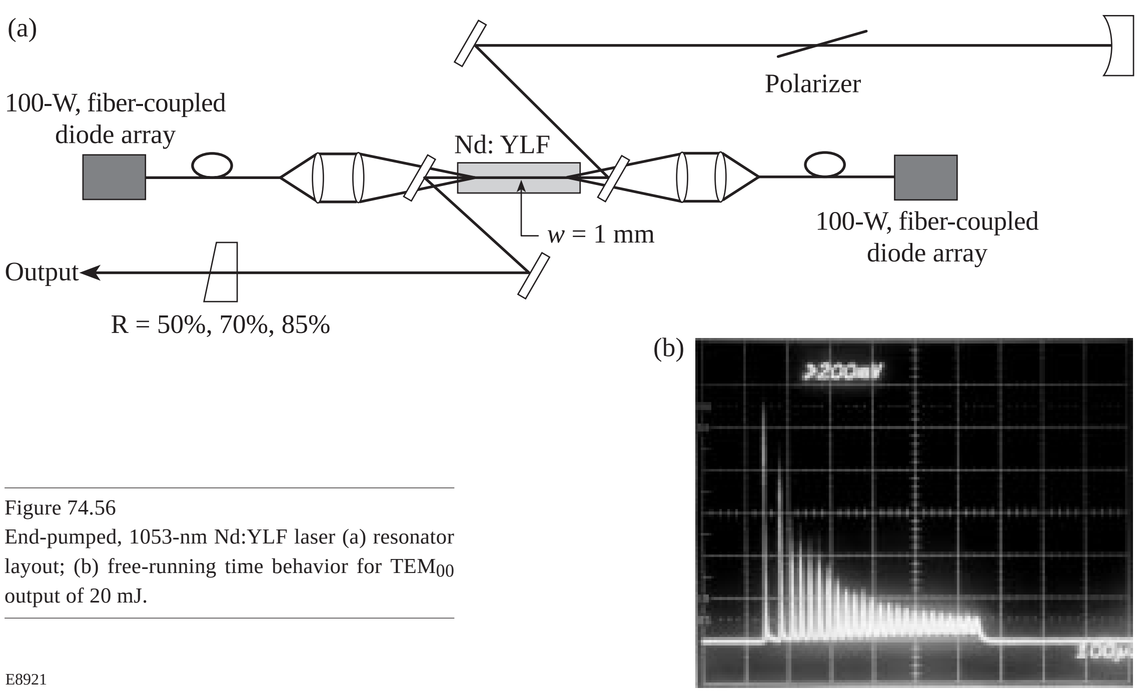


Figure 74.56
End-pumped, 1053-nm Nd:YLF laser (a) resonator layout; (b) free-running time behavior for TEM_{00} output of 20 mJ.

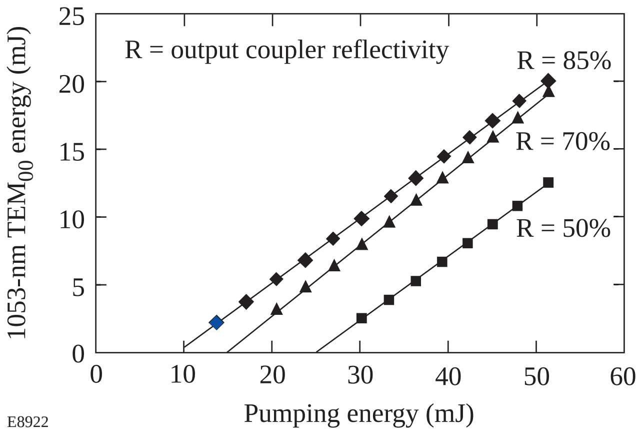


Figure 74.57
Measured, free-running, laser TEM_{00}-mode energy output at 1053 nm versus pump energy.

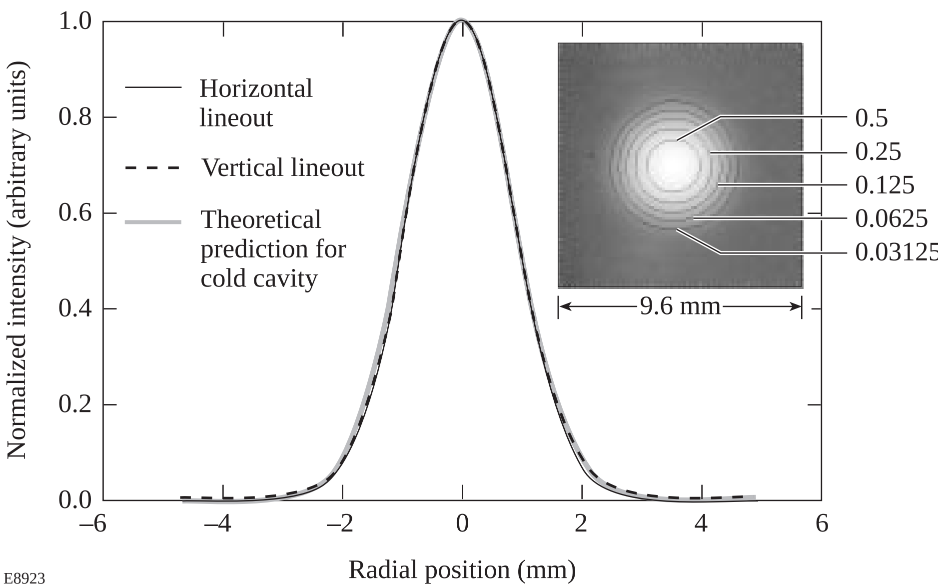
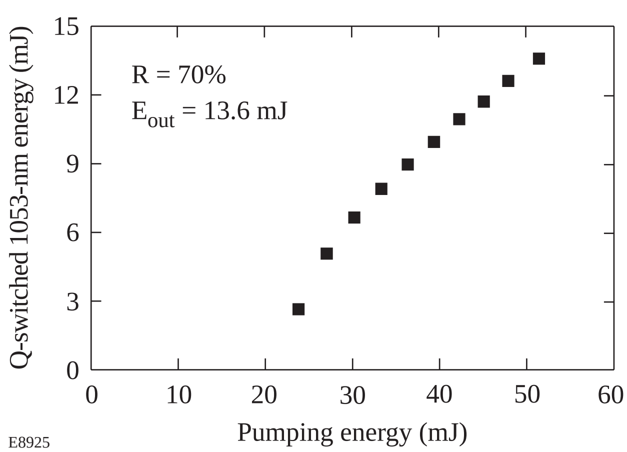


Figure 74.58
Experimentally measured and calculated output laser intensity beam profiles. An image of the laser beam on the logarithmic scale with superimposed contour lines is shown in the inset.



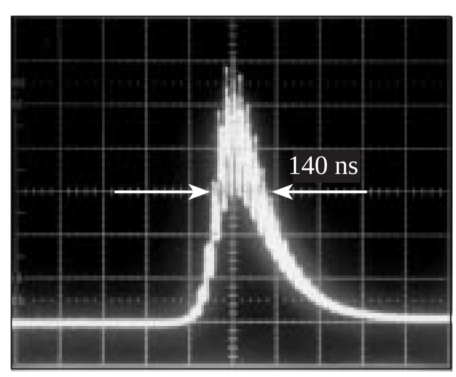


Figure 74.59
Measured *Q*-switched TEM_{00}-mode energy output versus pump energy.

Figure 74.60
Q-switching pulse temporal profile for TEM_{00} output of 13.6 mJ.

In conclusion we developed an efficient Nd:YLF laser at 1053 nm that was end pumped by two fiber-coupled, 100-W, quasi-cw diode arrays. A 20-mJ TEM_{00} energy output with 54% differential efficiency for a free-running mode and 13.6-mJ TEM_{00} energy output for *Q*-switched operation were demonstrated. We believe that this is the highest TEM_{00} energy output reported to date for the efficient end-pumped Nd:YLF laser operated at 1053-nm wavelength.

ACKNOWLEDGMENT

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