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Diode-pumped Nd:YAG Rod Laser with Single-side Pumping Geometry

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A pumping chamber for a diode-pumped Nd:YAG rod laser was developed. The pumping beam from a linear diode laser was incident on the rod from a single side. A planar-concave window was installed in front of the diode laser to expand the divergence angle of the emitted beam. The Nd:YAG rod was cooled by using a circulating coolant that flowed through the cooling tube. Due to the planar-concave window, even with a single-side pumping geometry, the uniformity of the pump beam's distribution in the Nd:YAG rod was improved.

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I. INTRODUCTION

The diode-pumped laser has been under development for more than 20 years [1]. For most of the development, continuous wave (cw) diode lasers have been used as a pumping source [2]. The employed gain medium was usually a solid state crystal, such as Nd:YAG or $Nd:YVO_4$. Due to their great advantages of high efficiency and low thermal load, cw diode-pumped lasers are replacing most of the low- or medium-power flashlamp-pumped cw solid-state lasers. The average power of single cw diode bar can reach several tens of Watts. These cw diode-pumped lasers can emit pulses when acousto-optic Q-switches are used inside the cavity. The average power of a cw diode-pumped, Q-switched laser can reach the kilowatt level; however, the pulse energy is limited to less than several millijoules and the pulse duration is usually longer than several tens of nanoseconds [3]. Nonetheless, in many cases, the peak power of pulse is too small for practical applications in LIDAR (light detection and ranging).

For pulsed excitation, flashlamps have been the most frequently used pumping source. Although the overall efficiency obtained in flashlamp pumping is typically limited to $1 \sim 3\%$, peak pumping power of several kilowatts can be easily achieved even with low-price flashlamps. To get higher pulse energies, pumping by using intense pulsed-diode lasers is required. Quasi-cw (QCW) diode lasers have been used for this application. Still, pulsed diode lasers with peak powers of several kilowatts are rather expensive and rarely used.

As diode lasers can have wavelengths very close to the absorption maximum of the gain medium, the absorption efficiency can be very large. Usually, due to the high absorption coefficient, the profile of the absorbed pump laser inside the gain medium becomes non-uniform when single-side pumping is used. Therefore, multi-side pumping is usually used to achieve uniform absorption of the pump laser's energy [4]. Moon *et al.* used three-side pumping [5]. Le Garrec *et al.* used five-side pumping [6]. Brioschi *et al.* used twelve-side pumping [7]. With the increase in the number of pumping directions, the mounting mechanism becomes more complicated, and a laser with a complicated mounting mechanism is more vulnerable to vibration. For applications requiring a robust mounting and high-power pumping, single-side pumping is the most suitable, considering its simple structure and maximum obtainable pumping power. However, achievement of uniform and efficient pumping in single-side pumping is still a challenge, so various designs of the reflector shape and the reflector material have been investigated [8–11]. Brand used a cusp-shaped reflector for uniform pumping [8]. Koshel and Walmsley used nonimaging optics [9,10]. In this work, we report on a QCW diode-laser-pumped Nd:YAG laser. The laser used a single-side pumping geometry. The pumping uni-

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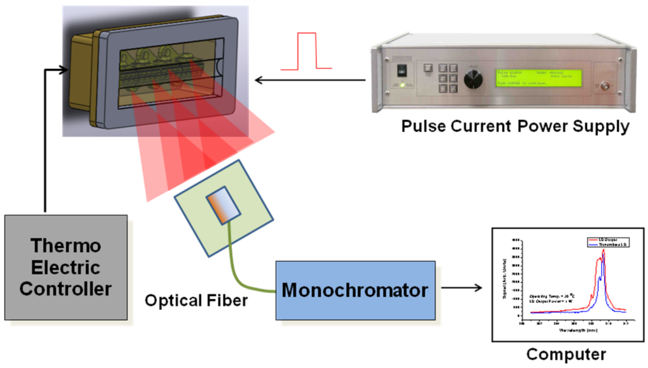

Fig. 1. (Color online) Schematic diagram of the experimental setup for measuring the diode laser spectral characteristics. The diode laser is enclosed inside a sealed metal box.

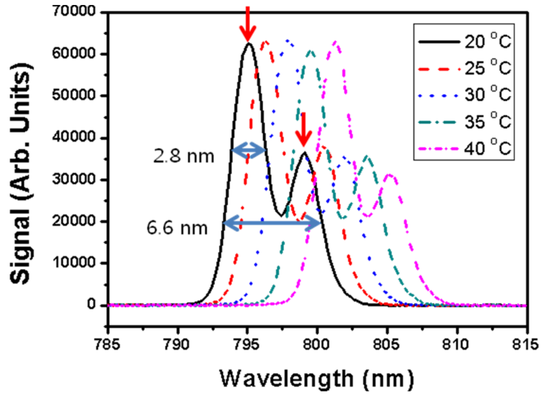

Fig. 2. Measured spectra of the diode laser at diode temperatures of 20, 25, 30, 35, and 40 °C.

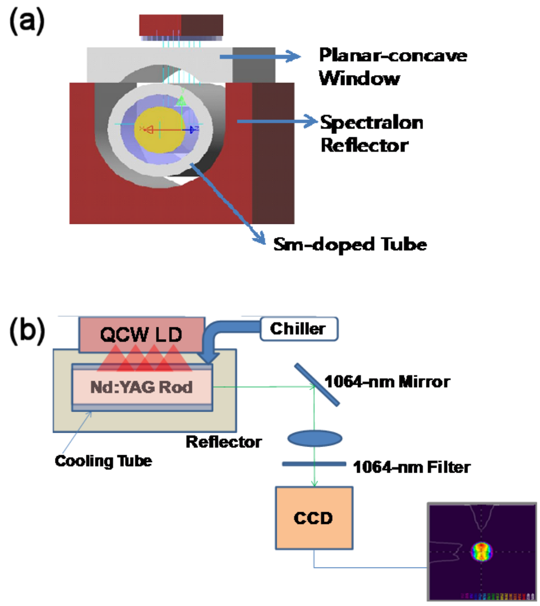

Fig. 3. (Color online) (a) Schematic structure of diode-pumped Nd:YAG laser chamber. (b) Experimental setup for measuring the diode laser's absorption profile in the Nd:YAG laser rod.

formity was enhanced through an improved design of the pumping chamber.

II. EXPERIMENTS AND RESULTS

The experimental setup for measuring the QCW diode-laser's characteristics is shown in Fig. 1. The QCW diode (Quantel laser diode, QD-Q1408-K) was installed inside a metal box to isolate it from dust. Insulated metal electrodes transmit a pulsed current to the diodes. Eight diode bars of 100-W peak power were assembled in a single conductively-cooled package. The emitting surface area of each diode was 10 × 2.8 mm^2. Four QCW diodes were used for pumping, and the peak power of each diode was 800 W. The diodes were mounted linearly, parallel to the laser rod. The current power supply (AVTEK, AV-108E-4-B-AK5-P) could supply a maximum pulse current of 150 amperes during a temporal interval of 20 ∼ 400 μs. The maximum duty cycle of the current pulse was 4%. The emitted spectrum of the diode laser was measured by using a mini spectrometer (Ocean Optics, USB4000). Part of the emitted light was collected and then transferred to the spectrometer through an optical fiber.

Square current pulses were applied to the diode laser. The duration of the applied pulse was fixed at 200 μs. The measured spectra in Fig. 2 have relatively broad spectral bandwidths. The pulse repetition rate of the QCW diode-laser's current pulse was 10 Hz. Usually, the spectral bandwidth of the emitted diode laser beam is 2 ∼ 3 nm. However, the bandwidth shown in Fig. 2 is about two times broader than usual value. Among the four QCW diodes, three diodes had the same spectral characteristics. However, one diode had a central wavelength 4 nm apart from the others. When the temperature of the cooling water was 20 °C, the spectrum had two peaks, 795.0 nm and 799.1 nm, and the total bandwidth was 6.6 nm. When the temperature was increased to 40 °C, the wavelengths of the peaks shifted to 801.3 nm and 805.0 nm, respectively. The spectrum was affected not only by temperature but also by the driving current, as well as the pulse repetition rate. Even when the diode's coolant temperature was the same, the temperature at the emitting surface of the diodes could be different, depending on the operating conditions. An increase in the driving current or the pulse repetition rate could raise the surface temperature.

To find the absorption coefficient in the Nd:YAG rod, we sent part of the diode beam to the Nd:YAG block with a 0.6-at% doping concentration and a 6-mm physical length. When the diode temperature was 20 °C and the driving current was 30 A, the measured absorption coefficient was 0.7 mm^{-1}. As the absorption coefficient is determined by a convolution of the diode spectrum and

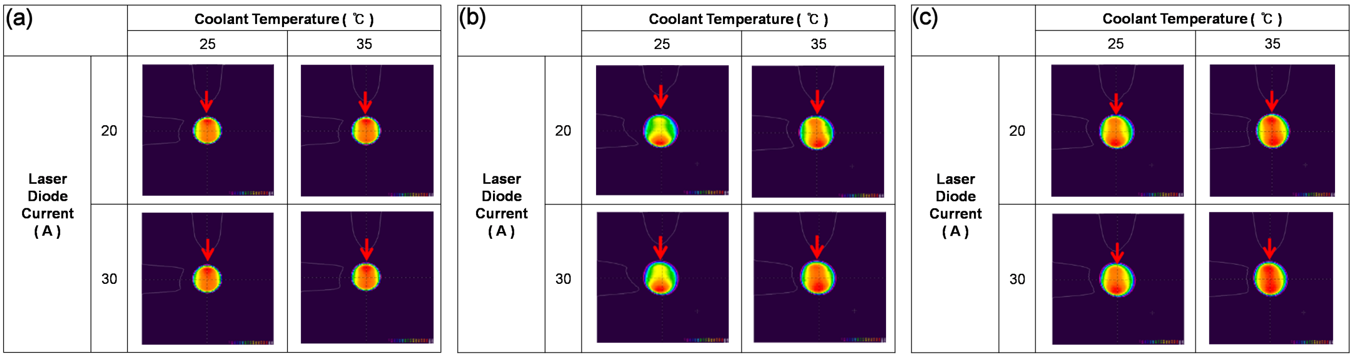

Fig. 4. (Color online) Measured absorption profile of the diode laser in the Nd:YAG crystal. (a) The laser rod's diameter is 4 mm, and the doping concentration is 1.0%. (b) the laser rod's diameter is 5 mm, and the doping concentration is 1.0%. (c) The laser rod's diameter is 5 mm, and the doping concentration is 0.6%.

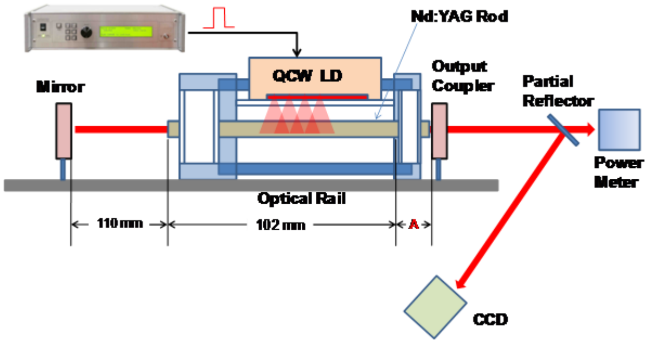

Fig. 5. (Color online) Experimental setup for measuring the lasing property of a QCW diode-pumped Nd:YAG laser. The cavity distance was adjusted by changing the distance from the rod to the output coupler (A).

Nd:YAG absorption spectrum, it changes as a function of the diode's current and pulse repetition rate and as a function of the coolant's temperature.

Figure 3(a) shows a schematic of the structure of the pumping chamber. The Nd:YAG rod was coaxially mounted inside a Sm-doped glass tube (Kigre Inc.). The outer surface of tube had no antireflection (AR) coating. The cooling water flowed inside the tube. The temperature of the cooling water was stabilized to within 0.1 °C. The Sm-doped tube was employed to prevent parasitic amplification in a direction transverse to the optical direction of the cavity because parasitic amplification can become a loss for a highly-pumped laser. An AR-coated cooling tube was also tested in place of the Sm-doped tube for comparison. The output energy from the pumping chamber using the AR-coated tube was about 4% larger than that from the one using the Sm-doped tube due to the reduced loss of pump beam.

To see the distribution of pump beam absorbed inside the Nd:YAG crystal, we observed the fluorescence from the crystal by using the setup shown in Fig. 3(b). A 1064-nm transmission filter was installed in front of a CCD (charge coupled device) camera, which imaged the fluorescence distribution. The diode laser beam inside the metal box was expanded while passing through a planar-concave window. The window isolated the diode laser package from dust, and, at the same time, it expanded the divergence angle of the diode beam. Before the planar-concave window, the divergence angle of the beam relative to the fast axis was 40°. After the planar-concave window, the angle was enlarged to 60°. This improved the uniformity of the absorbed diode distribution in the rod. According to an estimate made by using ray tracing, 28% of diode beam energy is reflected by the pumping chamber wall before absorption in the rod. When the planar-concave window is absent, only 12% of pump beam is reflected by the pumping chamber before absorption. The reflector was made of a diffusive material (Labsphere, Spectralon), and it enhanced the uniformity of the distribution. A semi-circular reflector can focus the diode beam inside the rod if it is made of a spectral reflecting material such as metal [12].

Figures 4(a) ∼ (c) show the measured absorption profiles. The arrows in the figure indicate the diode's pumping direction. In the measurement, we used three different kinds of Nd:YAG rods. The diameters and doping concentrations of the rods were; 4-mm diameter and 1.0 at.% doping, 5-mm diameter and 1.0 at.% doping, and 5-mm diameter and 0.6 at.% doping. The diode temperature was set at 25 °C or 35 °C. Figure 4(a) is the case of 4-mm diameter and 0.8 at.% doping. The absorbed energy profile for the diode laser in the pumping beam's direction is close to a square-hat profile. However, transverse to the pumping direction, the distribution is close to a Gaussian profile. Although it is different from the square-hat distribution, it shows a much enhanced distribution compared with the result shown in Ref. 7. The distribution for 25 °C is not very much different from that for 35 °C. For 35 °C the fluorescence is slightly elongated along the pumping direction. When the rod diameter was increased to 5 mm, the distribution became much more non-uniform, as can be seen in Fig. 4(b). The fluorescence intensity at the opposite side of the rod increased more due to focusing caused by refrac-

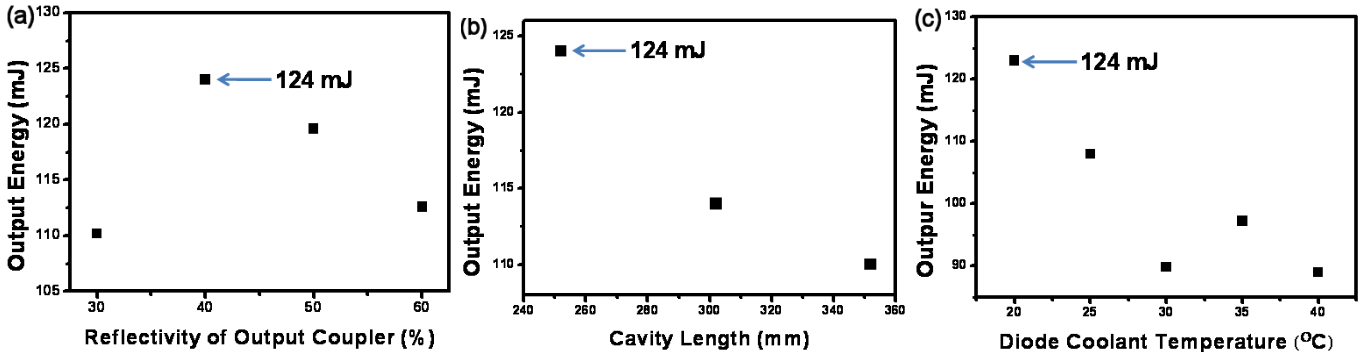

Fig. 6. Measured lasing property of a QCW diode-pumped Nd:YAG laser. (a) Dependence of the laser energy on the reflectivity of the output coupler. (b) Dependence of the laser energy on the cavity length. (c) Dependence of the laser energy on the diode's coolant temperature.

tion at the surface of the circular tube. An increase in the coolant's temperature from 25 °C to 35 °C shifts the profile toward a more uniform distribution. When the doping concentration was reduced to 0.6% with the same rod diameter, the distribution changed very much, as shown in Fig. 4(c). In the case of larger rod diameters, the temperature of the diode laser and the rod diameter affect the distribution very much.

The operating characteristics of the Nd:YAG laser using the fabricated diode pumping chamber was investigated using the setup shown in Fig. 5. The maximum laser output energy was about 124 mJ when the diode temperature was 20 °C and the peak driving current was 108 A, as shown in Fig. 6(c). In the experiment, a 4-mm diameter and a 1.0 at.% rod were used. The laser energy depended on the cavity length due to the built-up thermal lens in the rod, as shown in Fig. 6(b). The thermal lens for the rod, as calculated using commercial software, LASCAD, was 8 m [13]. The laser energy also depended on the reflectivity of the output coupler, as can be seen in Fig. 6(a). No intracavity Q-switching device was used in the experiment. The diode-laser energy used for pumping during 200 μs was 640 mJ, and the maximum energy conversion efficiency was 19.4%. The pulsewidth was almost the same as that of the pumping laser. The output simulated using LASCAD was 138 mJ, which is close to the experimental result.

III. CONCLUSIONS

A quasi-cw diode-pumped Nd:YAG laser was developed. The laser rod was single-side pumped by using four 800-W diodes. The spectrum from the diode was affected by various factors, such as the temperature, driving current, and pulse repetition rate. The diode laser distribution absorbed inside the Nd:YAG rod was measured. The profile showed reasonable uniformity in the pumping direction due to the enlarged divergence angle of the diode beam due to the planar-concave window. In the transverse direction, the distribution was close to a Gaussian profile. The laser energy from a linear cavity using the fabricated pumping chamber showed a maximum energy of 124 mJ and a conversion efficiency of 19.4%.

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