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Article

High Power Diode-Side-Pumped Q-Switched Nd:YAG Solid-State Laser with a Thermoelectric Cooler

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Abstract: A diode-side-pumped, high-energy, high-beam-quality, pulsed solid-state $Nd^{3+}:Y_3Al_5O_{12}$ (Nd:YAG) laser with a thermoelectric cooler (TEC) is investigated in this study. The pump laser was a pulsed laser diode array with maximum peak power of 15 kW. A 350 mJ laser pulse was obtained with a wavelength of 1064 nm, a pulse duration of 10 ns, a total electrical-to-optical efficiency of 7.5%, a relative stability of output energy of 5%, and a beam quality of $M^2 < 4$.

Keywords: diode-side-pumped; high-energy; Q-switched; Nd:YAG laser

1. Introduction

High-power, diode-pumped, solid-state lasers have been utilized as practical industrial tools for a wide variety of cutting, drilling and welding applications due to their long diode bar lifetime, high output power, and high laser beam quality. Over the past few years, as diode bars have become more powerful and lower in cost, diode-pumped lasers have been used more commonly to replace flash-lamp pumped systems. Recent progress in the development of diode stacks has offered significant power enhancement for diode-pumped, solid-state lasers [1]. Diode-pumped, active Q-switched lasers, which show good beam quality and high output peak power, are commonly utilized in material processing and nonlinear frequency conversion applications [2–6]. The Nd:YAG crystal has a long upper-state lifetime (230 μs) and superior thermal-mechanical and optical properties that allow it to easily generate high peak power and high energy Q-switched laser pulses [7].

The use of the side-pumped Nd:YAG gain medium configuration readily assists high power 1064 nm lasers, and laser diode (LD) end-pumped, Q-switched lasers can easily be used to fabricate TEM_{00}-mode lasers with an output power of several tens of watts. However, LD end-pumped lasers have the disadvantages of complex pump optics and severe thermal problems when reaching a high output power with good beam quality [8]. LD side-pumped lasers do provide an alternative to end-pumped lasers [9,10], but the optical-to-optical efficiency in TEM_{00}-mode operation is relatively low, typically between 10% and 15% [4,9,11,12]. In a 2007 study, researchers successfully obtained a 50 mJ output energy at 1064 nm with a 10 ns pulse duration, a 5 W average output power, and a 5 MW peak power with a 420 W quasi-CW laser-diode-array pumping at 808 nm and a modulating repetition rate of 100 Hz [13]. In 2009, Chen Xin-Yu *et al.* successfully demonstrated a 140 mJ 1064 nm laser with a pulse duration of 10 ns and a pulse repetition of 20 Hz; the beam divergence angle was less than 3 mrad, and the optical-to-optical conversion efficiency reached 11.7% [14]. In 2013, Bezyazychnaya *et al.* reported a maximum output energy of 210 mJ using an Nd:YAG laser with a pulse repetition rate of 30 Hz [15].

In this study, a high-power, diode-side-pumped, Q-switched Nd:YAG solid-state laser was tested under 808 nm side-pumping without a water cooler. At a pump diode current of 80 A and a pump pulse duration of 200 μs, a 350 mJ pulse laser was obtained with the following characteristics: a 10 ns pulse duration, a 10 Hz repetition rate, a 5% relative stability of output energy, and a 15% optical-to-optical conversion efficiency. The conversion efficiency of the entire laser system (electrical to 1064 nm optical radiation) was approximately 7.5%—which was much higher than that of a flash-lamp pumped laser system. The diameter of the beam was measured at 6.73 mm, with a divergence angle of less than 0.8 mrad and a beam quality of $M^2 < 4$. To the best of our knowledge, this demonstration represents the highest output power of a diode-pumped, Q-switched Nd:YAG solid-state laser with a TEC and with very good output energy relative stability.

2. Experimental Section

2.1. Theoretical Analysis

The Q-switched pulse duration is so short that both spontaneous emission and optical pumping can be neglected in the rate equations. The two coupled differential equations for photon density ϕ and population inversion density n are as follows [16]:

$$\frac{\partial \phi}{\partial t} = \phi(c\sigma n\frac{l}{l'} - \frac{\varepsilon}{t_R}) \tag{1}$$

$$\frac{\partial n}{\partial t} = -\gamma n \phi \sigma c \tag{2}$$

where σ is the stimulated emission cross section, l is the length of the laser medium, c is the speed of light, $t_R = 2l'/c$ is the round-trip time in the laser resonator of length l', and γ is the degeneration factor. The fractional loss ε per round trip is calculated as follows:

$$\varepsilon = \frac{t_R}{\tau_c} \tag{3}$$

where τ_c is the photon lifetime.

The output energy of the Q-switched laser can be expressed as follows:

$$E = \frac{h\nu A}{2\sigma\gamma} \ln\frac{1}{R} \cdot \ln\frac{n_i}{n_f} \tag{4}$$

where $h\nu$ is the laser photon energy, and A is the effective beam cross-sectional area. The initial and final population inversion densities, n_i and n_f, are obtained through the transcendental equation:

$$n_i - n_f = n_t ln\frac{n_i}{n_f} \tag{5}$$

where n_t is the population inversion density at threshold, that is,

$$n_t = \frac{1}{2\sigma l} \ln(\frac{1}{R} + L) \tag{6}$$

The pulse duration of the Q-switch pulse can also be expressed as a function of the inversion level, n_i, n_f, and n_t:

$$\Delta t_p = \tau_c \frac{n_i - n_f}{n_i - n_t(1 + \ln(n_i/n_t))} \tag{7}$$

The equations for pulse energy and pulse duration (and, therefore, peak power) are expressed in terms of the initial and finial population inversion densities, which are obtained via a transcendental equation. A successful analytical solution was reported in a study by Degnan [17], which revealed that key parameters, such as optimum reflectivity, output energy, extraction efficiency, pulse duration, and peak power, can all be expressed as a single dimensionless variable:

$$\mathrm{z} = \frac{2g_0 l}{L} \tag{8}$$

where $2g_0l$ is the logarithmic small-signal gain, and L is the round-trip loss.

The following expression for optimum reflectivity was derived:

$$R_{opt} = e^{-L\frac{(z-1-\ln z)}{\ln z}} \tag{9}$$

The energy output for an optimized system is:

$$E_{out} = E_{sc}(z - 1 - \ln z) \tag{10}$$

where E_{sc} is a scale factor with the dimension of energy that contains a number of constants:

$$E_{sc} = \frac{Ah\nu L}{2\sigma\gamma} \tag{11}$$

The FWHM pulse duration *versus z* is obtained as follows:

$$t_p = \frac{t_R}{L} \cdot \frac{\ln z}{z} \frac{1}{1 - (\frac{z-1}{\ln z}) \cdot (1 + \ln\frac{z \ln z}{z-1})} \tag{12}$$

The energy extraction efficiency can then be obtained:

$$\eta_{Ex} = 1 - \frac{1 + \ln z}{z} \tag{13}$$

The laser crystal we used had a diameter of 7 mm, with a laser resonator of 280 mm in length. Assuming a 5% round-trip cavity loss (L = 0.05), and with $h\nu = 1.86 \times 10^{-19}$ J and $\sigma = 2.8 \times 10^{-19}\text{cm}^2$, we calculated $E_{SC} = 2.13$ mJ. Based on Equation (10), the single dimensionless variable was $z = 170$. Finally, we obtained the optimum reflectivity of 20.2%, according to Equation (9).

2.2. Experimental Setup

The experimental setup for the high-power, Q-switch Nd:YAG laser is shown in Figure 1. The pump laser was a pulsed laser diode array (Institute of Laser Engineering, Beijing University of Technology, Beijing, China) emitting at 808 nm with a broadband width less than 3 nm to match the Nd:YAG absorption broadband. The LD module consisted of five similar parts. A cross-section of the LD module is depicted in Figure 2. Thirty bars with single maximum output peak power of 100 W comprised the LD bar array. The diode arrays, with maximum output peak power of 15 kW, were powered by an external power source with repetition rate of 1–15 Hz and pulse duration of 100–250 µs. In addition, the LD arrays formed an integrated module with the Nd:YAG crystal rod to decrease the size. The Nd:YAG crystal rod (JIEPU TREND, Beijing, China) (Ø7 mm × 100 mm) had doping concentration of 1.1 at% and 5″ parallelism. Both surfaces of the Nd:YAG crystal rod were anti-reflection (AR) coated to minimize reflection at 1064 nm. Two TECs (Beijing Huimao Cooling Equipment Co., Ltd., Beijing, China) were adopted to maintain the temperature of the LD module, with a controlling precision of 0.01 degrees. The TEC module had a maximum power of 66 W and was mounted under the LD module with thermally conductive silicone rubber. The rear mirror was a plane mirror (Beijing Qifenglanda Optics Technology Development Co., Ltd., Beijing, China) with a coating for high reflectivity (HR) at 1064 nm. The output coupler (OC) was a plane mirror coated for partial transmittance (T = 75%) at 1064 nm. To obtain linearly-polarized 1064 nm radiation, a Brewster polarizer (BP) (Beijing Qifenglanda Optics Technology Development Co., Ltd., Beijing, China) with T_p of 99.52% and T_s of 0.123% was inserted into the cavity. A KD*P crystal was used as the Q-switcher, with AR coatings on both faces at 1064 nm used to generate modulated pulses. A λ/4 plate was AR-coated at 1064 nm and used to change the polarization direction. The total cavity length was 280 mm.

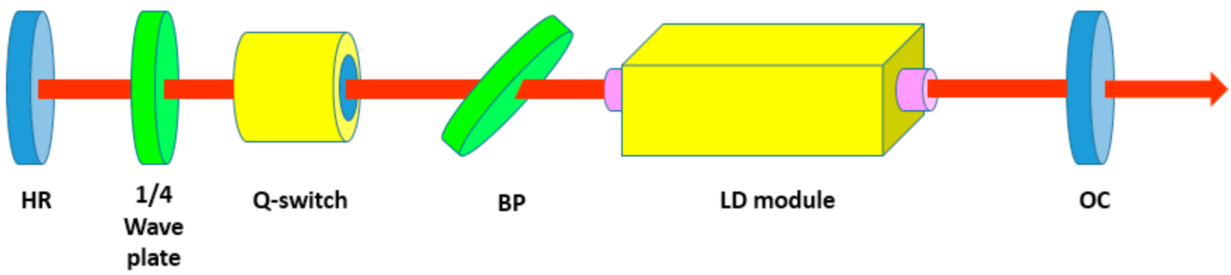


Figure 1. Schematic diagram of the diode-side-pumped Q-switched Nd:YAG solid-state laser. HR is the high reflective mirror; BP is the Brewster polarizer; and OC is the output coupler mirror.

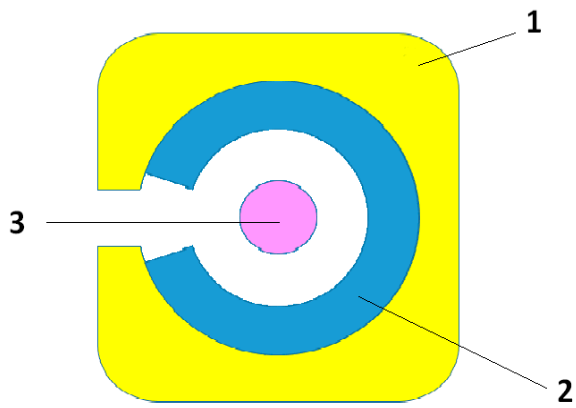
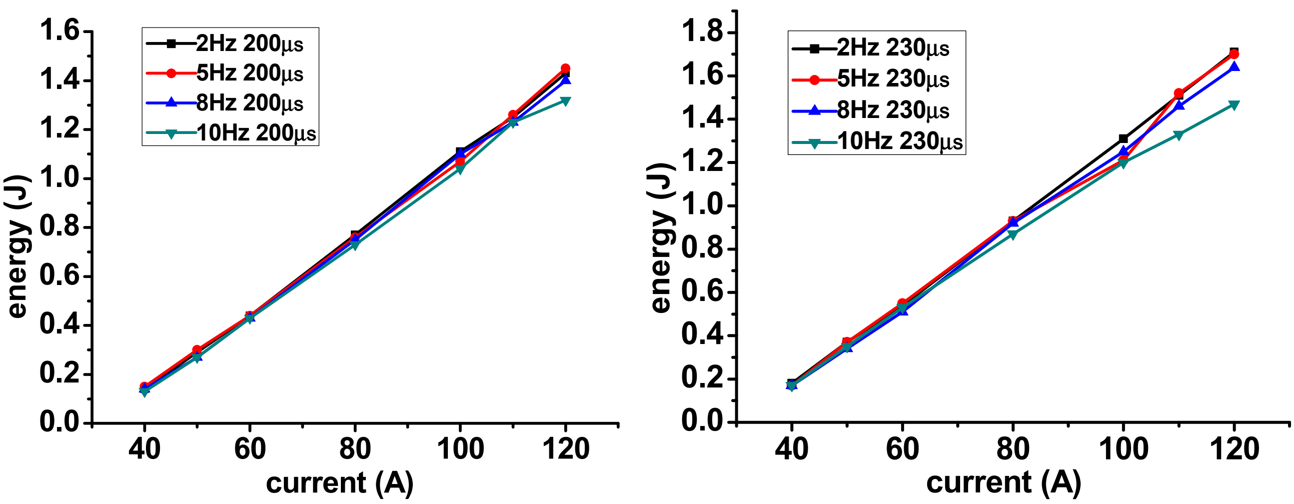


Figure 2. Cross-section of the LD module: (1) copper heat sink; (2) LD bar array consisting of 30 LD bars; and (3) Nd:YAG rod.

3. Results and Discussion

The output characteristics of the 1064 nm free-running laser were analyzed first. The output coupler was a 75% partial transmittance plane mirror, and the rear mirror was a high reflectivity plane mirror. The total cavity length was 280 mm. By adjusting the pumping current, the output energy of the free-running laser was measured for different currents, as shown in Figure 3.

As shown in Figure 3a, the threshold current was 30 A. The highest output energy (1.45 J) was obtained at a pump pulse duration of 200 μs, a pumping current of 120 A, and a pump repetition rate of 5 Hz. At a pump pulse duration of 230 μs, the highest output energy (1.71 J) was obtained with a pumping current of 120 A and a pump repetition rate of 2 Hz, as shown in Figure 3b. Figure 3 also shows that when pump repetition rate was low (2 Hz or 5 Hz,) there was no obvious difference in output energy—but as the pump repetition rate increased, the output energy decreased. This result occurred because higher pump repetition rates caused a higher thermal load, resulting in decreased output energy due to the thermo-optical effect.

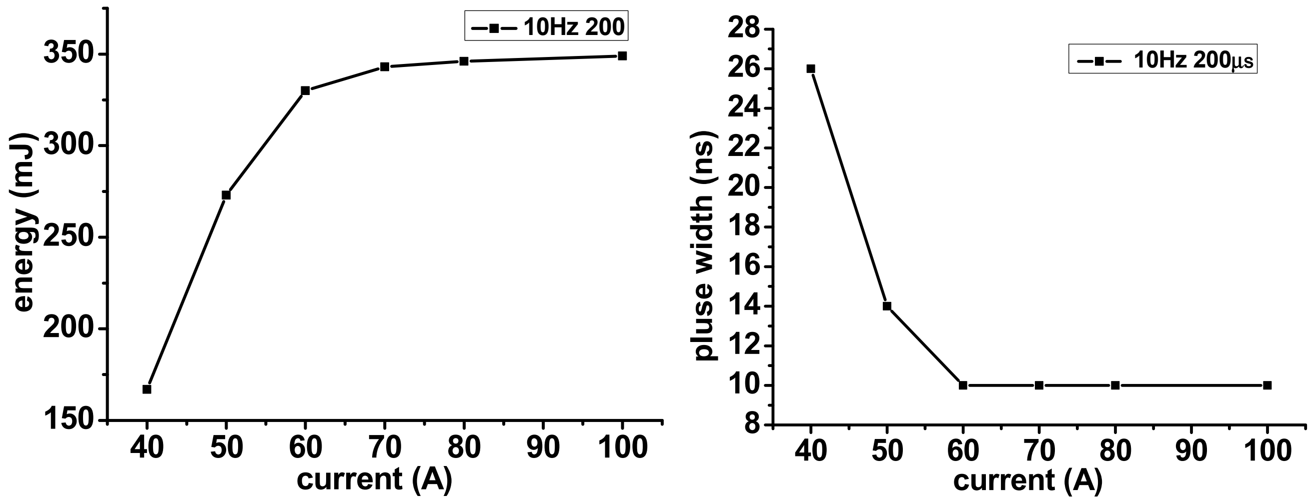


(**a**) (**b**)

Figure 3. Output energy *versus* pumping current with a pumping pulse duration of 200 μs (**a**) and a pumping pulse duration of 230 μs (**b**).

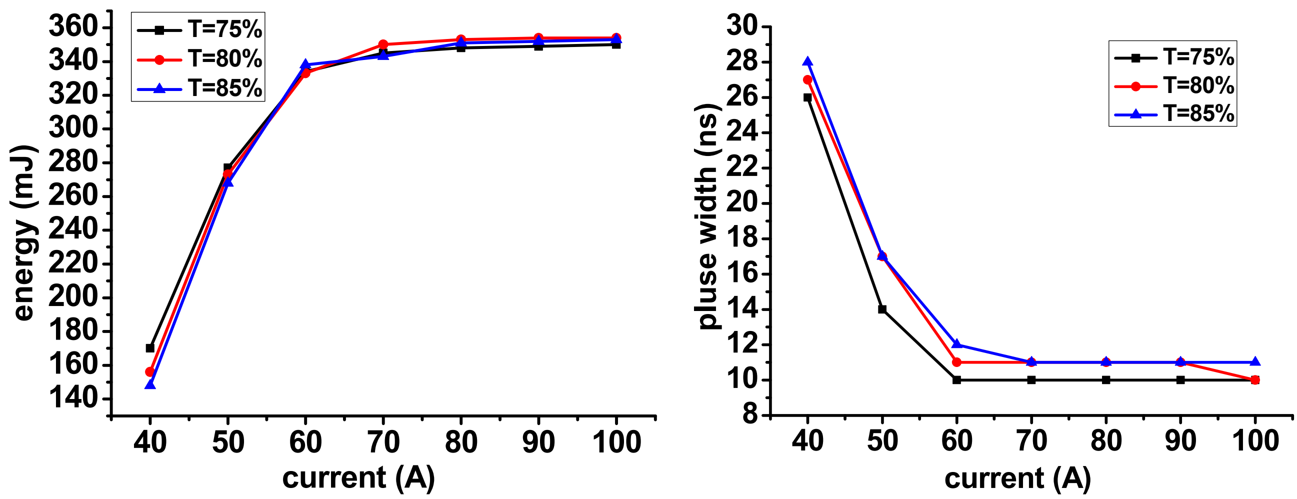
During the second step of the experiment, we put the Brewster polarizer (BP), Q-switch, and λ/4 plate into the cavity in proper order and aligned them to be coaxial. We then measured the output characteristics of the 1064 nm Q-switched Nd:YAG laser, as shown in Figure 3.

As shown in Figure 4a, output energy increased linearly when the pumping current was increased from 40 A to 60 A. When the pumping current increased further, the output energy increased more slowly, and the curve began to saturate. This behavior occurred because when the laser operated at high average power, the depolarization caused by thermally induced birefringence drastically distorted the output beam profile and drove down the output energy. As shown in Figure 4b, the pulse duration decreased when the pumping current was increased from 40 A to 60 A. When the pumping current was further increased, the pulse duration stabilized at 10 ns.



(**a**) (**b**)

Figure 4. Output characteristics of a 1064 nm Q-switched laser *versus* pumping current: (**a**) output energy (**b**) pulse duration.



(**a**) (**b**)

Figure 5. Output characteristics for different output coupler (OC) transmittance levels *versus* pumping current: (**a**) output energy (**b**) pulse duration.

The output characteristics of different OC transmittance levels (T = 65%, 70%, 75%, 80%, 85%, 91% and >98%) were also measured. The parameters were set as follows: a pumping current of 80 A, a pump pulse duration of 200 μs, and a pump repetition rate of 5 Hz. The output energy of 1064 nm laser reached no higher than 250 mJ when the transmittance of the output coupler equaled 70% or 91% and no higher than 200 mJ when the transmittance equaled 65%. When the transmittance of the output coupler was above 98%, there was no output energy obtained at all. Output energy *versus* pulse duration at 75%, 80%, and 85% are shown in Figure 5.

As shown in Figure 5, the output energy did not differ significantly for any of the three different transmittance percentages. When transmittance was 75%, however, the pulse duration of the laser was shorter than that of the others. To this effect, we selected a plane mirror coated for partial transmittance (T = 75%) at 1064 nm as the output coupler. The experimental results and theoretical results were compared, and the transmittance of OC (T = 75%) was very similar to the theoretical results (R = 20.2%, T = 79.8%). Notable differences between the results may have been caused by differences in the round-trip cavity loss between the actual value and the value that we assumed (L = 0.05).

The influence of the TEC controlling was also measured during the experiments. First, a TEC controlling source with 0.1 degree precision was adopted to control the temperature of the LD module, and then the output energy was varied (in a large amplitude, from 300 to 350 mJ,) with a pumping current of 80 A. A new controlling source with 0.01 degree precision was then adopted to increase the relative stability of the output energy. Both the output energy and center wavelength change as temperature changes; therefore, appropriate temperature control is a critical component of the system; we were able to maintain the LD modular temperature more steadily using the controlling source with a 0.01 degree precision. Finally, at a pumping current of 80 A, a pump pulse duration of 200 μs, and a pump repetition rate of 10 Hz, we obtained a laser pulse energy of 335–350 mJ at a wavelength of 1064 nm, a pulse duration of 10 ns, and an output energy relative stability of 5%. The beam diameter was measured as 6.73 mm, with a divergence angle of less than 0.8 mrad, and the beam quality was $M^2 < 4$.

4. Conclusions

This study investigated a high-power Nd:YAG laser pumped by pulsed laser diode arrays without a water cooler. We examined the output characteristics of different OC transmittance percentages and identified the optimum transmittance to be 75%, based on experimentation, which was very similar to the theoretical value (R = 20.2%, T = 79.8%). By comparing the experimental results, we observed that TEC controller precision impacted the relative stability of the output energy. At a pump pulse current of 80 A, a pump repetition rate of 10 Hz, and a pump pulse duration of 200 μs, we obtained a laser with 350 mJ of maximum pulse energy at 1064 nm, with a pulse duration of 10 ns, corresponding to an electrical-optical efficiency of 7.5%, with a beam quality of $M^2 < 4$.

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Author Contributions

Xue-Sheng Liu and You-Qiang Liu conceived and designed the experiments; Xue-Sheng Liu, Jian Dong and Chao Peng performed the experiments; Jian Dong analyzed the data; Zhi-Yong Wang contributed materials and analysis tools; Jian Dong wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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