Design and Development of a High-Performance LED-Side-Pumped Nd:YAG Rod Laser

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We present a design and development of a high-performance light-emitting diode (LED)-side-pumped Nd:YAG rod laser with strong pulse energy, high efficiency, and consistency, very good beam quality, and high uniform pumping intensity in the active area which reduces the effects of thermal gradient significantly. A five-dimensional 810 nm LED array with a full width of 30 nm at half maximum was intended to achieve high coupling efficiency by putting the LED array as close as possible to the side of the Nd:YAG laser rod for overcoming the large pumped divergence. Under 2.25 J pump energy, maximum single pulse energy of 35.86 mJ with duration of 1.24 μs at 1063.68 nm was obtained, equivalent to optical efficiency of 1.59% and a slope efficiency of 2.53%. The laser was set to repeat at a rate of 10 Hz with a beam quality factor of $M_x^2 = 2.94$ and $M_y^2 = 3.35$, as well as with the output power stability of $< 4.1\%$ (root mean square) and $< 7.3\%$ (peak to peak). To the best of our ability, this is the highest performance for an LED-side-pumped Nd:YAG rod laser oscillator with a 10-mJ-level output ever reported.

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In recent years, while performance of commercial light-emitting diodes (LEDs) has increased significantly, the cost has been significantly reduced due to mass production and applications. Likewise, compared to laser diodes, LEDs were less sensitive to electrostatic discharges and have a lifetime of 3–4 times higher than laser diodes. Because of their low cost, high environmental suitability, and long lifetime, LEDs have evolved into a viable option for solid-state lasers.[1–7] Recently, LED pumping has piqued the interest of newcomers. Several types of LED-pumped lasers were re-examined. Various gain media and Nd^{3+} doped media most notably have been now directly pumped by LEDs.[8–14] Among the findings of the latest research, LED-pumped solid-state lasers were also demonstrated successfully, including the first LED pumped Nd:YVO_4 laser with a wavelength centered close to 850 nm,[9] an uncooled Ce:Nd:YAG rod laser pumped by 460 or 810 nm LEDs,[10] Nd:YVO_4 lasers pumped by Ce:YAG concentrators with 430 nm LEDs,[11] an Nd:YAG laser pumped by LEDs at 750 nm,[12] and Nd:YAG rod laser pumped at 810 nm.[13] Nevertheless, LED-pumped solid-state lasers are still ineffective owing to the optical conversion efficiency is less than 6%.[13] The lower optical conversion efficiency is usually due to LED array current handling limitations, the relatively low coupling efficiency of the LED light output to the laser rod, as well as the low fill factor of the available LED arrays.

In comparison with the most previous LED-side pumping configuration, employing the two-dimensional pumping schemes for solid-state lasers provided advantages of high efficiency and compact structure. However, the number of LEDs acting as a pump source was greatly limited, which could not achieve lasing with high-performance output. Moreover, the multi-dimensional LED-side pumped configuration for solid-state lasers had superiorities in strong pulse energy, high efficiency, and good beam quality.

In this Letter, we aim to address many problems met by some groups to analyze various efficiencies involved with LED pumping systems. Firstly, the pump density is improved by creating LED arrays with a centralized configuration to increase the area fill factor. A high-brightness small-dispersion angle LED chip is utilized to increase the pump density. Secondly, it is known that higher spectral absorption efficiency can be obtained by using LED chips with appropriate pump wavelengths and narrower FWHM concerning the gain medium. Additionally, the coupling efficiency is improved by shortening the distance between the Nd:YAG laser rod and the LED array. By fine-tuning the LED pumping configuration, an efficient LED-side-pumped Nd:YAG rod laser can be achieved with a thoughtful plan to assemble the LED arrays to improve its fill factor. Finally, process of properly driving and cooling the high-power LED arrays operated at quasi continuous wave (QCW) is one of the most important criteria for achieving an effective LED-side-pumped system. When these methods are completed concurrently, it is very possible to obtain LED-side-pumped lasers with high performance for practical applications.

In experiments, a single pulse with a maximum energy of 35.86 mJ at 1063.68 nm was acquired, corresponding to optical efficiency of 1.59% and a slope efficiency of 2.53%. The laser was used by employing a pulse repeti-

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tion frequency (PRF) of 10 Hz with a beam quality factor of $M_x^2 = 2.94$ and $M_y^2 = 3.35$, and the output power stability was RMS < 4.1% (root mean square) and PTP < 7.3% (peak to peak). To the best of our ability, this is the highest performance for an LED-side-pumped Nd:YAG rod laser oscillator with a 10-mJ-level output reported before.

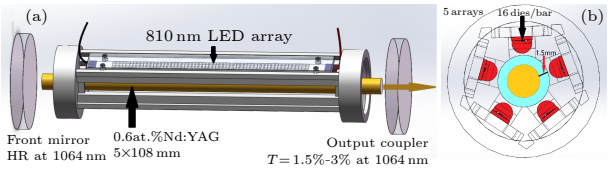

Fig. 1. (a) The experimental setup for LED pumping of Nd:YAG and (b) schematic of a fivefold symmetric LED pump module.

Figure 1(a) schematically shows the experimental setup of the LED-pumped Nd:YAG laser. A programmable pulse power supply was used as the power supply (MH150-30DM). The NIR LED dies used throughout this work were produced by Luminus (SST-10-IRD-810 nm). Each LED package includes a light collector to ensure that the emitting light has a low divergence (lens angle 90°), in which the emitting light of LEDs was easier to perform in regards to the optical design and to obtain a flat-top pumping distribution on the Nd:YAG crystal. All of these dies were created to be driven at a continuous current of 1.5 A per element. Although each LED array was rated at a maximum continuous current of 1.5 A, the maximum drive current advised was only 1 A. We used a $\Phi 5 \times 108$ mm anti-reflection coated cylindrical laser rod with a gain medium doping concentration of 0.6 at.%. Anti-reflection coating was applied to both ends of the gain medium (AR, $R < 0.1\%$) at 1064 nm. The output characteristics of the LED-side-pumped rod lasers at a laser wavelength of 1063.68 nm were investigated in a linear plano-plano cavity to withstand changes in thermal focal length as well as misalignment.[15] The front mirror was extremely reflective at 1064 nm (HR, $R > 99.9\%$) and the output coupler was a plane mirror with 1.5% and 3% transmittance at 1064 nm, respectively. A schematic of the LED pumping configuration is given in Fig. 1(b). The pump LED array was specially designed and built by 80 810-nm LED dies with an emission area of approximately 1 mm^2 for each die. We divided them into five groups, and every 16 chips were connected in series to form a nearly 78-mm-long LED array. Each row's area fill factor was calculated to be 34%. The Nd:YAG rod was surrounded by an anti-reflection-coated flow tube, meaning that the crystal was sufficiently cooled. The gap between the crystal and the LED array was reduced to less than 1.5 mm, which was a very extreme distance, to boost the pumping efficiency.

Simultaneous cooling of the crystal and high-power LED arrays was one of the most important requirements for achieving an efficient LED pumping system. We created a new water cooling device with two built-in water paths to separate and cool the crystal and high-power LED arrays. The Nd:YAG laser rod was loaded inside the quartz glass with an outer diameter 8 mm flow tube (1.5-mm-thick water-cooling ring) used for water cooling to 20 ℃, which provided an excellent environment for 1064 nm excitation. Each LED array was temperature-controlled by removable water-cooled copper block individually to implement fine adjusting the radiative wavelength, ensuring that the majority of the pump lights were absorbed. The radiative center wavelengths of the LED arrays shift to 808 nm at a coolant set point of 5 ℃. Based on this highly efficient cooling system, to achieve high-power laser output, the pump power density could be increased.

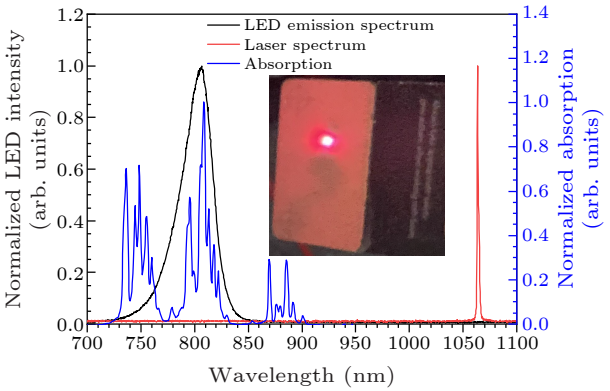

Fig. 2. Absorption spectra of Nd:YAG (blue line) and lasing spectrum of Nd:YAG (red line) and LED (black line) in the QCW regime (50 ms, 2.5 A, 10 Hz, 5 ℃). The inset is an unfocused image of the physical spot.

Figure 2 depicts the NIR LED lamp's emission spectrum as well as its absorption spectrum and laser spectrum of Nd:YAG. The inset of Fig. 2 shows an unfocused image of the physical spot. The distribution of the normalized relative intensity spectrum of the LED is shown with the y-axis on the left (black line), and the normalized Nd:YAG absorption spectrum is shown with the y-axis on the right (blue line). The emission spectrum after cooling the LED at 5 ℃ overlapped with the absorption spectrum of the laser crystal at the highest intensity. The output spectrum of the laser was recorded using a spectrum analyzer (Ocean, HR4000) at a resolution of 0.02 nm. We collected spectra at different drive currents and found that the FWHM and peak wavelength of the laser reached 2.2 nm and 1064.65 nm, respectively, when the drive current was 1.7 A. As the current is increased from 1.7 A to 3.3 A, the peak wavelength of the laser appears to be blue-shifted and the FWHM of the laser is greatly reduced, corresponding to 1063.68 nm and 0.96 nm, respectively. These experimental findings reveal a new perspective to understand the LED pumping system and LD pumping system properties from Nd:YAG crystal laser emission and how it changes in relation to the pump power of the control fields.[16]

The output QCW free-running of the Nd:YAG laser as a function of the incident pump energy is plotted as shown in Fig. 3(a). The laser thresholds were very close to the different output couplings (OCs) of 1.5% and 3% at 1064 nm, corresponding to the power output increasing approximately linearly with the pump power occurred. Under pump energy of 2.25 J, the maximal single pulse energy

of 35.86 mJ at 1063.68 nm is obtained, equivalent to optical efficiency of 1.59%, and efficiency of slope of 2.53%, with the 1.5% output coupler, linear fitting is used to achieve this as shown in Fig. 3(a). The obtained single pulse energies are significantly higher than those reported by Pichon *et al.* (263 μJ),[14] Huang *et al.* (346 μJ),[12] Cho *et al.* (1.42 mJ).[13] In contrast to the case of OC transmittance at 1.5%, another 3% output coupler is expected to produce more energy with a higher output maximum single pulse energy of 15.23 mJ at 1063.68 nm that is actually obtained, corresponding to optical efficiency of 0.72% and a slope efficiency of 1.19%, linear fitting is used to achieve the results shown in Fig. 3(a).

The output power dependence on the input current of a single LED operating at 10 Hz with a 50 ms duration is shown in Fig. 3(b). Each chip's peak output power could reach 282 mW at 0.7 A during the drive time, and the effectiveness of electric-optical conversion was about 13.4%. According to experimental findings, there is no sign of saturation of the output power at the maximum LED pump energy, which has not been observed for various OCs. This means that more output laser pulse energy and higher efficiency of the conversion transition could be further improved, together with the optimizing design of the laser structure.

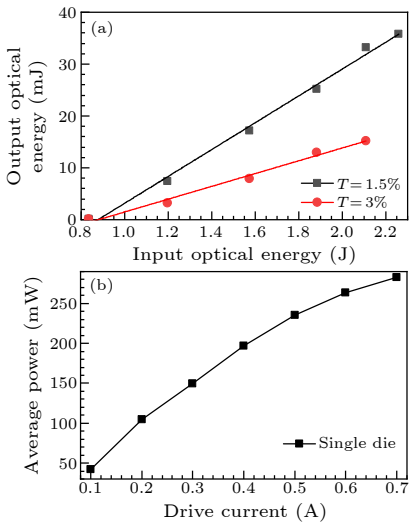

Fig. 3. (a) Output laser pulse energy versus input LED pulse energy and (b) average power output of a single 810 nm LED versus drive current.

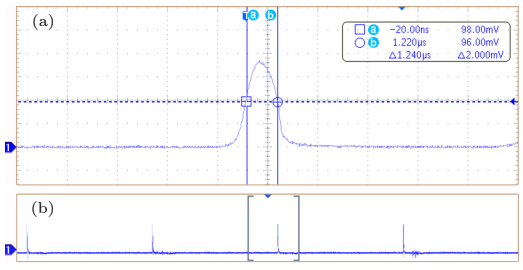

Fig. 4. Temporal shape of the single-pulse (a) and the long-term pulse (b) sequences at the PRF of 10 Hz.

Figure 4 demonstrates the temporal shape of the single pulse and the long-term pulse sequence at a PRF of 10 Hz. A fast photodiode was used to record the pulse temporal behaviors (Thorlabs PDA10A2) connected to a Tektronix digital oscilloscope (MDO3034, 350 MHz). A single laser pulse's expanded profile, indicating that the pulse width was 1.24 μs with a peak power of 28.87 kW, which was less than the pump source's pulse width due to the temporal gain narrowing effect as the result of the buildup time of the laser oscillation.[17] In the long-term pulse train, no pulse mode loss was observed, but the variation of pulse amplitude was more than 20%. The most likely cause of pulse amplitude instability was uneven heat dissipation of the LED array resulting in unstable luminescence. This could be solved by improving the LED array's heat dissipation.

Additionally, after focusing the laser beam through a lens with a focal length of 100 mm at maximum output energy, the camera (Cinogy, CMOS-1201) was moved close to the focal point of the lens to record the horizontal and vertical diameter. Hyperbolic fitting was used to calculate the beam waist diameter and far-field divergence. Under a doping concentration of 0.6 at.%, the 1063.68 nm laser beam propagation quality factor M^2 is measured to be about 2.94 and 3.35 in the x and y directions, respectively, as shown in Fig. 5. The intensity profile of the laser beam at the laser waist is shown in the inset of Fig. 5, indicating a nearly single output mode. The beam quality values showed moderate uniformity symmetry. The thermal lens effect typically had the greatest impact on the beam quality among all kinds of thermal effects. This five-dimensional pumping device was created by us, which not only improved the pumping efficiency but also greatly reduced the thermal effect caused by the uneven heat of the crystal surface, and markedly improved beam quality in QCW high-power mode.

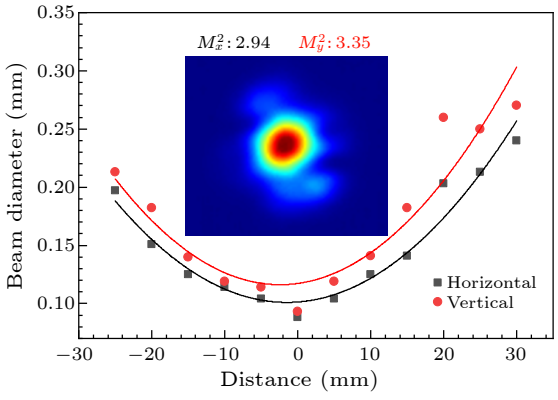

Fig. 5. Beam quality and far-field distribution at the PRF of 10 Hz.

The stability of the laser energy in the QCW regime for the average power is shown in Fig. 6. The obvious benefit is that the energy stability of the output laser is sufficiently high, corresponding to RMS < 4.1% and PTP < 7.3%. Most of the experimental pieces of equipment were designed and 3D printed by ourselves, and all

of the printing materials were high-strength photosensitive resin. This method was cheap and easy to implement, but its resistance to the effects of water and the efficiency of heat dissipation was far less than that of metal parts such as copper blocks. Although this stable performance will never be matched by a diode-pumped Nd:YAG laser under the same condition. To obtain higher stability, the pumping geometry should be raised by replacing all resin components are combined with metal components machined on high-precision lathes.

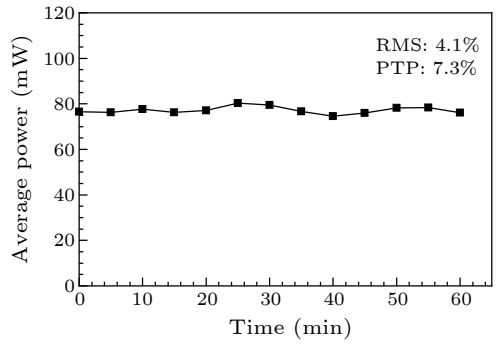

Fig. 6. Stability of the laser energy in the QCW regime for the average power.

In summary, we have shown an LED-side-pumped Nd:YAG rod laser oscillator with high power, high beam quality, high slope efficiency, and high stability. By fine-tuning the LED pumping configuration and laser parameters, maximum single pulse energy of 35.86 mJ with duration of 1.24 µs at 1063.68 nm is obtained, equivalent to optical efficiency of 1.59% and a slope efficiency of 2.53%. The repetition rate of the laser is set to 10 Hz with a beam quality factor of $M_x^2 = 2.94$ and $M_y^2 = 3.35$, and the output power stability is RMS $< 4.1\%$ and PTP $< 7.3\%$. To the best of our knowledge, this is the highest performance for an LED-side-pumped Nd:YAG rod laser oscillator with a 10-mJ-level output reported before.

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