# A High Peak Power Passively *Q*-Switched Nd:YAG Dual-Rod 532 nm Laser Based on LED Side Pumping

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In this paper, we present a high peak power passively *Q*-switched intracavity frequency-doubled green laser based on an efficient LED-pumped Nd:YAG dual-rod laser module. In quasi-continuous wave (QCW) running operation, the average output power of the fundamental laser at 1064 nm reaches as high as 20.98 W at a repetition rate of 50 Hz with a maximum single pulse energy of 419.6 mJ, corresponding to a maximum optical conversion efficiency of 38.8% and a slope efficiency of 41%. Under passively *Q*-switched conditions, the maximum output peak power at 1064 nm is 1.4 MW with a pulse duration of 88 ns. By fine-tuning the incident angle of the KTP crystal to satisfy noncritical phase matching conditions, over 2 W of 532 nm average power is generated with a corresponding pulse duration of 68 ns, resulting in a peak power of 0.61 MW for the 532 nm laser. To the best of the authors' knowledge, this represents the highest average power QCW 1064 nm laser and the highest peak power passively *Q*-switched intracavity frequency-doubled 532 nm laser based on LED pumping reported to date.

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High-power green laser sources have broad applications in precision welding of copper,[1–3] pumping titanium-sapphire lasers,[4–6] and underwater optical communication and detection.[7–9] Traditionally, high-energy narrow-pulse lasers are mostly pumped by laser diodes (LDs).[10–12] However, it has been proven that high-power light-emitting diodes (LEDs) can serve as an effective pump source for producing lasers with high pulse energy and large mode size.[13–20] Firstly, compared to LDs, LEDs have a moderately broad emission spectrum, the average output power of the fundamental laser often overlaps well with a set of high absorption lines in the laser material.[21,22] With the development of LED performance, the optical power of a single LED chip can be increased to watt-level, while its price has decreased by an order of magnitude over the past decade,[23] making large-scale commercial applications of LEDs as pump sources possible. However, the divergent nature of Lambertian-emitting LED light sources poses significant technical challenges in efficiently concentrating the luminous flux into a small pump volume, making it particularly difficult to achieve precise coupling with the laser resonator mode, especially the TEM00 mode. Accordingly, the optical conversion efficiency of current LED-pumped lasers remains relatively low, with the highest reported average output power for an LED-pumped Nd:YAG 1064 nm laser being 17 W.[24] Secondly, since passive *Q*-switching is triggered by the laser radiation itself, it does not require high-voltage, fast electro-optic drivers, or RF modulators. Therefore, passively *Q*-switched lasers offer the benefits of straightforward construction, compact size, and low cost.[25] Moreover, passively *Q*-switched operation is more conducive to achieving narrow pulse laser output and does not require additional polarization optical components. However, its precision in external control performance is limited, and the energy output falls short compared to electro-optically or acousto-optically *Q*-switched lasers. Consequently, current research reports only mention LED-pumped actively *Q*-switched green lasers with a peak power of 4.1 kW[26] and LED-pumped passively *Q*-switched green lasers with a single pulse energy of 4.5 mJ.[27] Hence, comprehensive research efforts are necessary to address these challenges and objective to investigate the full potential of LED-pumped solid-state green lasers.

Dual-rod configuration is essentially a technical solution for coherent beam combining, which effectively increases the length of the laser gain medium. By increasing the number of rods, the output power is proportionally increased while maintaining nearly the same beam quality compared to a single-rod cavity.[28–30] In this paper, through significant improvements to the laser module and water-cooled system, an LED side-pumped high average power Nd:YAG solid-state laser with a dual-rod structure in the resonator is designed. Firstly, in QCW running operation, under a pump power of 54 W and a repetition rate of 50 Hz, the fundamental laser at 1064 nm achieves an average power output of 20.98 W, with an optical conversion

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efficiency reaching up to 38.8%, capable of generating pulse energies as high as 419.6 mJ. This result suggests that the dual-rod structure can produce high average power and relatively high optical conversion efficiency, forming the basis for achieving $Q$-switched laser output with high peak power. Secondly, with the insertion of a passive $Q$-switch, a $Q$-switched 1064 nm laser output is achieved, featuring a pulse width of 88 ns and a peak power of 1.4 MW. This high megawatt-level peak power enables efficient harmonic conversion, making high-efficiency green laser output effectively. Thirdly, through intracavity second harmonic generation (SHG), a green laser with a maximum power of 2.08 W and a pulse width of 68 ns is recorded, corresponding to a peak power of 0.61 MW, which stands for the highest peak power known for LED-pumped solid-state green lasers.

Figure 1(a) shows the construction of the 1064 nm high peak power passively $Q$-switched all-solid-state laser, which consists of two LED side-pumped Nd:YAG modules, a $Q$-switching crystal, and the resonant cavity. Specifically, the LEDs operate at a central wavelength of 810 nm with a full-width-half-maximum (FWHM) of ∼30 nm and a beam angle of 90°. Firstly, a row of 20 LED beads forms an LED stack array, and five rows of LED stack arrays make up the side-pumping source, which is uniformly arranged around the crystal rod, thereby enhancing pump uniformity and mitigating the thermal effects on the crystal rod. To optimize the performance of the LED pump module, the LEDs operate at a frequency of 50 Hz, with a total power supply duration of 120 ms per second. Meanwhile, to ensure the stability of the LED pump, the LED arrays are mounted on the water-cooled copper blocks maintained at 3 ℃. Secondly, the two Nd:YAG crystal rods (5 mm in diameter, 120 mm in length, containing 1.0 at.% $Nd^{3+}$) are encapsulated within modules equipped with precision-designed cooling water circulation structures, where the water temperature is maintained at approximately 17 ℃. Moreover, the sides of the crystals are polished to achieve uniform roughness, ensuring the pump light is evenly distributed on the crystal sides. Thirdly, the 1064 nm fundamental laser cavity consists of a rear reflector M1 ($R > 99.9\%$ at 1064 nm) and an output plane coupler M2 ($T_{OC} = 10\%$ and 15% at 1064 nm) with the length of 410 mm. The passively $Q$-switched crystal, $Cr^{4+}$:YAG (cross-section diameter of 6 mm, initial transmittance $T_0 = 70\%$, 76%, and 86%), is inserted between the Nd:YAG crystal rods and M2.

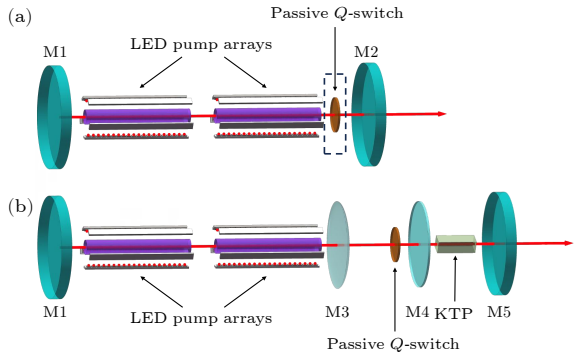


**Fig. 1.** Schematic diagram of (a) the LED-pumped $Q$-switched 1064 nm laser and (b) the intracavity SHG green laser.

Figure 1(b) depicts the structure of the 532 nm high peak power green laser. The cavity length is set to 600 mm. Initially, the fundamental 1064-nm cavity consists of the rear reflector M1, the Nd:YAG modules, the plano-convex lens M3 ($f = 200$ mm), the passive $Q$-switch, and the dichroic mirror M5 ($R > 99.9\%$ at 1064 nm & $T > 95\%$ at 532 nm). Furthermore, the green laser resonator consists of the harmonic-separator mirror M4 ($T > 95\%$ at 1064 nm & $R > 99.9\%$ at 532 nm), a KTP crystal as the second harmonic generator, and the M5. Finally, the KTP crystal (4 mm × 4 mm × 10 mm, HT at 1064 nm & at 532 nm) is placed near the focal point of M3, precisely controlled at 20 ℃ by a water-cooled copper mount to enhance the pump light intensity and improve frequency doubling efficiency. Additionally, the KTP crystal exhibits a type II phase match, with phase matching angles of $\phi = 23.5°$ and $\theta = 90°$ at room temperature.

Figure 2 shows the normalized spectra of the passively $Q$-switched laser and the green laser. Employing a spectrometer (Ocean, HR4000, resolution of 0.02 nm), the peak wavelength of the $Q$-switched laser is measured to be 1063.44 nm with a corresponding FWHM of 1.16 nm, while the peak wavelength of the green laser is measured to be 531.53 nm with an FWHM of 1.17 nm. Additionally, it is observed that variations in the power supplied to the LEDs and the water-cooled temperature cause shifts in the central wavelength of the laser, and these shifts are considered to be within an acceptable range.

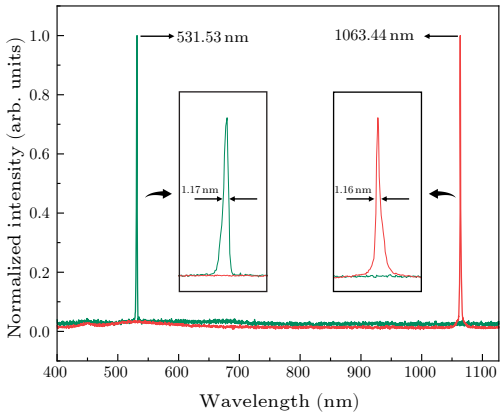


**Fig. 2.** Laser output spectra of fundamental frequency light and frequency doubled light.

The average output power of 1064 nm laser in the QCW operation is measured at two distinct coupling transmittances, as Fig. 3 illustrates. The result shows that for the laser with an output mirror transmittance $T = 15\%$ at 1064 nm, the highest average power reaches 20.98 W, corresponding to a single pulse energy of 419.6 mJ and an optical conversion efficiency of 38.8%. The slope efficiency approaches 41%. To the best of our knowledge, this is the highest reported average output power for a LED-pumped 1064 nm solid-state laser. From the graph, it is evident that the QCW laser output power does not saturate

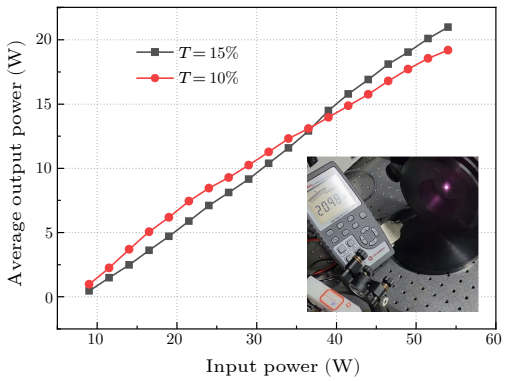


**Fig. 3.** 1064 nm average output power versus LED incident power in the QCW operation. Inset, highest average output power of 1064 nm.

at various transmittances, which indicates that higher transmittance output coupling mirrors coupled with precisely optimized power supply parameters and advanced cooling system refinements could significantly boost conversion efficiency. Therefore, the dual-rod configuration exhibits high pumping efficiency and can effectively enhance intracavity pumping power density, enabling the attainment of high peak power $Q$-switched lasers and intracavity frequency-doubled green lasers.

Figures 4(a) and 4(b) show the variations in average output power and pulse width of a 1064 nm laser after inserting passive $Q$-switch crystals with different initial transmittances ($T_0$) at different output coupler transmittances ($T_{OC}$), respectively. When $T_0$ = 76% and $T_{OC}$ = 15%, the $Q$-switched laser achieves a peak power of up to 1.4 MW, corresponding to an average power of 7.92 W at 1064 nm and a pulse duration of 88 ns, as shown in Figs. 4(a) and 4(b). Meanwhile, in a series of experiments varying the initial transmittances, an increase in the transmittance of the $T_{OC}$ resulted in the pulse width decreasing from 196 ns to 54 ns, as the higher intracavity power density causes a faster saturable absorber saturation, leading to a faster reduction in absorption and ultimately resulting in a narrower pulse width, as shown in Fig. 4(b). Figure 4(c) shows the average output power and pulse width of the $Q$-switched green laser. Through intracavity frequency doubling, the highest average power is 2.08 W at 532 nm with a duration of 68 ns, corresponding to a peak power of 0.61 MW. To the best of the authors' knowledge, this represents the highest peak power achieved to date for an LED-pumped solid-state 532 nm laser.

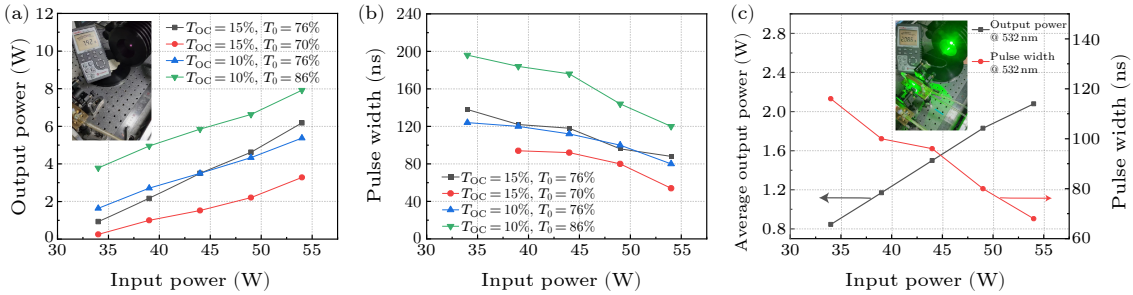


**Fig. 4.** (a) Average output power (inset, maximum $Q$-switched average output power) and (b) pulse duration of 1064 nm as a function of incident pump power under different combinations of OC and $Q$-switches. (c) Average output power and pulse duration of 532 nm as a function of incident pump power (inset, maximum average output power of 532 nm).

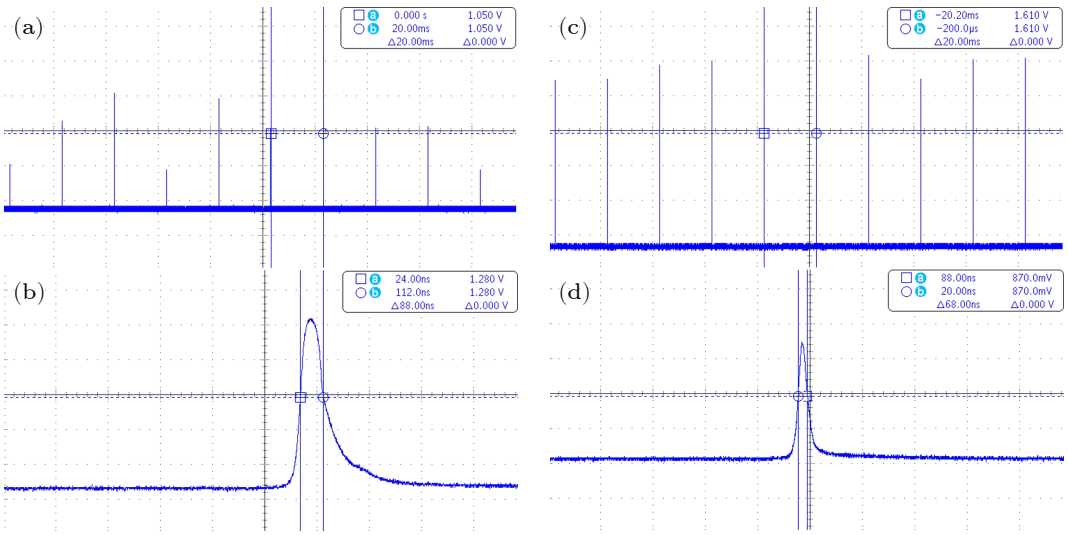


**Fig. 5.** Temporal profile of (a) the pulse trains and (b) single pulse width for $Q$-switched 1064 nm, (c) the pulse trains and (d) single pulse width for $Q$-switched 532 nm.

A fast photodiode (Thorlabs PDA10A2) linked to a digital oscilloscope (Tektronix MDO3034) records the pulse temporal behaviors. The long-term pulse sequence and the temporal shape of a single pulse for both $Q$-switched 1064 nm and 532 nm lasers, as shown in Fig. 5. In detail, at an average output power of 6.18 W, a pulse width of 88 ns accompanies a peak power reaching a maximum of 1.4 MW and the pulse trains along with the pulse width at 1064 nm are illustrated in Figs. 5(a) and 5(b). At the maximum average output power of 2.08 W, the pulse width narrows to 68 ns with a corresponding peak power of 0.61 MW, and the pulse trains along with the pulse width of the 532 nm output, which are shown in Figs. 5(c) and 5(d), exhibit a peak-to-peak fluctuation of less than 20% owing to multi-mode operation caused by uneven heat dissipation in the LED arrays.

Figure 6 illustrates spatial beam profile near the laser beam waist under moderate output power conditions for (a) $Q$-switched 1064 nm operation and (b) $Q$-switched 532 nm laser. The $Q$-switched 1064 nm and 532 nm lasers at different places are taken using a beam analyzer (Cinogy, CMOS-1201). By performing a least-squares curve fitting, the $M^2$ factors of the $Q$-switched 1064 nm laser are found to be 9.53 and 9.49 in the $x$ and $y$ directions, respectively, while the $M^2$ factors of the 532 nm laser are 7.81 and 5.17 in the $x$ and $y$ directions, respectively. The high $M^2$ value is due to the short intracavity structure, which allows a multi-transverse mode oscillation and a lower diffraction loss in the cavity. The insets in Fig. 6 show the transverse mode patterns of the $Q$-switched 1064 nm and 532 nm lasers.

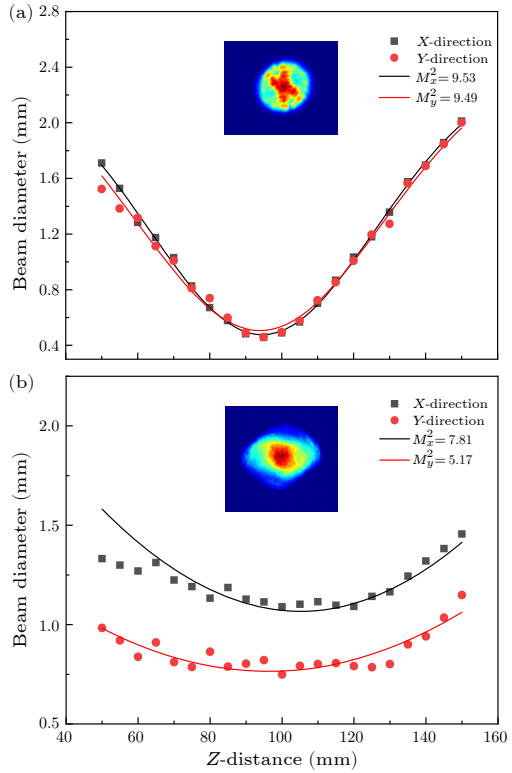


**Fig. 6.** Beam quality and 2-dimensional laser beam profiles of (a) $Q$-switched 1064 nm operation and (b) the intracavity SHG 532 nm laser.

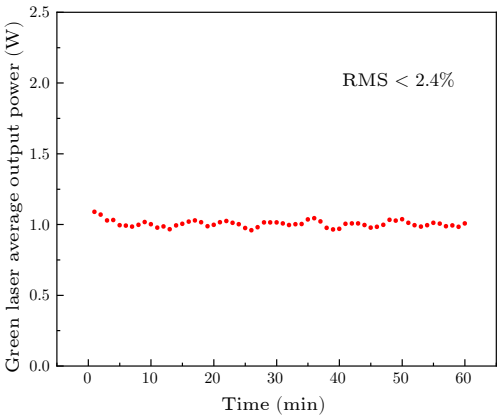


**Fig. 7.** Power fluctuations of the $Q$-switched 532 nm laser within an hour.

Figure 7 illustrates the stability of the average power for the green laser operating in the $Q$-switched regime. The data, captured at one-minute intervals over a 60-minute period, indicates that the root mean square (RMS) of the output power remains under 2.4%. Notably, the output power exhibits fluctuations corresponding to temperature variations during each cooling cycle. These fluctuations are primarily driven by three key factors: (1) prolonged operation results in increased temperature at the PN junction of the LED reducing the likelihood of radiative recombination between electrons and holes within the potential well, and leading to non-radiative recombination and a subsequent drop in the LED's internal quantum efficiency (IQE) simultaneously;[31] (2) the redshift phenomenon, which dramatically reduces the pumping efficiency and SHG, arises at the peak wavelength of the LED chips when the operating temperature of the LEDs rises; and (3) thermal lensing effects induced by the temperature gradients in the Nd:YAG rod and KTP can significantly decrease the beam quality, and thus influence the output power stability.

In summary, an LED side-pumped passively $Q$-switched 532 nm laser with high single pulse energy and peak power is demonstrated. The results suggest that the dual-rod structure can produce high average power and relatively high optical conversion efficiency, forming the basis for achieving $Q$-switched laser output with high peak power. Firstly, in QCW running operation, under a pump power of 54 W and a repetition rate of 50 Hz, the fundamental laser at 1064 nm attains a peak average power of 20.98 W, resulting in the highest optical conversion efficiency of 38.8% and a single pulse energy reaching 419.6 mJ. This system exhibits the highest average power output of any reported LED-pumped solid-state laser systems at the 1064 nm wavelength so far. Secondly, in $Q$-switched operation, the laser achieves a maximum peak power of 1.4 MW, corresponding to an average output power of 6.18 W and a pulse width of 88 ns, with the beam quality characterized by $M^2$ factors of 9.53 in the $x$-direction and 9.49 in the $y$-direction. Finally, through intracavity frequency doubling, the green laser generates a peak power of 0.61 MW, corresponding to a pulse width of 68 ns and an average output power of 2.08 W, with a

conversion efficiency of nearly 34%. The beam quality is characterized by $M^2$ factors of 7.81 in the $x$-direction and 5.17 in the $y$-direction, and the RMS of the output power remains under 2.4%. Thus far, this stands as the highest peak power reported for the passively $Q$-switched green laser based on LED-pumped Nd:YAG. The paper provides a new technical proposal for generating high peak power nanosecond pulses at 1064 nm and 532 nm from an LED-pumped passively $Q$-switched solid-state laser.

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