

# Efficient and compact diode-end-pumped conductively cooled $Q$ -switched Nd:YLF laser operating at 527 nm

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A novel, compact diode-end-pumped conductively cooled  $Q$ -switched Nd:YLF laser is developed. A diode-end-pumped pair of Nd:YLF slabs and an intracavity-frequency-doubled configuration are adopted to increase conversion efficiency. Using 49.8-mJ incident pump pulse energy at 500-Hz repetition rate, the laser obtains 11-mJ pulse energy and 5.5-W average output power at 527-nm wavelength, achieving an optical-optical conversion efficiency of 22%. The pulsewidth is less than 15 ns, and the beam quality factors are  $M_x^2=1.28$  and  $M_y^2=1.12$ .

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High beam quality and compact, diode-end-pumped  $Q$ -switched solid-state green lasers are important radiation sources for both scientific and industrial applications, such as remote sensing, underwater laser communication, precise micromachining, medical treatment, and laser display, etc. Typically, intracavity or external second-harmonic generation based on  $Q$ -switched Nd:YAG, Nd:YVO<sub>4</sub>, Nd:YLF, or other Nd<sup>3+</sup>-doped, solid-state lasers is an effective way to obtain green lasers<sup>[1–5]</sup>. Compared with Nd:YAG or Nd:YVO<sub>4</sub>, Nd:YLF has a longer fluorescence lifetime (480  $\mu$ s), making the storage of higher pump energies in higher energy level easier. Moreover, the natural birefringence of Nd:YLF crystals is much larger than thermally induced birefringence, allowing linearly polarized lasing at 1053 nm (or 1047 nm) for highly efficient intracavity-frequency-doubled operations. Moreover, the weak thermal lensing effect of Nd:YLF on the  $\sigma$  polarization, corresponding to 1053 nm lasing, provides the possibility of high-power operation with near-diffraction-limited laser beam output. Hence, the TEM<sub>00</sub>-mode green output from an intracavity-frequency-doubled Nd:YLF laser can be scaled to a considerably high level.

Recently, Nd:YLF lasers have regained interest, and some excellent results have been reported<sup>[6–12]</sup>. Sun *et al.*<sup>[6]</sup> achieved 1.12 W of average power at 1053 nm with repetition rate of 50 kHz and conversion efficiency of 31.2% using laser diode (LD)-end-pumped and acousto-optic  $Q$ -switching configurations. The pulsewidth was compressed to 41.4 ns. The beam quality factors were measured as  $M_x^2=1.247$  and  $M_y^2=1.285$ . Using 19.5 W of diode pump power and an intracavity-frequency-doubled LBO crystal, Zhang *et al.*<sup>[7]</sup> obtained as much as 2.15 W of continuous-wave (CW) output power at 527 nm, achieving an optical-optical conversion efficiency of 11.2%. The 527-nm laser was operating at TEM<sub>00</sub> mode, and the  $M^2$  factor was approximately 1.46. Li *et al.*<sup>[8]</sup> developed a novel, electro-optically  $Q$ -switched, diode-end-pumped water-cooled solid slab laser and obtained 15.1 mJ of pulse energy at 523 nm via external second-

harmonic generation (SHG). The pulselength was 5.5 ns at 1.0-kHz repetition rate, and the beam profile was one-dimensional (1D) top hat beam. However, researchers are still experiencing difficulties in generating high pulse energies with narrow pulsewidths from  $Q$ -switched Nd:YLF laser oscillator because of the poor thermal mechanical property of Nd:YLF, which limits the maximum allowable pump power density. Moreover, high gain is not easily achievable because of the relatively smaller stimulated emission cross section of Nd:YLF. To date, 527-nm TEM<sub>00</sub> mode green lasers with pulse outputs of tens of millijoules, from inductively cooled electro-optically  $Q$ -switched Nd:YLF lasers have not been reported.

In this letter, a compact electro-optically  $Q$ -switched diode-end-pumped laser with a dual Nd:YLF slab intracavity-frequency-doubled configuration and TEM<sub>00</sub> mode output was developed. A dual Nd:YLF slab arrangement in the resonator effectively overcomes the disadvantages of low fracture limit and gain in end-pumped Nd:YLF lasers. More than 11 mJ of pulse energy at 527 nm was obtained with 49.8 mJ of incident pump pulse energy while safely operating at pulse repetition rate of 500 Hz. Up to 22% of optical conversion efficiency from incident pump energy to green output was achieved, and the narrow pulsewidth was less than 15 ns. To the best of our knowledge, we firstly report on high-efficiency pulsed 527-nm TEM<sub>00</sub> mode green lasers from intracavity-frequency-doubled diode-end-pumped Nd:YLF lasers.

A compact U-type folded cavity structure is designed, as shown in Fig. 1. The folded resonator consists of a concave, high-reflectivity mirror M1 with curvature radius of 1100 mm; two flat, high-reflectivity mirrors M2 and M3 ( $R>99.8\%$ ) at 1053 nm with high transmission ( $T>92\%$ ) at 806-nm wavelength; a flat, high-reflectivity mirror M4 ( $R>99.5\%$ ) at both 1053 and 527 nm. In the investigation of fundamental wavelength lasing performance, M4 was replaced by an output coupler at 1053 nm. The total cavity length was 420 mm.

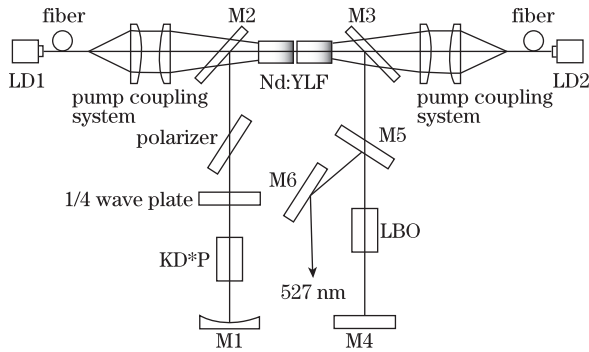


Fig. 1. Schematic diagram of the 527-nm intracavity-frequency-doubled Nd:YLF laser resonator.

Flat mirrors M5 and M6 served as the output couplers for the SHG. M5 was coated to achieve high reflectivity ( $R > 99.5\%$ ) at 527 nm and high transmission ( $T > 98\%$ ) at 1053 nm, whereas M6 was coated to achieve high reflectivity ( $R > 99.5\%$ ) only at 527 nm. A KD\*P Pockel cell, a polarizer, and a 1/4 wave plate were used as the electro-optic  $Q$ -switch. The laser crystal is a pair of a-cut, 1.0 at.-%, Nd<sup>3+</sup>-doped Nd:YLF slabs  $4 \times 4 \times 12$  (mm) each. The end faces were polished and anti-reflection coated at 806 and 1053 nm. These two Nd:YLF slabs were mounted on a conductively cooled copper heat sink and positioned at the center of the resonator with the same  $c$ -axis orientation. The gap between the two Nd:YLF slabs was less than 1 mm, and the temperature of the heat sink was kept at  $18 \pm 0.5$  °C. Although the uniaxial, a-cut Nd:YLF crystal was capable of lasing two characteristic wavelengths at 1047 and 1053 nm simultaneously, only one fundamental line of 1053 nm was permitted to build up the lasing in this resonator as the 1047-nm lasing was suppressed by the polarizer.

The TEM<sub>00</sub> mode size was simulated using LASCAD. The diameter of the TEM<sub>00</sub> mode waist at the central position of the resonator was about 1.1 mm. A type I phase-matched,  $4 \times 4 \times 12$  (mm) LBO crystal was located near plane mirror M4.

Two fiber-coupled LD modules with 80-W maximum output power and 3-nm linewidth were used as the pump source. The fiber core diameter was 600  $\mu\text{m}$ , and its numerical aperture was 0.22. Each pump laser beam was focused using an optical transfer system, and the focal spot size inside each crystal was about  $\phi 1.5$  mm in diameter, matching the TEM<sub>00</sub> mode volume well. A Nd:YLF crystal has three absorption peaks at 792, 797, and 806-nm (Fig. 2)<sup>[11]</sup>. 806-nm pump wavelength was used to distribute the pump absorption over the Nd:YLF slabs because of the small tensile strength of Nd:YLF, which is approximately 33 MPa. Finally, approximate 95% of the pump power was absorbed. This method has been proven effective in overcoming low fracture limits and helpful in improving the maximum incident pump power. For quasi continuous wave (QCW) operation, the pump diodes were driven mostly at repetition rate of 500 Hz with the driven-pulse duration of 480  $\mu\text{s}$  (full-width at half-maximum), corresponding to a duty cycle of 25%. Therefore, laser damage in the Nd:YLF slabs due to thermally induced fracture under high pump power was effectively avoided.

Firstly, a high efficient, 1053-nm laser with CW

TEM<sub>00</sub> mode output was demonstrated in the compact U-type folded cavity when the flat mirror M4 was replaced by an output coupler. Figure 3 shows the CW output power of the fundamental 1053-nm laser as a function of the incident pump power for three kinds of output couplers. As the pump power was increased to 24.9 W, the highest output power of 8.04 W at 1053 nm was achieved with an output coupler of 48%, resulting in a 32.3% optical-optical conversion efficiency. The slope efficiency was 36.8%. The results show that the output coupling of 48% is a critical value for this folded resonator.

The  $Q$ -switched performance of the 48% output coupler at 1053-nm wavelength was studied, and the KD\*P Pockel cell was located close to the concave mirror M1. Figure 4 shows the output pulse energy as a function of the pump pulse energy in free-running mode and  $Q$ -switched regime at 500-Hz repetition rate. In the  $Q$ -switched regime, 11.6-mJ pulse energy at 1053-nm wavelength was obtained. When 49.8-mJ pump pulse energy was applied, the optical-optical conversion efficiency was about 23.2% with respect to a slope efficiency of 25.5%. And higher incident pump power cannot be applied because of the limitations of conductively cooled system.

The high pulse energy output at 527 nm was demonstrated by inserting type I phase-matched LBO crystal in the cavity for SHG and replacing M4 with plane high-reflectivity mirror ( $R > 99.5\%$ ) at both 1053 and 527 nm. The LBO crystal was cut to  $4 \times 4 \times 12$  (mm), wrapped with indium foil, mounted on

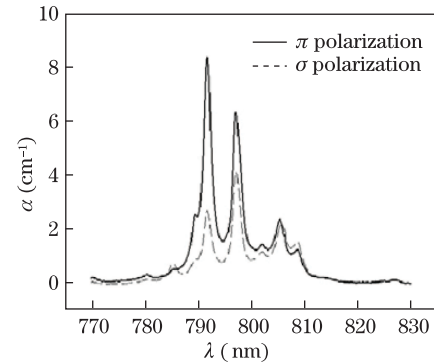


Fig. 2. Absorption spectra for 0.8% doped Nd:YLF crystal.

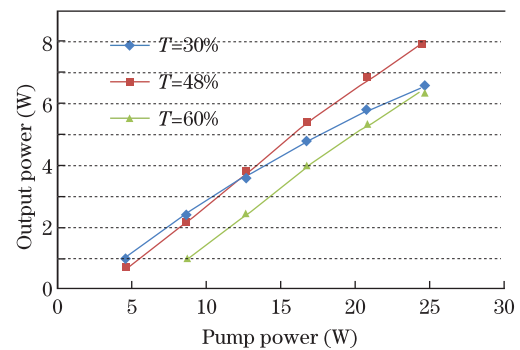


Fig. 3. 1053-nm laser output power versus incident pump power under CW operation with three values of output coupler  $T$ .

heat sink, and cooled using thermo-electric cooler. Both sides of the LBO were anti-reflection coated at the 1053- and 527-nm wavelengths. When the pump LDs were driven at repetition rate of 500 Hz with 49.8 mJ of incident pump pulse energy, no thermally induced fracture occurred and the maximum pulse energy output of  $\sim 11$  mJ at 527 nm was obtained. The pulsewidth was less than 15 ns. The energy fluctuation of the 527-nm pulse was less than 3% during the 2-h operating period. Figure 5 shows the pulse trace recorded using an oscilloscope. The optical-optical conversion efficiency was 22%, and the slope efficiency reached up to 23.3%, as shown in Fig. 6.

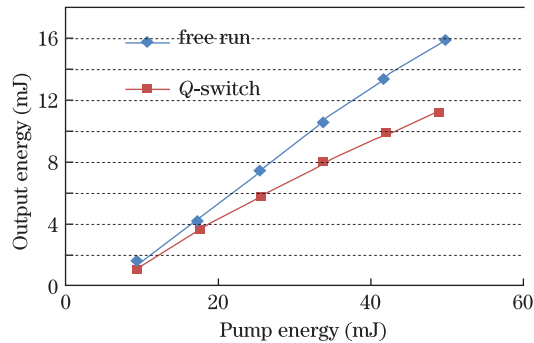


Fig. 4. Output energy of 1053 nm as a function of pump energy in free-running and  $Q$ -switched modes.

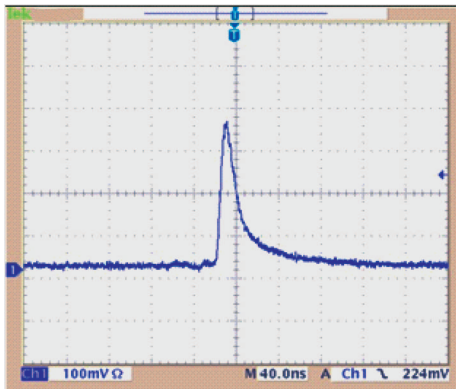


Fig. 5. Pulse waveform of 527 nm.

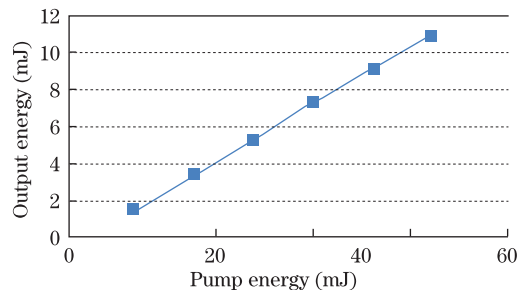


Fig. 6. Output energy of 527-nm laser as a function of pump pulse energy.

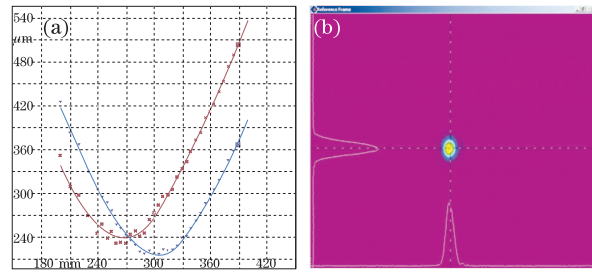


Fig. 7. Measurements obtained by the Spiricon M<sup>2</sup>-200 beam propagation analyzer. (a) Beam quality measurement; (b) spatial distribution in far field.

The beam quality of the  $Q$ -switched, green laser was measured using a Spiricon M<sup>2</sup>-200 laser beam analyzer. While the Nd:YLF green laser was operating at the maximum pump power level with approximately 11 mJ of pulse energy at 527 nm laser output, the beam quality was measured as  $M_x^2=1.28$  and  $M_y^2=1.12$ , as shown in Fig. 7(a). The far-field beam profiles of the green laser (Fig. 7(b)) was detected. The results revealed that a near-diffraction-limited laser beam was achieved.

In conclusion, we design a compact, diode-end-pumped, conductively cooled intracavity-frequency-doubled Nd:YLF laser operating at 527 nm. This laser successfully generates 11-mJ pulse energy in TEM<sub>00</sub> mode with pulsewidth of less than 15 ns at the repetition frequency of 500 Hz, corresponding to the peak power of 0.733 MW. The green laser beam quality is measured as  $M_x^2=1.28$  and  $M_y^2=1.12$ . Such a compact high-energy 527-nm TEM<sub>00</sub> mode laser with good beam profiles can be widely used in industry and scientific field applications.

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