Diode-end-pumped double Nd:YLF slab laser with high energy, short pulse width, and diffraction-limited quality

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We have developed a novel electro-optic Q-switched diode-end-pumped solid slab laser that combines high energy, short pulse width, high repetition rates, and diffraction-limited beam quality. With two partially end-pumped Nd:YLF slabs and a 100 mm long off-axis positive branch stable–unstable oscillator, 24.2 mJ, 7.1 ns electro-optic Q-switched pulse at 1 kHz repetition rate with a beam quality of $M_x^2 = 1.4$ and $M_y^2 = 1.3$ was generated. The peak power reached 3.5 MW. Efficient external second-harmonic generation was achieved by use of lithium triborate with low peak-power intensity.

OCIS codes: 140.3480, 140.3540, 140.5680.

Diffraction-limited high-energy 1.0 μm nanosecond laser pulse and efficient green and UV radiation by second-harmonic generation and third-harmonic generation are widely used in industry. Many integrated industrial laser devices require the combination of high energy, short pulse width, high repetition rates, good beam quality, and compact size. It is difficult for traditional rod solid lasers to have all the features at the same time. Slab lasers with an unstable resonator or a stable–unstable hybrid resonator have been verified to be successful for the generation of laser radiation with diffraction-limited beam quality at a high power level [1,2]. As far as we know, it is still a challenge to generate a diffraction-limited laser beam with several tens of millijoules of energy and around a 10 ns pulse width at a multikilohertz repetition rate by a robust and compact resonator design. Here we demonstrate a Nd:YLF slab laser that achieves such features.

In a four-level laser crystal family, Nd:YLF is suitable for a Q-switched laser with high pulse energy and good beam quality because of its long fluorescence lifetime ($\sim$480 μs) and a weak thermal lens effect. The main drawback of Nd:YLF crystal is its small tensile strength ($\sim$33 MPa), which limits the maximum average pump power absorption density that is due to the damage induced by thermal stress in the crystal [3]. The other drawback that limits the pump absorption intensity is the strong energy transfer that is due to the upconversion effect inside the Nd:YLF crystal, which generates extra heat in the laser crystal [4,5]. The low pump power absorption intensity and the relatively smaller stimulated emission cross section result in low gain of such a crystal so that lasering the Nd:YLF is inefficient. In our previous Nd:YLF slab system, the optical–optical efficiency reached only about $\sim$22% [6]. For efficient high-power generation with Nd:YLF, two key points are how to increase the total pump power absorption at low pump power density and how to achieve high total gain with a small stimulated emission cross section. One typical technique is a Nd:YLF slab multipass oscillator side pumped by 806 nm laser diodes [7]. With such a long optical path inside the laser medium, the gain can be high so that the laser operation is efficient. But such an oscillator cannot generate a Q-switched pulse with high energy and short pulse duration, because of its long resonator length and small laser mode size. We propose to use two partially end-pumped Nd:YLF slabs in series inside one oscillator so that the absorbed pump power and the total gain can be doubled without change of the laser crystal geometry. In a previous work [8], a stable resonator with two Nd:YLF slabs was discussed. Pulses with high energy, short duration, and a 1-D top-hat beam profile were generated. Here we present a stable–unstable hybrid resonator design. With this design, the beam quality was improved to be diffraction limited in both directions.

Figure 1 illustrates the setup of the Nd:YLF crystal with a 1.0 at. % doping concentration, with a size of 12 mm × 10 mm × 1 mm, and a cut with the c axis along the 1 mm direction (noted as $c1$ or fast direction). Each crystal was mounted between water-cooled heat sinks with two large faces (12 mm × 10 mm). Indium foil was used for effective and uniform thermal contact and cooling. Only the 1 mm × 10 mm end surfaces were polished and coated with AR 1047 and HT 806 nm to pass the pump radiation

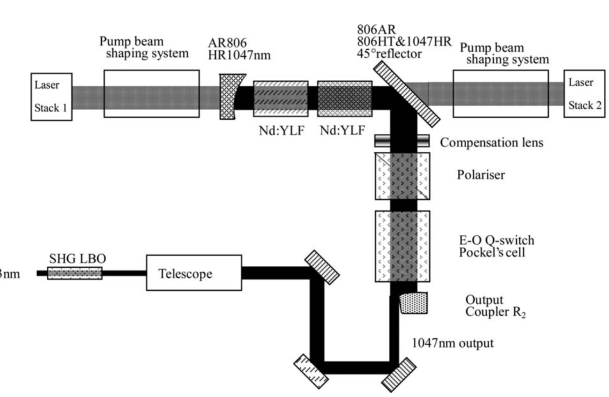

Fig. 1. Schematic of the experimental setup.

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and laser beam. Two four-bar laser stacks were used with an 806 nm central wavelength and a spectral width (FWHM) of 2.5 nm. Figure 2 shows the absorption features of Nd:YLF around 806 nm. The peak absorption coefficient is 2.6 cm^{-1} at 805 nm with a c axial pump and 2.2 cm^{-1} at 805.6 nm with one a axial pump. Both Nd:YLF crystals were positioned near each other. Appropriately 86% of the pump power was absorbed by the first crystal. The residual pump power was absorbed by the second crystal so that more than 90% pump power was absorbed by both crystals. The cw radiation of laser stack 1 and stack 2 was coupled into the two Nd:YLF crystals. The pump spot size was 0.4 mm $\times$ 12 mm, and the pump beam had a top hat profile along the 12 mm direction, the slow direction. A flat mirror with a HR1047/HT806/45° dichroic coating was used to fold the resonator and couple the pump from laser stack 2. Two highly reflective cylindrical mirrors, R_1 (R_1=600 mm) and R_2 (R_2=−400 mm), were used as resonator mirrors. Mirrors R_1 and R_2 formed a positive branch confocal unstable resonator in the slow direction with a 100 mm cavity length. Mirror R_2 was narrow in size and was polished at one edge so that the output laser beam was coupled around the edge. As the thermal lens effect of Nd:YLF slabs was very small, even at more than 100 W pump power, a positive cylindrical lens (f=250 mm) was used to form a stable resonator in the fast direction. With such a resonator configuration, the output coupling was $1-1/M=1-R_2/R_1$ =33%. In [8], the authors found that the optimal output coupling for cw operation was 25%. We selected a larger output coupling to reduce the power intensity inside the resonator to prevent optical surface coating damage.

Figures 3(a) and 3(b) show the typical near-field and far-field beam profiles of the output beam. In the slow direction the near field of the output beam was a good top-hat Fresnel diffraction pattern, and the far field was a typical Fraunhofer diffraction pattern with a square sinc function intensity-beam profile. In the fast direction, the beam was a good Gaussian profile in both the near field and the far field because of mode-size matching design. The beam quality was measured with a focal length lens (f=300) and a CCD camera [9]. In our experiment, the near-field size of the output beam was 4 mm (full width) in the slow direction and 0.25 mm (beam waist at $1/e^2$) in the fast direction; the far-field beam waist (at $1/e^2$) with a 300 mm focal length lens was 70 μm in the slow direction and 520 μm in the fast direction so that M_x^2 =1.4 and M_y^2=1.3 estimated by $M^2=(w_0\theta)/(\lambda/\pi)$ with a spatial filter for the lobes, where w_0 is the beam waist at $1/e^2$ of peak intensity and θ is the half-divergence angle. We also found that the size of the beam profile had a minor change (<10%) from low power to maximum power, resulting in a small thermal lens effect, even with high pump power. The main effect of the deviation of the beam quality from diffraction limited in the unstable resonator direction is the inhomogeneity of the crystal and the pump line. For the stable resonator direction, the main effect of the deviation is caused mainly by the mismatched pump volume size and the laser fundamental mode size.

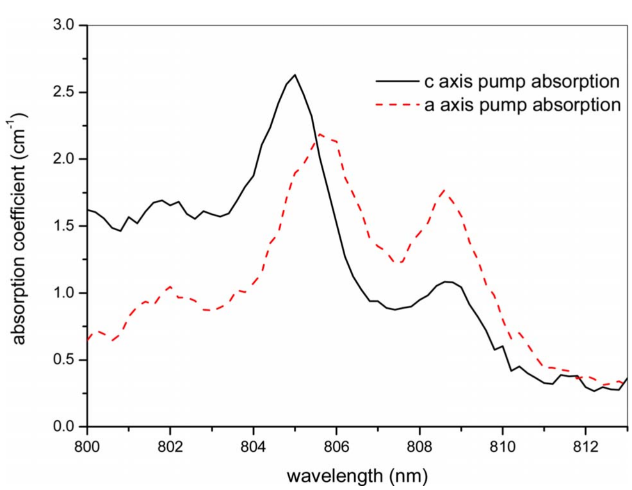


Fig. 2. (Color online) Absorption coefficient of Nd:YLF near 806 nm with a 1 at. % doping concentration.

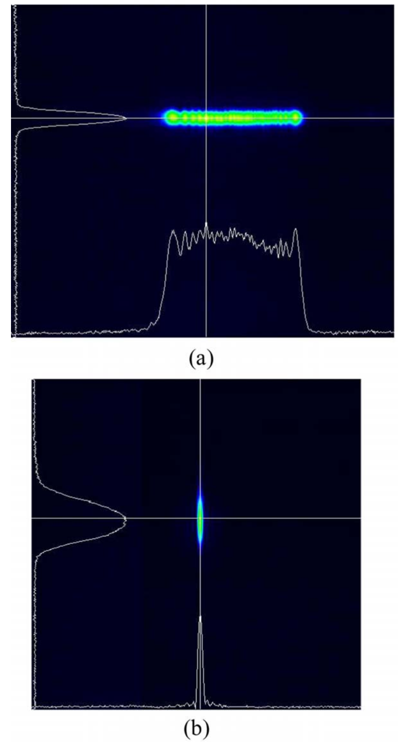
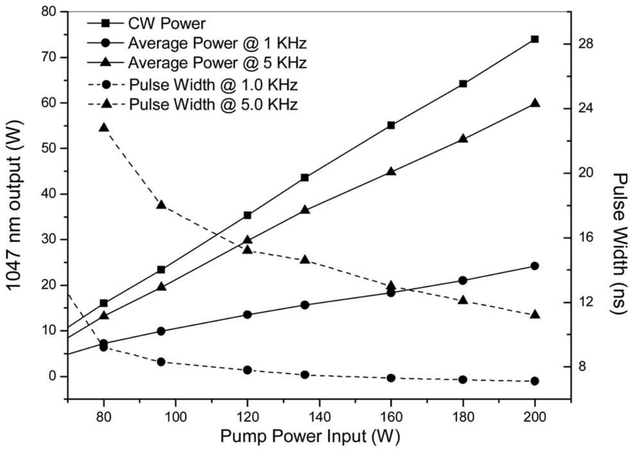


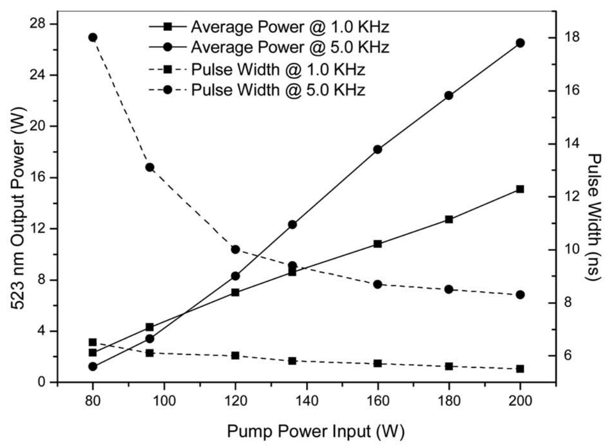
Fig. 3. (Color online) Output beam profile, of 1047 nm in the (a) near field and (b) far field with an f=300 mm focal length lens.

Figure 4(a) shows the 1047 μm output properties of such a stable–unstable resonator. The solid lines represent the output power versus total input pump power launched in crystals, and the dashed lines represent the pulse width. With 200 W input pump power (100 W for each crystal), we obtained 74 W cw output, which meant 37% optical–optical efficiency. The maximum pulse energy was 24.2 mJ with a 7.1 ns pulse width at a 1 kHz repetition rate. The rms pulse energy stability was 1%.

The output beam was symmetrized using a cylindrical telescope. Efficient second-harmonic genera-



(a)

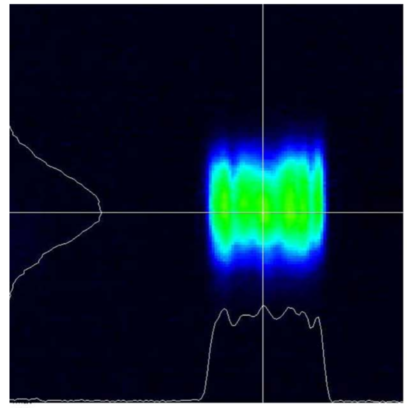


(b)

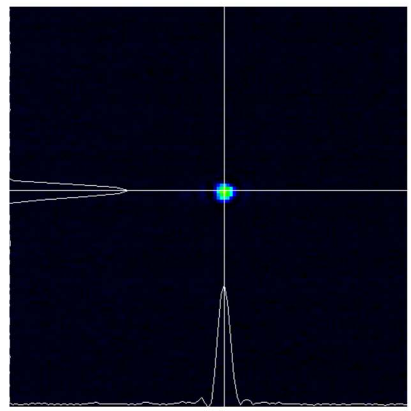
Fig. 4. (a) Output properties of 1047 nm and (b) second-harmonic generation of 523 nm.

tion was achieved with such a high peak power pulse with diffraction-limited beam quality. In the second harmonic generation experiment, we collimated the laser beam only to size 1.2 mm (full width at $1/e^2$) in both directions. For efficient second-harmonic generation we used a lithium triboast crystal with a 15 mm length type I critical phase matching. Figure 4(b) shows the power properties of 523 nm. With a fundamental laser pulse energy of 24.2 mJ, we obtained 15.1 mJ pulse energy at 523 nm. The pulse length at 523 nm was 5.5 ns at a 1.0 kHz repetition rate. The corresponding second-harmonic generator efficiency was 62.3%. The near-field and far-field beam profiles of the second-harmonic generator are shown in Fig. 5, which are also diffraction limited.

We have presented a novel Nd:YLF slab oscillator design with two partially end pumped Nd:YLF slabs in series inside one stable–unstable hybrid resonator. Such a compact resonator design was demonstrated successfully for the generation of laser pulses with high energy, short pulse width, and diffraction-limited beam quality. With our experiment, the Nd:YLF was verified as an excellent laser crystal with slab geometry and as 806 nm wing pump technique. Highly efficient second-harmonic generation was demonstrated. We also showed generation of a



(a)



(b)

Fig. 5. (Color online) Beam profile of 523 nm in the (a) near field and (b) far field.

1-D top hat beam and a 2-D symmetrized Gaussian beam with diffraction limited quality in Figs. 3 and 5 with a hybrid slab resonator and a cylindrical telescope. High-energy pulses with such beam profiles have wide applications in industry and in the scientific field.

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