Laser diode partially end-pumped electro-optically Q-switched Yb:YAG slab laser

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A laser diode partially end-pumped, electro-optically Q-switched, Yb:$Y_3Al_5O_{12}$ (Yb:YAG) slab laser was reported. We obtained output energy of 14.6 mJ/pulse with a pulse width of 30 ns at a repetition frequency of 2 kHz, and the corresponding peak power was 480 kW. The beam quality factors M^2 in the unstable direction and the stable direction was 1.32 and 1.25, respectively.

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A partially end-pumped slab (Innoslab), which was invented by Du *et al.*[1], has been verified in generating laser radiation with diffraction limited beam quality at a high level of output power. Electro-optical Q-switching is a widely used Q-switching method due to its advantages of short switching time, high peak power, and narrow output pulse width[2,3]. There have been reports on electro-optically Q-switched Nd:YVO_4, Nd:$LiYF_4$ (Nd:YLF), and Nd:$Y_3Al_5O_{12}$ (Nd:YAG) Innoslab lasers with a stable–unstable hybrid resonator[4–6]. Besides, the Yb:YAG Innoslab has been applied maturely to continuous-wave oscillators[7] and laser amplifiers[8]; it is also well suitable for achieving high pulse energy and good beam quality for Q-switched lasers. In 2014, a Q-switched Yb:YAG Innoslab laser with a multiple folded stable resonator was reported[9]. However, there have been no reports on an electro-optically Q-switched Yb:YAG Innoslab laser with a stable–unstable hybrid resonator yet.

In this Letter, a Yb:YAG Innoslab laser with a stable–unstable hybrid resonator was reported, achieving an output energy of 14.6 mJ/pulse; we measured the beam quality in the unstable direction and the stable direction, where the M^2 was 1.32 and 1.25, respectively.

Figure 1 shows the experimental setup for the electro-optically Q-switched Yb:YAG slab laser. The laser crystal was a slab-shaped 2.0 at.% doped, 12 mm × 10 mm × 1.2 mm Yb:YAG, which was mounted between two water-cooled copper heat sinks with two large faces (12 mm × 10 mm) serving as thermally conducting surfaces. To improve the thermal conductivity, an indium foil was inserted between the Yb:YAG crystal and the heat sink. Only two 12 mm × 1.2 mm end faces of the slab laser were polished for passing the pump radiation and laser beam and were coated for high transmission at 1030 nm and 940 nm. The Yb:YAG crystal was end-pumped by a laser diode stack with four bars along the y direction, and the radiation emitted by each bar was collimated individually in the fast direction by a micro-cylindrical lens. The pump wavelength was controlled at around 940 nm by operating a cooling water temperature of 20°C. The laser diode stack and Yb:YAG shared the same cooling circulation system.

It is known that Yb:YAG is a quasi-three-level system, and high pump density is required for a Yb:YAG laser operating at room temperature. So, the threshold pump power will be high. To increase the pumping power density, three cylindrical lenses were used to condense light of the diode stack; the pumping light was focused into a nearly homogeneous 0.5 mm × 5 mm pumping line on the crystal end surface. The respective focal lengths of the cylindrical lenses S1, S2, and S3 were $f_1 = 90$ mm, $f_2 = 80$ mm, and $f_3 = 90$ mm, respectively. After passing through the shaping system, about 30% of the pump power was absorbed by S1, S2, and S3. Cylindrical mirrors M1 and M2 only focusing or diverging the beam in the x direction constituted an off-axis unstable positive confocal resonator cavity in the direction of the pumping line's width (x–z plane shown in Fig. 1). Their radii were $R_1 =$ 250 mm and $R_2 = -150$ mm, respectively. Both mirrors were coated for high transmission at 940 nm and high reflectivity at 1030 nm. The geometric cavity length was 50 mm, and the magnification $M = 1.7$. The corresponding output coupler transmission was calculated to be $1-|1/M| = 40\%$. The mirror M2 was cut and polished at one edge, and the laser beam was coupled out by the edge. Because the pumping geometry was line-shaped, the heat conduction was quasi-one-dimensional in the vertical direction; therefore, a considerable thermal lens was formed, and the flat–flat cavity in the vertical direction became thermally stabilized. With a pump line in 1 mm × 4 mm, the focal length of thermal lens was calculated by Eq. (1) to be 30–40 mm:

$$f_T = \frac{SK_c}{P_{in}\eta_{abs}\eta_p\eta_h(\mathrm{d}n/\mathrm{d}T)}. \tag{1}$$

There were many electro-optic crystals widely used, like KH_2PO_4 (KDP), $LiNbO_3$ (LN), $KTiOPO_4$ (RTP),

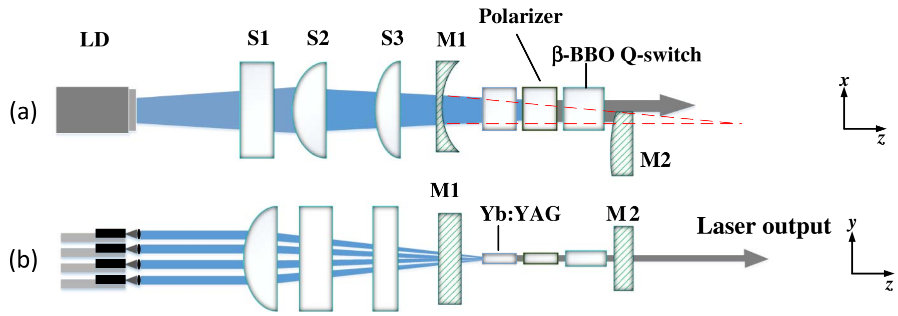

Fig. 1. Schematic diagram of the experimental device view (a) in the x–z plane and (b) in the y–z plane.

$LiGaS_2$ (LGS)[10], and β-BaB_2O_4 (β-BBO). One of the most significant advantages of β-BBO is its high optical damage threshold (5000 MW/cm^2), while it is 100 MW/cm^2 for LN, 600 MW/cm^2 for KDP, 950 MW/cm^2 for LGS, and 1800 MW/cm^2 for RTP. Besides, β-BBO has high extinction ratio (>2000∶1) and is not easily deliquescent[11]. When applying a quarter-wave amplitude voltage to the β-BBO crystal, the laser was in a high-Q state, and thus no laser was produced. When the quarter-wave amplitude voltage was removed, a linearly polarized laser at 1030 nm was produced in the resonator. This high-voltage square wave pulse was controlled by an external drive power supply. The quarter-wave voltage for Q-switching operation was 3500 V.

Figure 2 shows the comparison of free running results and Q-switched average output power under continuous pumping. The Q-switched repetition frequency was 2 kHz. After Q-switched operation, an average output

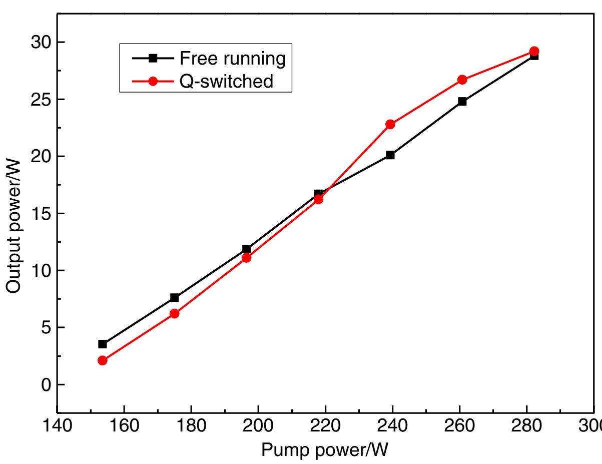

Fig. 2. Comparison of free running and Q-switched average output power under continuous pumping.

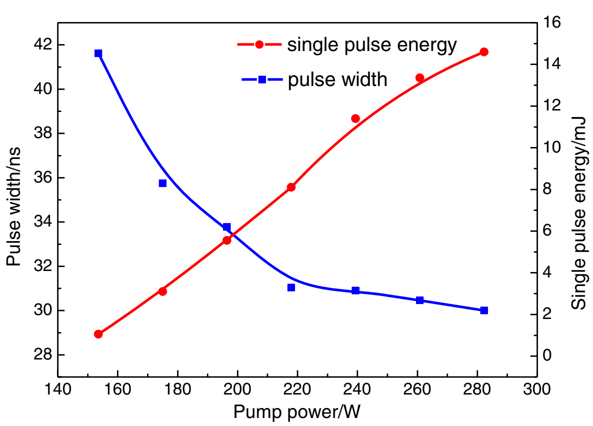

Fig. 3. Pulse energy and pulse width at 2 kHz repetition rate.

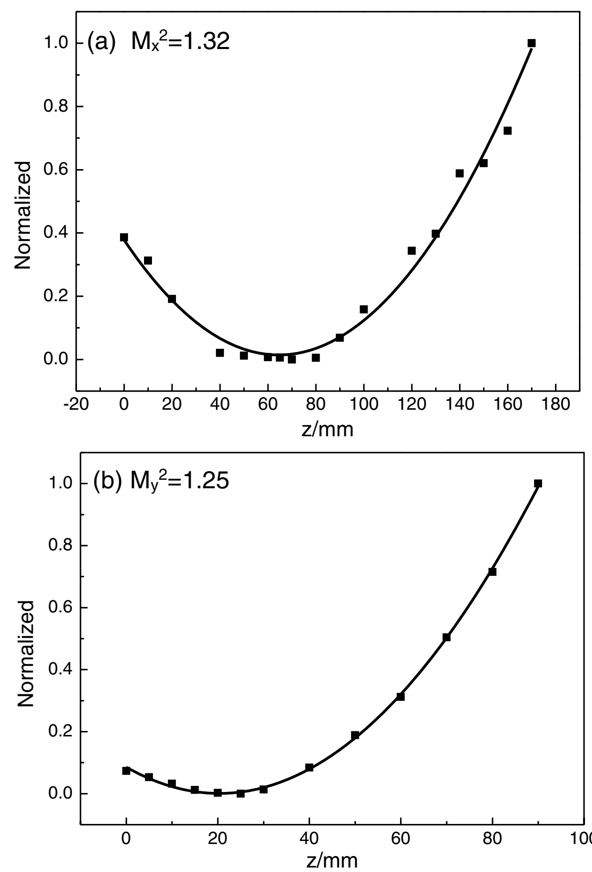

Fig. 4. Beam quality factor M^2. (a) The beam quality M^2 in the unstable direction. (b) The beam quality M^2 in the stable direction.

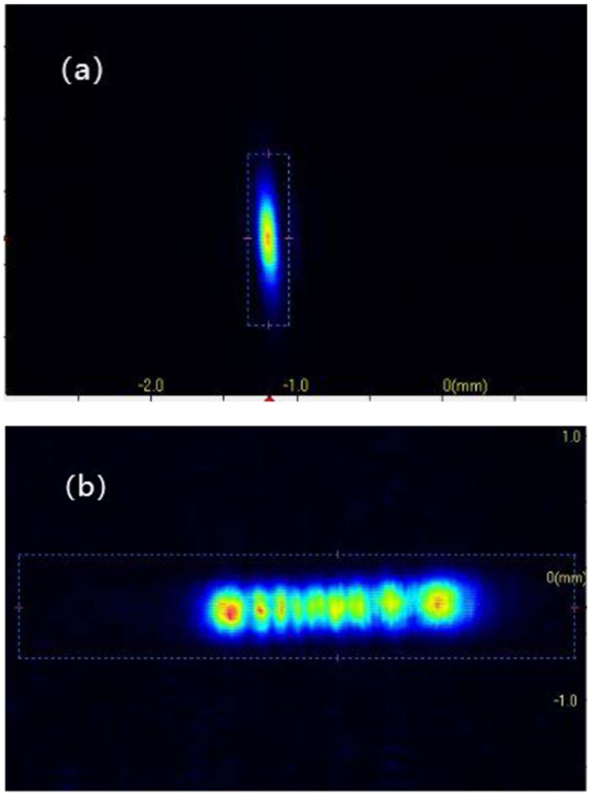

Fig. 5. Spot images around the beam waist. (a) Unstable direction. (b) Stable direction.

power of 29.2 W at 1030 nm was obtained at the pump power of 282 W. The output power was approximately linearly increased with pump power. The corresponding optical–optical efficiency was 10.4%, and the slope efficiency was 22.3%. To get a further improvement of the optical–optical efficiency, the pump density on the crystal end surface could be increased through optimizing the shaping system. The output pulse energy and the pulse width versus pump power at a repetition frequency of 2 kHz are shown in Fig. 3. The pulse energy increased linearly with pump power. Based on the Q-switching theory, the width of the pulse falling edge was dependent on the cavity length, and the width of rising edge depended on the gain coefficient in the cavity. As the pump power increased, the number of population inversion to the upper level increased in unit time; thus, the rise-edge width of the pulse became narrower. At a pump power of 282 W, the output energy was 14.6 mJ, and the pulse width was measured to be 30 ns. With the pulse width and energy, the peak power was calculated to be 480 kW.

A CCD camera and a spherical lens ($f = 300$ mm) were used to measure the output laser beam quality. According to the propagation law of the Gaussian beam, the beam quality M^2 factors in the stable and unstable directions were calculated as 1.25 and 1.32, respectively, at an output pulse energy of 14.6 mJ. The fitting curves in the two directions are shown in Fig. 4. We also recorded the spot images around their own beam waist in the unstable direction and the stable direction, as shown in Fig. 5.

To summarize, we demonstrated a laser-diode, end-pumped, electro-optically Q-switched Yb:YAG slab laser, which has a stable–unstable positive-branch confocal hybrid cavity. With this structure, we obtained single pulse energy of 14.6 mJ with a pulse width of 30 ns at a repetition frequency of 2 kHz and the corresponding peak power of 480 kW. The optical–optical efficiency was 10.4%, and the slope efficiency was 22.3%. The beam quality factors M^2 in the unstable and stable directions were 1.32 and 1.25, respectively.

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