Diode-end-pumped, electro-optically Q-switched $Nd:YVO_4$ slab laser and its second-harmonic generation

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We describe the operation of a near-diffraction-limited, 1064-nm electro-optically Q-switched $Nd:YVO_4$ slab laser that is end pumped by laser-diode stacks and its efficient second-harmonic generation by using a lithium triborate (LBO) crystal. The energy per pulse of 3.6 and 0.8 mJ and pulse widths of 5 and 13.5 ns were obtained at repetition of 5 and 40 kHz, respectively. With a LBO crystal, a maximum output power of 15.6 W at 532 nm was obtained at the repetition rate of 40 kHz, the corresponding conversion efficiency was 60%, and the pulse width was 11.3 ns. At 10 kHz, the pulse energy of 532 nm was 1.2 mJ, and the pulse width was 5 ns. © 2003 Optical Society of America

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1. Introduction

There are many applications for high-repetition-rate Q-switched lasers with high average power that can be frequency converted by use of nonlinear optics. Some examples are middle-infrared remote sensing, visible display applications, and UV material-processing applications. Excellent beam quality and high peak powers are required to achieve efficient nonlinear frequency conversion. However, the short pulses required for high peak power are difficult to achieve in laser materials such as Nd:YAG and Nd:YLF. One material that offers the possibility of achieving high peak power at high pulse rates is $Nd:YVO_4$,[1–5] owing to its higher emission cross section and shorter fluorescence lifetime. Even though $Nd:YVO_4$ crystals have been identified as promising materials for diode-pumped lasers, power scalability is limited by thermally induced lensing and thermal fracture damage. Different designs have been investigated to obtain high output power,[6–9] and 49.5-W multimode and 31-W TEM_{00} have been reported in continuous wave.[9] By use of four fiber-coupled diode bars to dual end pump two vanadate crystals, a TEM_{00} power of 48 W was achieved when the acousto-optic Q switch was operated at 100 kHz.[4]

Partially end-pumped slab lasers with a stable–unstable hybrid resonator have been proved to be a favorable concept for power scaling at high beam quality and efficiency because they have both the properties of the high overlapping efficiency of end-pumped rod lasers and the excellent cooling conductivity of slab lasers.[10–12] In this paper we report a partially end-pumped $Nd:YVO_4$ slab laser oscillator. The $Nd:YVO_4$, which is a thin plate, is placed in a hybrid resonator that is stable in the direction normal to the plate (stabilized by thermal lensing and gain guiding) and unstable in the direction parallel to the plate. The laser was electro-optically Q switched at high repetition rates, and its efficient second-harmonic generation with a lithium triborate (LBO) crystal is also demonstrated.

2. Experimental Setup and Results

The experimental arrangement of the slab laser is shown in Fig. 1. The slab $Nd:YVO_4$ crystal was with 0.3 at. % doping concentration. It had a size of 1 mm × 10 mm × 12 mm and was a cut, and its c axis was parallel to its 12-mm face. It was mounted between two water-cooled brass heat sinks with two large faces (12 mm × 10 mm) serving as thermally conducting surfaces. As mentioned in Ref. 10, only two end faces (1 mm × 12 mm) of the slab crystal needed to be polished for passing the pump radiation and laser beam, and both of the faces were coated for high transmission at 1064 and 808 nm. Indium foils were used for effective and uniform thermal contact and cooling. The pumping unit consisted of a stack

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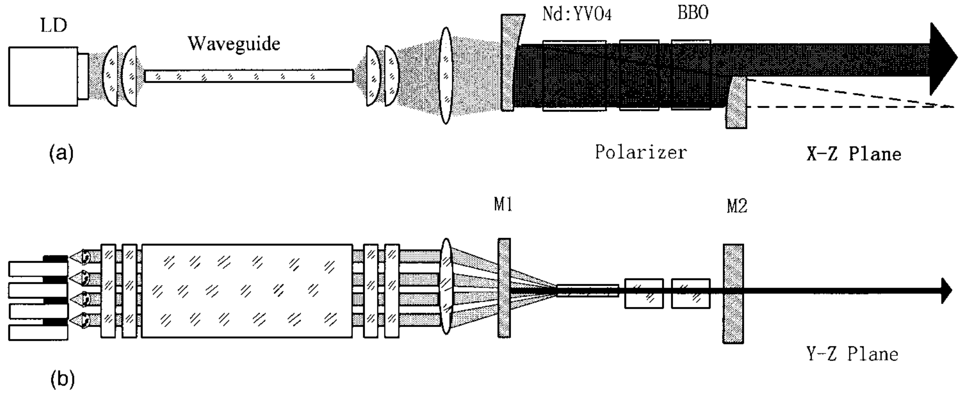


Fig. 1. Schematic of the electro-optically Q-switched Nd:YVO_4 slab laser with a hybrid resonator: (a) In the y–z plane and (b) in the x–z plane. LD, laser diode; BBO, β-barium borate.

with four diode bars, and the radiation emitted by each diode-laser bar was individually collimated by microlenses. The four collimated beams were focused into a planar waveguide by two cylindrical lenses. By use of an imaging system with magnification of 4, a homogeneous pumping line with dimensions of 0.5 mm × 12 mm was generated inside the Nd:YVO_4 slab. By use of such a pumping unit, 88% of the diode-laser power was transmitted to the Nd:YVO_4 slab. By controlling the temperature of the cooling water, we fixed the central wavelength of the emission at around 808 nm. We estimated approximately 95% of the pump light was absorbed by the laser crystal.

The laser had a positive-branch, confocal unstable resonator in the plane of the pumping line (x–z plane in Fig. 1), with a magnification $M = 2$, and a geometric cavity length of 80 mm, which provided a collimated output beam. The radii of curvature of the hard-edge output coupling mirror and of the totally reflecting rear mirror were −125 and 250 mm, respectively. The output coupling was $1 - 1/M = 50\%$, which corresponds to an output coupler of 50% transition. With the line-shaped pumping geometry, the heat conduction was quasi one dimensional, and the temperature gradient was perpendicular to the pumping line; therefore there was a considerable thermal lens effect in the direction perpendicular to the pumping line (y–z plane), and hence the flat–flat cavity in the y–z plane became thermally stabilized. At first, an acousto-optical Q switch was tried, but the combination of the Q switch and the 50% output coupler resulted in insufficient round-trip losses to prevent significant prelasing during the build-up period before the opening of the Q switch. So a birefringent polarizer and a high-power β-barium borate electro-optic Pockels cell were used for Q switching.

The output pulse energy and pulse width of the fundamental light versus the repetition rates are shown in Fig. 2. The pump power incident upon the input mirror M1 was 127 W. The energy per pulse of 3.6 mJ was obtained at a repetition rate of 5 kHz; with a repetition rate as high as 40 kHz, the average output power was 32.5 W, and the energy per pulse was above 0.8 mJ. As expected for a high-gain system with short cavity length and high output coupling, the pulse widths were short. The pulses were measured by a 600-MHz-bandwidth Tektronix digital signal analyzer (DSA 602) and fast photodiode (~0.3-ns rise time). At a repetition rate of 5 kHz, the pulse width was approximately 5 ns, and the pulse width was 13.5 ns when the repetition rate was 40 kHz. A typical pulse at 15 kHz is shown in Fig. 3(a); also, given in Fig. 3(b) is that of its second harmonic, which was recorded by a 500-MHz-bandwidth Tektronix digital real-time oscilloscope (TED 644B). No double-pulsing phenomenon was observed as we changed the repetition rate from 5 to 40 kHz while the pump power remained at 127 W. As the cavity length was short, the axial mode separation was more than 1 GHz, and mode beating could not be observed with the oscilloscopes used in the experiments.

To measure the laser beam quality, we used the same method as used in Ref. 5. The attenuated output beam was imaged by a lens ($f = 300$ mm). By measuring the beam sizes at a distance of the focus lengths f (when the distance from the output coupler

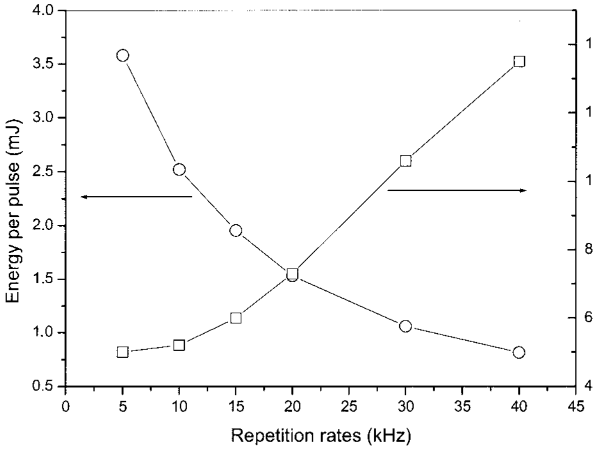
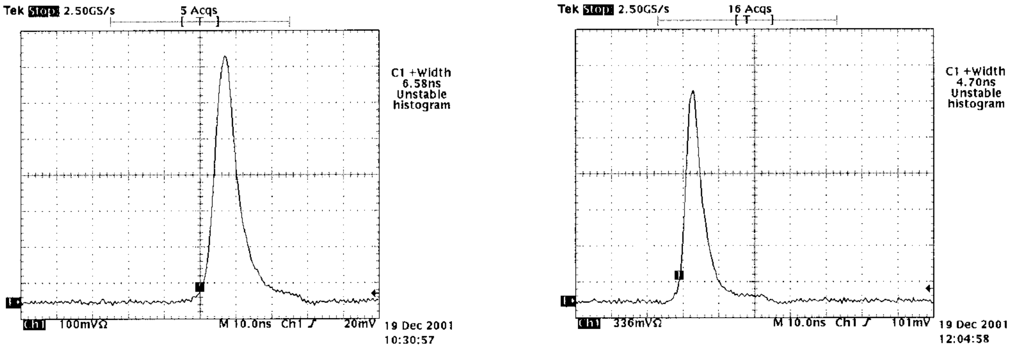


Fig. 2. Output pulse energy and pulse width of the fundamental light versus the repetition rates.



(a) (b)

Fig. 3. Q-switched pulse of (a) 1064 and (b) 532 nm obtained at 15 KHz.

to the lens was f) and $2f$ (when the distance from the output coupler to the lens was $2f$) with a digital video camera (Polytec) behind the focusing lens, we calculated the M^2 factors according to the propagation law of the Gaussian beam. As with end-pumped rod lasers, gain guiding results in a Gaussian-like intensity profile in the stable plane; along the unstable axis the profile is typical, with side maximums that are due to diffraction on the edge of the output coupling mirror. At the pump power of 127 W, the beam quality factor M^2 in both the stable and the unstable directions were less than 1.3, indicating a near-diffraction-limited beam. The focal length of the thermal lens in the stable direction was also estimated from the beam size at the output coupler and the divergence angle of the output beam. At the pump power of 127 W, it was approximately 180 mm.

For the second-harmonic generation, a LBO crystal with a size of 3 mm × 3 mm × 15 mm at hand was used. It was cut for type-I phase matching at room temperature ($\theta = 90°$, $\phi = 11.2°$) and was used, and both ends of the LBO crystal were antireflection coated for both 1064 and 532 nm. As the cross section of the fundamental laser beam at the output coupler had a size of $\approx$0.4 mm × 6 mm, so a group of prisms was used to compress the infrared beam diameter along the unstable direction by a factor of 12, resulting in a beam diameter of 0.4 mm along the stable direction and 0.5 mm along the unstable direction. At low repetition rates (5–15 kHz) the infrared beam was focused with a lens of $f = 200$ mm to generate a spot size of 0.4 mm × 0.32 mm in the LBO. This relatively large spot size had to be chosen to prevent damage of the LBO owing to the high peak powers of 720 kW at 5 kHz. At higher repetition rates (30–40 kHz), the peak power was low enough (60 kW) to focus tighter into the LBO by use of a 100-mm lens.

The average green output power at different repetition rates is shown as a function of the infrared input power in Fig. 4. During the experiments, the pump power incident upon M1 remained 127 W. At a repetition rate of 40 kHz, a maximum output power of 15.6 W at 532 nm was obtained when the power of 1064 nm was 26 W. The corresponding conversion efficiency was 60%, and the pulse width was 10.5 ns. At a repetition rate of 10 kHz, the pulse energy of 532 nm was 1.2 mJ, and the pulse width was as short as 5 ns. In Fig. 5 the energy per pulse and pulse width

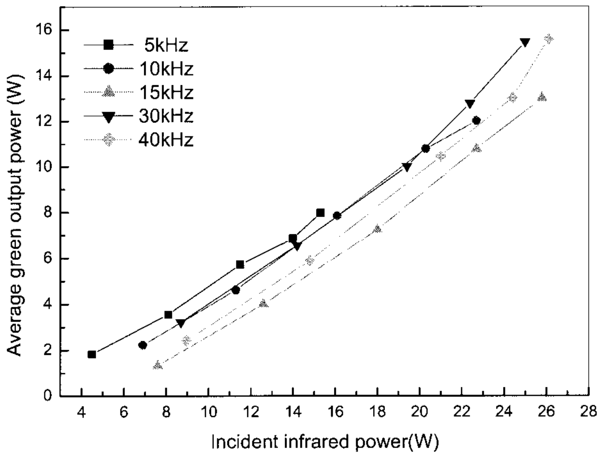


Fig. 4. Average output power of green light at different repetition rates versus the infrared power.

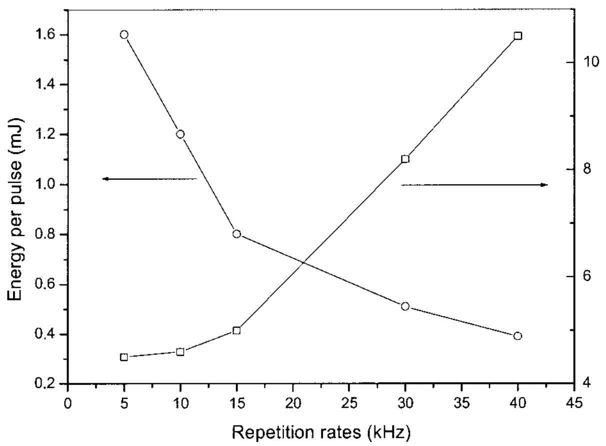


Fig. 5. Output pulse energy and pulse width of the green light versus the repetition rates.

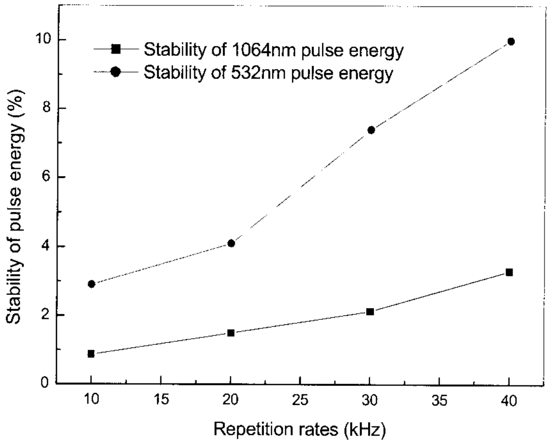


Fig. 6. Stability of the pulse energy of 1064- and 532-nm light.

of the green output are shown as a function of repetition rates.

The stability of 532- and 1064-nm pulse energies was also measured by the Tektronix digital signal analyzer from 10 to 40 kHz. At each repetition rate, 1000 pulses were counted, and stability was obtained when the standard deviation was divided by the average value. The results are given in Fig. 6, from which we can see that, as repetition rates rise, the stability becomes worse. The reason for this may be that, as the repetition rates increased, the inverse ion population became smaller, and hence the Q-switched output energy is sensitive to the noise of spontaneous emission. We think the stability may be better when the pump power is further increased.

3. Conclusion

In summary, with a stable–unstable hybrid cavity and a Nd:YVO$_4$ slab crystal, a diode-end-pumped, high-power, high-repetition-rate electro-optical Q-switched slab laser and its efficient second-harmonic generation were demonstrated. At the repetition rate of 5 kHz, the energy per pulse and pulse width were 3.6 mJ and 5 ns, respectively. At 40 kHz, an average power of 32.5 W was obtained. With a LBO crystal, a maximum green output power of 15.6 W was obtained with 26-W fundamental power, and the optical conversion efficiency was more than 60%, whereas at 10 kHz, the energy per pulse and pulse width of the green light were 1.2 mJ and 5 ns, respectively.

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