Applied Physics B (2018) 124:195
https://doi.org/10.1007/s00340-018-7064-0

Applied Physics B
Lasers and Optics

RTP voltage-increased electro-optic Q-switched Ho:YAG laser with double anti-misalignment corner cubes

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Received: 24 March 2018 / Accepted: 9 September 2018 / Published online: 14 September 2018

Abstract

We describe a pulsed Ho:YAG laser with double anti-misalignment corner cubes that uses an $RbTiOPO_4$ crystal as the electro-optic Q-switch. Two polarizers coated with high reflectivity coatings for the s-polarized light at the laser wavelength were employed to achieve linearly polarized laser output. The maximum s-polarized output power of 2.95 W at 2091.3 nm was obtained under the absorbed pump power of 12.9 W by increasing the voltage applied on $RbTiOPO_4$ electro-optic crystal to 1000 V. The corresponding optical-to-optical conversion efficiency was 22.9% and the slope efficiency was 67.9%. For the Q-switched operation, the pulse energy of Ho:YAG laser was 7.8 mJ with a pulse width of 57 ns at the repetition rate of 100 Hz, resulting in a peak power of 136.8 kW. The beam quality factor M^2 of Ho:YAG laser was 1.33.

1 Introduction

Q-switched solid-state lasers operating near 2 μm eye-safe spectral range with a high energy and short pulse are desirable for a variety of applications such as coherent laser lidar [1], differential absorption lidar [2], remote sensing [3] and mid-infrared radiation via pumping optical parametric oscillators [4]. The main 2 μm pulse laser media are Tm-doped, Ho-doped and Tm, Ho co-doped crystals. Compared with Tm-doped crystals, Ho-doped crystals are attractive materials to generate high energy pulse due to their longer upper level lifetime and larger stimulated emission cross section [5]. Ho-doped lasers based on yttrium lithium fluoride (YLF) [6], yttrium aluminum garnet (YAG) [7] and yttrium aluminum perovskite (YAP) [8] host materials have been extensively investigated in 2 μm laser. Ho:YAG was an attractive crystal to generate 2 μm lasers due to its excellent thermo-mechanical properties. The 2 μm pulse lasers are commonly obtained by actively Q-switched such as acousto-optic Q-switched or electro-optic Q-switched. The electro-optic Q-switched is desirable in terms of size and agility. Among the commonly used electro-optic crystals such as $KTiOPO_4$ (KTP), $LiNO_3$ and $RbTiOPO_4$ (RTP), the RTP crystal has high optical damage threshold, good optical transparency and low piezo-electric effect [9]. So, the RTP electro-optic Q-switched Ho:YAG lasers are suitable to generate pulse laser output.

A corner cube is the retroreflector with three adjacent and mutually orthogonal plane surfaces. It is highly desirable in interferometers, laser resonators and atmospheric absorption measurements [10, 11] because the incident light on the corner cube at arbitrary angles can be returned strictly parallel to the incident beam [12]. Especially in laser resonators, the corner cube is highly anti-misalignment due to its insensitivity to impact, vibration and temperature. This property can reduce the effects of mechanical insensitivity on the laser system. In 1982, Chen proposed a Q-switched corner-mirror resonator. The Q-switched laser was obtained with the pulse energy of 2.6 mJ and the peak power of 400 kW [13]. In 2006, Gao et al. reported a passively Q-switched Nd:YAG laser with a corner cube that used a Cr:YAG crystal. By rotating the corner cube, the highest peak power was 10.36 MW, the lowest peak power was 8.59 MW. The adjustment range of pulse width was 2.95 ns [14]. In 2015, Wu et al. reported a linearly polarized Ho:YAG laser with a single corner cube. A maximum linearly polarized output power of 5.8 W was achieved when the pump power was 23.3 W [15]. However, the electro-optic Q-switched laser with double anti-misalignment corner has not been reported.

In this paper, we report a RTP electro-optic Q-switched Ho:YAG laser with double anti-misalignment corner cubes. A pair of polarizers was considered as the output coupler to obtain bidirectional s-polarized laser output. The output

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power could be changed by adjusting the voltage applied on the RTP crystal. In the continuous-wave operation, a maximum bidirectional s-polarized output power of 2.95 W was achieved by rotating the quarter-wave plate (QWP) when the absorbed pump power was 12.9 W at the voltage applied on the RTP crystal of 1000 V. The corresponding optical-to-optical conversion efficiency was 22.9% and the slope efficiency was 67.9%. For the Q-switched operation, the output energy of Ho:YAG laser was 7.8 mJ, with a pulse width of 57 ns and a repetition frequency of 100 Hz. The beam quality factor M^2 of Ho:YAG laser was 1.3.

2 Experimental setup

A RTP voltage-increased electro-optic Q-switched Ho:YAG laser is shown in Fig. 1. The pumping source was a Tm: YLF solid-state laser end pumped by a 792 nm laser diode. The pump beam was shaped and focused by a plane convex lens f_1 with focal length of 240 mm. The beam radius of pumping source in the center of the Ho:YAG crystal was nearly 300 μm. The pump beam absorption efficiency of the Ho:YAG crystal was about 42%. The resonator of Q-switched Ho:YAG laser was a 1.1 m ring cavity with double anti-misalignment corner cubes, which was convenient for injection seeding due to its bidirectional output. The material of a pair of corner cube prisms was JGS3 with a diameter of 40 mm and a height of 35 mm. The incident surface of corner cube was coated with high transmission coating at 2.1 μm and the three reflecting surfaces with the angle precision of ± 2″ were uncoated. Lenses f_2 and f_5 were both plane convex lenses with focal length of 240 mm, and coated with high transmission coatings at 2.1 μm. Lenses f_3 and f_4 were both plane concave lenses with curvature radius of 75 mm, and coated with high transmission coatings at 2.1 μm. Lenses f_2, f_3, f_4 and f_5 were placed symmetrically to compensate the thermal lens effect of Ho:YAG crystal. A pair of polarizers (P1 and P2) was considered as output coupler coated with high reflectivity coating at 1.9 μm, and high reflectivity coating for s-polarized light and high transmission coating for p-polarized light at 2.1 μm. The QWP2 coated with high transmission coating at 1.9–2.1 μm was inserted to achieve the maximum power output by rotating it. A Φ4 × 45 mm^3, with 0.5 at.% Ho-doping concentration Ho:YAG crystal was considered as the gain medium. The crystal was wrapped with indium foil and installed on a copper heat sink. The temperature of the Ho:YAG crystal was kept at 15 °C precisely by a thermoelectric cooler (TEC). Both sides of the crystal were coated with antireflection (AR) coatings at 1.9 μm and 2.1 μm. An electro-optic modulator made by two RTP crystals with the dimension of $3 \times 3 \times 10$ mm^3 was inserted into the cavity to achieve Q-switching experiments.

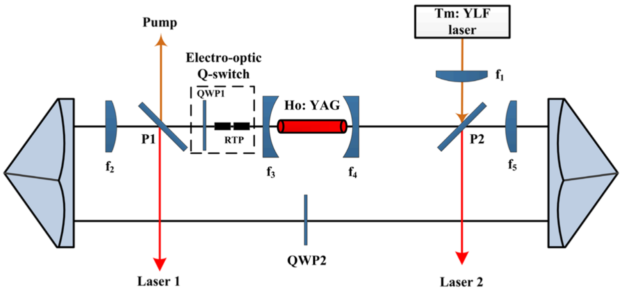


Fig. 1 Experimental setup of the RTP electro-optic Q-switched Ho:YAG laser

The maximum output power was obtained by rotating the QWP2 first. The phase retardation was generated in RTP crystal due to the natural birefringence. So, the QWP1 was introduced in the cavity to compensate the phase retardation. When no voltage was applied on the RTP crystal, the p-polarized light would be changed to s-polarized light after through the RTP crystal and the QWP1, resulting in a high cavity loss, and no light output. When a 1000 V voltage applied on the RTP crystal, the polarization state of oscillating laser was not changed after through the RTP crystal and the QWP1, and the s-polarized pulse light was obtained.

3 Experimental results and discussion

The output power could be changed by adjusting the voltage applied on the RTP crystal because the polarization state of oscillating laser in the cavity was changed. When the absorbed pump power was 12.9 W, the bidirectional output power under different voltages is shown in Fig. 2. The maximum s-polarized output power from two directions was

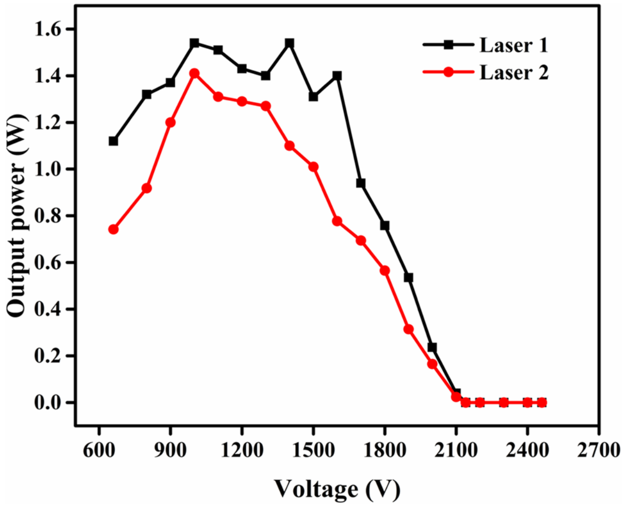


Fig. 2 Output power of CW Ho:YAG laser under different voltages

1.54 W and 1.41 W, respectively, when the voltage applied on the RTP crystal was 1000 V. Under this condition, the bidirectional output power versus absorbed pump power was investigated, as shown in Fig. 3. The maximum combined output power was 2.95 W under the absorbed pump power of 12.9 W, corresponding to the optical-to-optical conversion efficiency of 22.9% and the slope efficiency of 67.9%. The output spectrum of CW Ho:YAG laser with double corner cubes was measured by a wavemeter (Bristol, ± 0.2 pm accuracy) when the absorbed pump power was 12.9 W, as shown in Fig. 4. The wavelength was centered at 2091.3 nm. The incident plane of two corner cubes was perpendicular to the oscillating beam of the cavity in the initial state. The anti-misalignment characteristic of the corner cube was investigated by rotating one of the corner cubes around the direction perpendicular to the laser axis of the cavity when the voltage applied on the RTP crystal was 1000 V and the absorbed pump power was 12.9 W. The relationship between the rotating angles and the reduction rate of power is shown in Fig. 5. The output power was reduced by 30%, but the laser still operated stably when the corner cube was rotated to 11.8° around the direction perpendicular to the laser axis of the cavity.

The Q-switched output performance of the Ho:YAG laser with double corner cubes at the repetition rates of 100, 200 and 500 Hz is shown in Fig. 6. The output energy increased with the absorbed pump power at the same repetition rate.

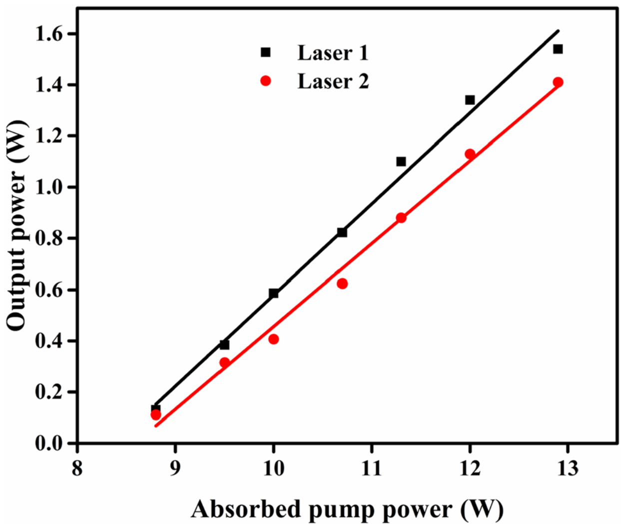


Fig. 3 Bidirectional output power of CW Ho:YAG laser versus the absorbed pump power

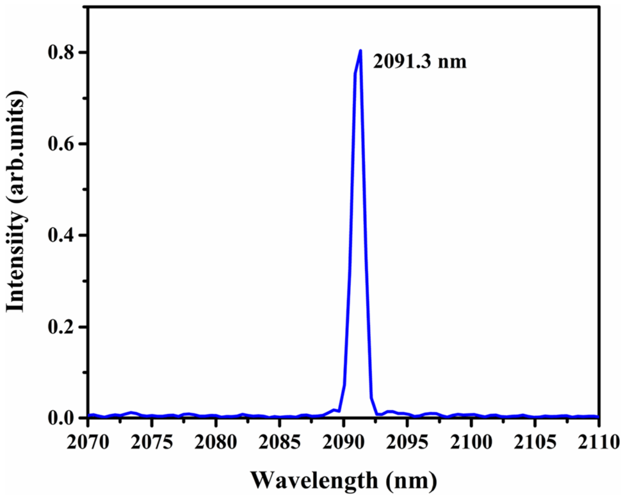


Fig. 4 Output spectrum of CW Ho:YAG laser

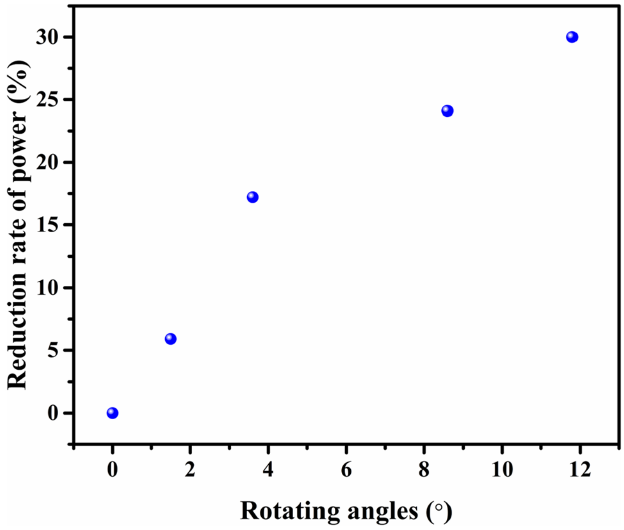


Fig. 5 Reduction rate of Ho:YAG laser output power versus the rotating angles

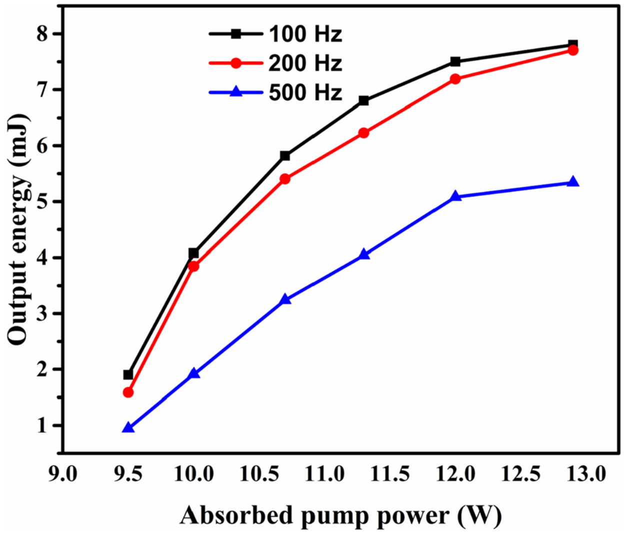


Fig. 6 Output energy versus absorbed pump power under different repetition rates

At the repetition rate of 100 Hz, the output pulse energy of 7.8 mJ was achieved under the absorbed pump power of 12.9 W. At the repetition rate of 500 Hz, the output pulse energy reached 5.3 mJ when the absorbed pump power was 12.9 W. The pulse traces of voltage-increased Q-switched Ho:YAG laser was detected by an InGaAs detector connected with a digital telescope (Tektronix TDS3032B). The relationship between the laser pulse width and the absorbed pump power at the repetition rates of 100, 200 and 500 Hz is shown in Fig. 7. The pulse width decreased with the absorbed pump power, and increased with the repetition rate. As a result, the pulse width was 57 ns at the repetition rate of 100 Hz when the absorbed pump power was 12.9 W. The temporal shape of single pulse at the pulse width of 57 ns and the long-term pulse sequence are shown in Fig. 8.

The output beam radius of Ho:YAG laser was measured by the 90/10 knife-edge technique at several positions when the absorbed pump power was 12.9 W, as shown in Fig. 9. By fitting Gaussian beam standard expression to experimental data, the beam quality factor M^2 of 1.33 was estimated.

4 Conclusion

In conclusion, we reported a RTP voltage-increased electro-optic Q-switched Ho:YAG laser with double anti-misalignment corner cubes. The output power could be changed by adjusting the voltage applied on the RTP crystal. A maximum output power of 2.95 W at 2091.3 nm was achieved under the absorbed pump power of 12.9 W by adjusting the voltage applied on the RTP crystal, corresponding to an optical-to-optical conversion efficiency of 22.9% and a slope efficiency of 67.9%. When one of the corner cubes was rotated to 11.8° around the horizontal direction, the resonator still operated stably. At the repetition rate of 100 Hz, the pulse energy of 7.8 mJ was obtained with a pulse width of 57 ns. The beam quality factor M^2 of Ho:YAG laser was 1.33.

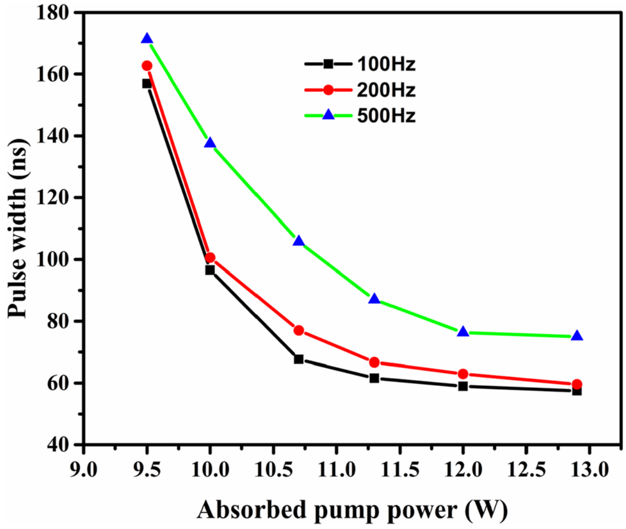


Fig. 7 Pulse width versus absorbed pump power at different repetition rates

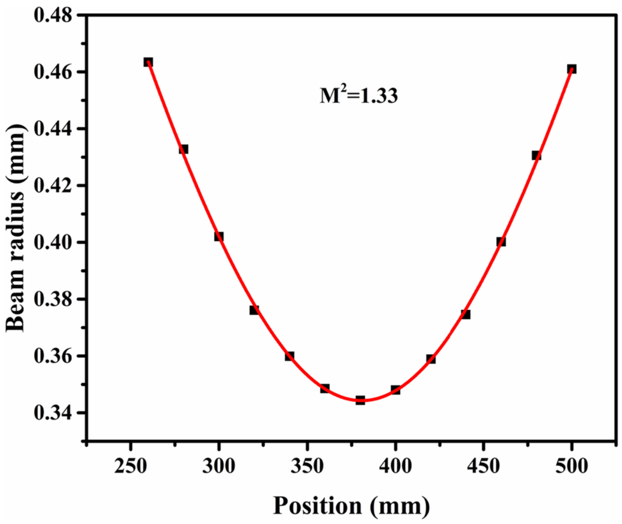
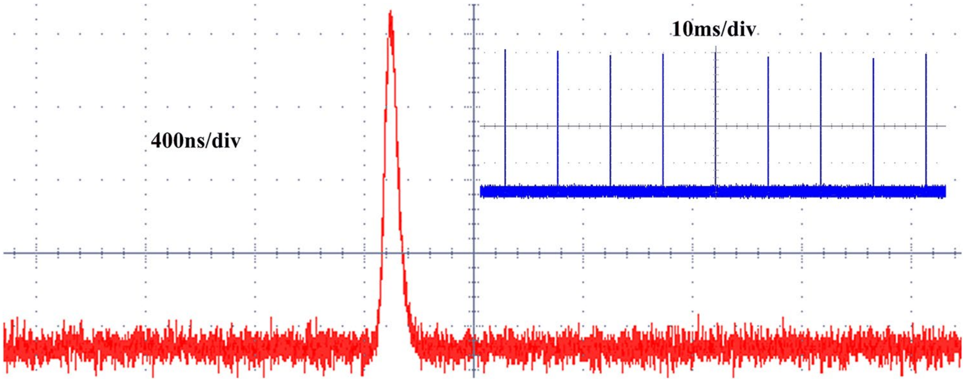


Fig. 9 Beam quality of Ho:YAG laser

Fig. 8 The temporal shape of a single pulse at 57 ns and the long-term pulse sequence



Acknowledgements This work was supported by the National Natural Science Foundation of China (no. 61405047).

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