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HIGH-POWER IN-BAND PUMPED *a*-CUT Ho:YAP LASER

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Abstract

We report the continuous wave and acousto-optically Q-switched operation of an in-pumped a-cut Ho:YAP laser at room temperature. We obtained a continuous-wave output power of 17.2 W at 2118 nm under an absorbed pump power of 29.8 W, corresponding to a slope efficiency of 63.2%. For the Q-switched mode, we achieved a maximum pulse energy of about 1.7 mJ and a minimum pulse width of 24 ns at a repetition rate of 10 kHz, resulting in a peak power of 70.8 kW.

Keywords: solid-state lasers, 2 μm lasers, YAP laser.

1. Introduction

Solid-state lasers operating at 2 μm have applications in remote sensing, medicine, and as pump sources for 3–12 μm optical parametric oscillators. Since rare-earth-ion holmium Ho^{3+} has a significantly high emission cross section in the 2 μm region, Ho-based lasers are ideally suited for these applications. Primary work was focused on Tm,Ho co-doped laser materials, which can be high-power pumped by a commercial laser diode operating at approximately 800 nm. However, in these lasers cryogenic cooling should be used in order to achieve a high-efficiency laser output [1–3]. In recent years, with the development of 1.9 μm lasers as efficient pump sources, in-band-pumped Ho lasers have avoided these drawbacks. Direct (in-band) pumping the Ho $^5\mathrm{I}_7$ manifold offers several advantages, including high quantum efficiency, minimum heating, as well as reduced up-conversion losses caused by sensitized Tm. To date, in-band pumping of singly Ho-doped lasers such as YAG [4–6], LuAG [7], YVO_4 [8], and YLF [9, 10] lasers have been reported.

Aside from these host materials, one of the most interesting crystals is yttrium aluminum oxide YAlO_3 (YAP, YAlO). The YAP crystallizes in the orthorhombic space group, and this low symmetry (as compared to the cubic YAG) has two important consequences: anisotropic luminescence and linearly polarized laser emission [11]. In addition, the properties of YAPs are similar to those of YAGs [12], and the YAP favors laser operation at high power level without thermally induced birefringence. To date, extensive studies have been carried out to investigate the laser performances of Tm:YAP and Tm,Ho:YAP crystals, which show great advantages for the development of high efficiency lasers [13–17]. In contrast, prior work on the laser performance of singly Ho-doped YAP crystals is not yet done in detail.

Our previous experiment has revealed that the Ho:YAP laser can efficiently operate at room temperature. In the continuous wave (CW) operation, output powers of 11.2 and 14.6 W at 2118 nm from b-cut and a-cut Ho:YAP lasers have been obtained [18, 19]. At Q-switched operation, a maximum pulse

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energy of about 1.3 mJ and a minimum pulse width of 31 ns at the repetition rate of 5 kHz were achieved in *b*-cut Ho:YAP lasers, resulting in a peak power of 41.3 kW [20]. The maximum output power of 9.8 W at a repetition rate of 10 kHz was obtained in *a*-cut Ho:YAP lasers [21].

In this paper, we demonstrate the room temperature, CW, an acousto-optically Q-switched operation of an in-pumped *a*-cut Ho:YAP laser. A CW output power equal to 17.2 W at 2118 nm was obtained under an absorbed pump power of 29.8 W, corresponding to a slope efficiency of 63.2%. At the same absorbed pump power, the active Q-switched operation of the laser has an average output power of 16.5 W when the repetition rate was set at 10 kHz. The maximum Q-switched pulse energy was about 1.7 mJ. The minimum pulse width was measured to be about 24 ns, corresponding to a peak power of 70.8 kW.

2. Experimental Setup

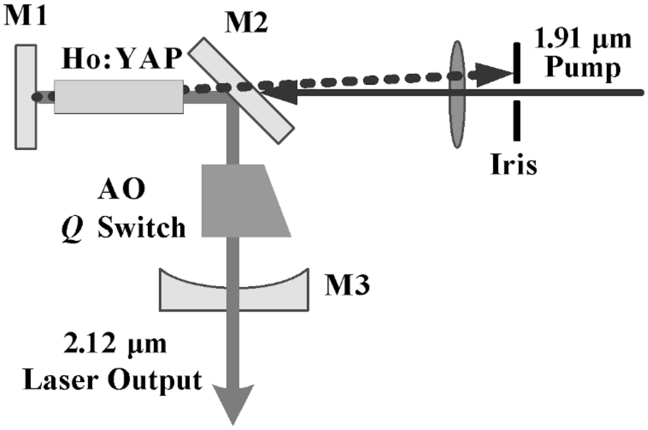

Fig. 1. Experimental setup of an *a*-cut Ho:YAP laser in-band pumped by a Tm:YLF laser.

The experimental configuration is shown in Fig. 1. A diode-pumped Tm:YLF laser with emission wavelength of 1.91 μm is utilized as a pump source of the Ho:YAP laser. The YAP crystal with 0.3 at.% Ho^{3+} concentration is grown by the Czochralski technique. The *a*-cut Tm:YAP crystal for the experiment has dimensions of 4×4 mm^2 in cross section and 44 mm in length. Both end faces of the crystal are anti-reflection coated for the laser wavelength and the pump wavelength. The laser crystal is wrapped in indium foil and clamped in a copper crystal-holder held at a temperature of 15°C with a thermoelectric cooler. The transmission losses provide about 95% of the pump-power input to the Ho:YAP crystal. The actual fraction of the incident power absorbed by the Ho:YAP laser measured near the threshold was 63%. In endeavoring to obtain high absorbed efficiency, we used the double-pass pump structure, leading to 86.3% pump absorption by the Ho:YAP crystal. The flat mirror M1 has high reflectivity ($R > 99\%$) in the wavelength range $1.9 - 2.2$ μm. The flat 45° dichroic mirror M2 has high reflection ($R > 99.5\%$) at 2.12 μm and high transmission ($T \sim 97\%$) at the *p*-polarized wave in the wavelength range 1.9–1.92 μm. The output coupler M3 is a plano-concave mirror with a radius of curvature of 150 mm. The Q-switching experiments are achieved with a 46 mm long fused silica acousto-optical (A-O) Q-switch (QS041-10M-HI7, Gooch & Housego). Its maximum RF power is 50 W, and the repetition rate could be tuned continuously from 1 to 50 kHz. The cavity physical length is 120 and 65 mm with and without the Q-switch crystal, respectively. The calculated TEM_{00} beam diameter is about 430 μm in the Ho:YAP crystal. The radiation of the Tm pump is focused to fill the mode volume of the Ho:YAP resonator.

Using a knife edge, we measured the pump spot at the input surface of the Ho:YAP crystal to be approximately 500 μm in diameter, and the diameter of the pump beam is nearly unchanged over the Ho-crystal length. As a result, good overlap of the pump-to-Ho-resonator mode is achieved. To prevent the Tm:YLF laser from being influenced by feedback, an iris is placed in the pump path, and the axis of the Ho resonator is misaligned from the pump axis by several mrad.

3. Experimental Results

In our experiments, we used a Coherent PM30 as the power meter. First, without the Q-switch crystal in the laser cavity, using different output transmissivities of 20%, 29%, and 51%, we investigated the CW laser performance of the a-cut Ho:YAP crystal. The output power as a function of the absorbed pump power is shown in Fig. 2. The highest efficiency operation was achieved at the transmissivity of 29%, and a laser maximum output power equal to 9.4 W with a slope efficiency of 56.8% was obtained when the absorbed pump power was 18.8 W. With a transmissivity of 20%, the maximum output power was 8.7 W when the absorbed pump power was 18.8 W. The slope efficiency was 51.6%. With a transmissivity of 51% and at the same absorbed pump power, a maximum output power equal to 7.4 W with a slope efficiency of 46.7% was obtained. We recorded the output wavelength of the Ho:YAP laser employing a WA-650 EXFO spectrum analyzer combined with a WA-1500 EXFO wavelength meter. As shown in Fig. 3, the output laser wavelength was centered at 2118.1 nm with FWHM of ~0.3 nm. The Ho:YAP laser emission wavelength does not depend on the reflectivity of the output coupler, which was observed for output transmission of 20%, 29% and 51%, respectively.

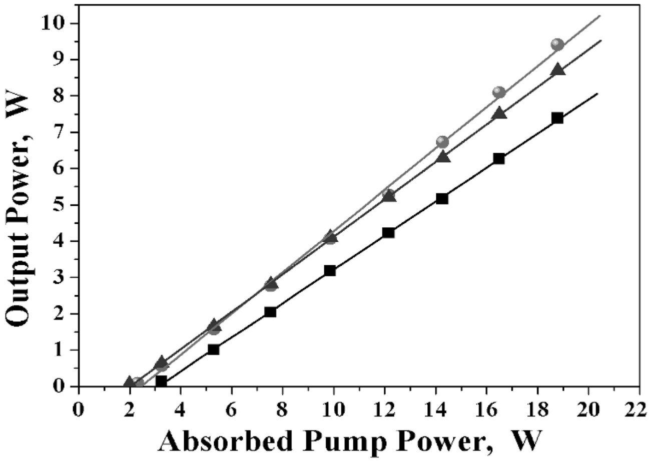

Fig. 2. The CW output power of the a-cut Ho:YAP laser with transmissivity $T = 20\%$ (▲), $T = 29\%$ (●), and $T = 51\%$ (■).

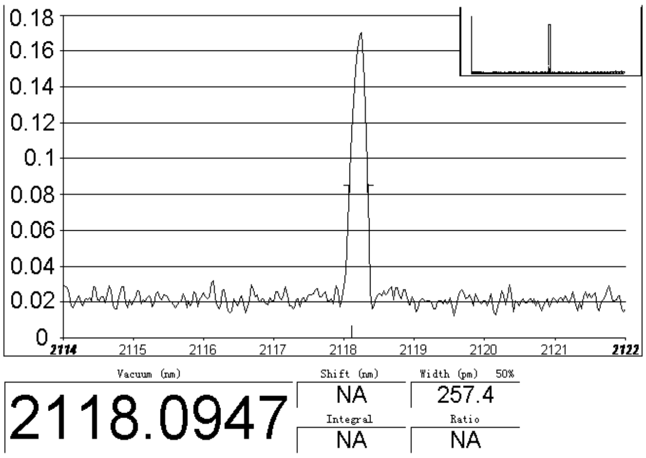

Fig. 3. Output spectrum of the a-cut Ho:YAP laser at a transmissivity of 29%.

We investigated the laser performance of the a-cut Ho:YAP crystal in the CW and Q-switched regimes using an optimized output transmission of 29%. The output power as a function of the absorbed pump power is shown in Fig. 4. The maximum CW output power was 17.2 W at an absorbed pump power of 29.8 W, corresponding to a slope efficiency of 63.2%. Operating at the Q-switched mode, the Ho:YAP laser provided an average output power of 16.5 W under an absorbed pump power of 29.8 W at a repetition rate of 10 kHz, corresponding to a slope efficiency of 61.4%. The Q-switched laser pulses were detected by an InGaAs photodiode and recorded with a 350 MHz Wavejet 332, LeCroy digital oscilloscope. In Fig. 5, we show the dependence of the laser pulse width on the absorbed pump power at a fixed repetition rate of 10 kHz.

The pulse width decreases sharply when the incident pump power increases. As a result, the minimum pulse width was 24 ns at 10 kHz repetition rate when the incident pump power was 29.8 W; its profile is shown in Fig. 6. The energy per pulse was about 1.7 mJ, corresponding to a peak power of ~70.8 kW. We

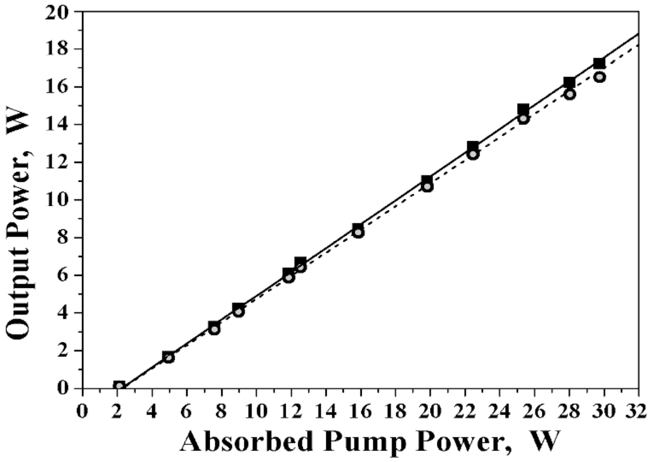

Fig. 4. The CW (■) and 10 kHz repetition-rate (●) output powers of the *a*-cut Ho:YAP laser.

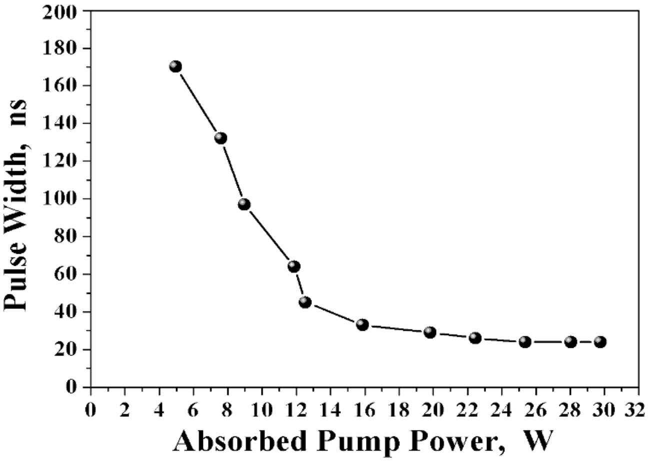

Fig. 5. The pulse width of the *a*-cut Ho:YAP laser vs the absorbed pump power at a repetition rate of 10 kHz.

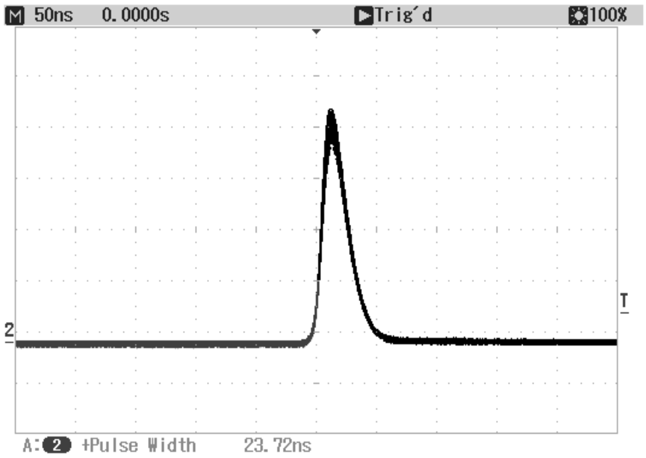

Fig. 6. Pulse profile of the minimum pulse width at 10 kHz.

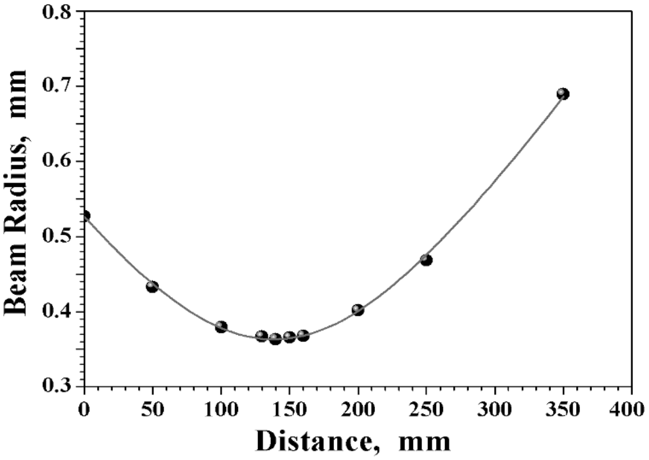

Fig. 7. Beam quality determination for the *a*-cut Ho:YAP laser at the maximum output power.

measured the output-beam radius at 10 kHz using the 90/10 knife-edge technique at several positions. By fitting the Gaussian-beam standard expression to these data, we estimate the beam quality as $M^2 \sim 1.5$.

4. Summary

In conclusion, we demonstrated a room-temperature efficient CW and Q-switched a-cut Ho:YAP laser double-pass-pumped by a diode-pumped Tm:YLF laser. At the CW regime, we achieved the maximum output power equal to 17.2 W at a slope efficiency of 63.2% under an absorbed pump power of 29.8 W. In the Q-switched mode, we obtained a maximum energy per pulse equal to ∼1.7 mJ at a repetition rate of 10 kHz and an average output power of 16.5 W with a pulse width of 24 ns. This result is better than available in the literature for Ho:YAP lasers, to our knowledge. Our laser operates in a single mode TEM_{00} with a beam quality factor of $M^2 \sim 1.5$, which was demonstrated by a knife-edge method.

Acknowledgments

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