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Room temperature efficient continuous wave and Q-switched operation of a Ho:YAP laser

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Abstract We report the continuous wave and acousto-optically Q-switched operation of a Tm:YLF-pumped Ho:YAP laser at room temperature. Continuous wave output power of 6.8 W at 2118 nm was obtained under the incident pump power of 13.4 W, corresponding to a slope efficiency of 65.6% and a conversion efficiency of 50.7%. For the Q-switched mode, a maximum pulse energy of 1.28 mJ and a minimum pulse width of 31 ns at the repetition rate of 5 kHz were achieved, resulting in a peak power of 41.3 kW. In addition, the Ho:YAP laser was employed as a pumping source of ZGP optical parametric oscillator, the total average output power of which was 3.2 W at 4.08 and 4.41 μm with a slope efficiency of 69.5%, corresponding to the diode-to-mid-IR conversion efficiency of 9.0%.

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1 Introduction

Solid-state lasers at 2 μm have applications in remote sensing, medicine, and as pump sources for mid-IR optical parametric oscillators [1, 2]. The rare-earth-ion thulium (Tm^{3+}) and holmium (Ho^{3+}) co-doping materials are commonly used to obtain the 2 μm laser. However, liquid-nitrogen cooling has to be used in these lasers in order to achieve a high efficiency laser output [3–5]. In recent years, with the development of 1.9-μm laser as an efficient pump source, 2-μm lasers based on holmium (Ho) ions have become prominent in these applications. Direct (inband) pumping Ho $^5I_7$ manifold offers several advantages, including high quantum efficiency, minimal heating, as well as reduced upconversion losses compared to Tm-sensitized material. High efficiency Ho lasers based on several hosts such as $Y_3Al_5O_{12}$ (YAG), $LiYF_4$ (YLF), and $Lu_3Al_5O_{12}$ (LuAG) were reported [6–9]. Among rare-earth doped host materials, $YAlO_3$ (YAP) was chosen for study as a promising efficient singly-doped laser material. YAP crystallizes in the orthorhombic space group Pbnm (D_{2h}^{16}) and this low symmetry (as compared to cubic YAG) has two important consequences: anisotropic luminescence and linearly polarized laser emission [10]. In addition, properties of YAP are similar to those of YAG [11], and YAP favors laser operation at high power level without the thermally induced birefringence. Lasing of Tm:YAP [12] and Tm, Ho:YAP [13] have been reported. The spectral characteristics and room-temperature laser actions of Ho:YAP laser were investigated, and continuous wave (CW) output power of 5.5 W with 47% slope efficiency in incident pump power of the 1 at.% Ho:YAP crystal was obtained [14].

In this paper, we demonstrate an efficient CW and Q-switched Ho:YAP laser double-pass pumped by a diode-pumped Tm:YLF laser at room temperature. A slope efficiency of 65.6% and a conversion efficiency of 50.7% were obtained with CW output power of 6.8 W under the incident pump power of 13.4 W. A repetitively Q-switched laser achieved an average output power of 6.4 W at 5 kHz, corresponding to a slope efficiency of 59.8% and a conversion efficiency of 46.4%. In addition, using the Ho:YAP laser as a pumping source of ZGP optical parametric oscillator, the total average output power of 3.2 W at 4.08 and 4.41 μm was achieved.

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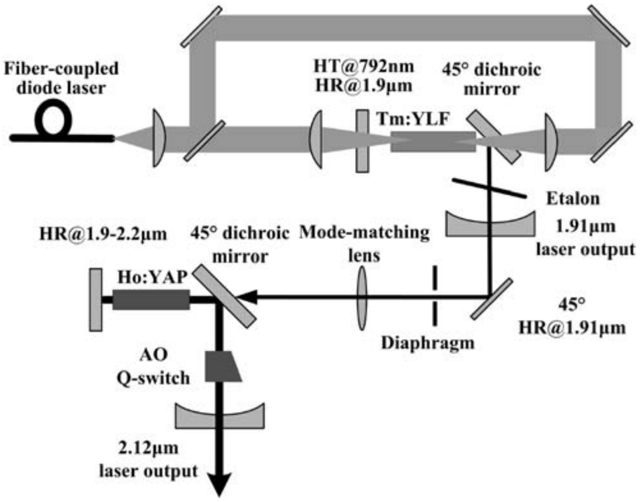

Fig. 1 Experimental setup of the Ho:YAP laser at room temperature

2 Experimental setup

The experimental configuration is shown in the Fig. 1. A diode-pumped Tm:YLF laser with emission wavelength of 1.91 µm was utilized as a pump source of Ho:YAP laser, since other high power lasers coinciding with the absorption peaks of Ho:YAP were not available to us. Tm:YLF crystal for the experiment was a-cut with dimensions of $3 \times 3 \times 12\ \text{mm}^3$, and the doped concentration was 4 at.%. The pump source of Tm:YLF laser was a 60 W laser diode (MIF4S22-793.3-60C-H200H, DILAS) coupled by a fiber with core-diameter of 400 µm and numerical aperture of 0.22. By use of dual-end-pumped configuration, the pump waist was imaged to 360 µm, which is positioned ∼4 mm inside the Tm:YLF crystal. Considering the transmission losses, nearly 90% of the pump power was incident onto the Tm:YLF crystal. The Tm:YLF laser resonator was folded with a physical cavity length of 130 mm. The output coupler coated with 22% transmittance at 1.91 µm was a plano-concave mirror with radius of curvature of 300 mm. A quartz etalon (0.1 mm in thickness) was used to tune the Tm:YLF lasing at 1.91 µm. The Ho laser performance was influenced by the energy transfer upconversion (ETU) losses [15]. One way to alleviate ETU is to lower the Ho^{3+} dopant concentrations. This will not only improve the Ho laser efficiency, but also reduce thermal loading of the laser crystal. Therefore, we used Ho:YAP crystal with low Ho^{3+} concentrations in this work. YAP crystal with 0.5 at.% Ho^{3+} concentration was grown by the Czochralski technique. The Ho:YAP crystal for the experiment was 35 mm in length and $4 \times 4\ \text{mm}^2$ in cross-section. Both end faces of the crystal were antireflection coated for the laser wavelengths around 2.1 µm and the pump wavelength around 1.91 µm. The absorption coefficient of Ho:YAP at 1.91 µm was about $0.36\ \text{cm}^{-1}$, implying nearly 92% double-pass pump absorption by the crystal. The laser crystal was wrapped in indium foil and clamped in a copper crystal-holder held at a temperature of 15°C with a thermoelectric cooler. The Ho:YAP laser resonator was folded with a physical cavity length of 100 mm. The flat mirror was high reflectivity ($R > 99\%$) in the wavelength range 1.9–2.2 µm. Flat 45° dichroic mirror was high reflection ($R > 99.5\%$) at 2.12 µm and high transmission ($T \sim 97\%$) for p-polarized in the wavelength range 1.9–1.92 µm. Considering the transmission losses, nearly 95% of the Tm pump power input to the Ho:YAP crystal. The output coupler coated with 52% transmittance at 2.12 µm was a plano-concave mirror with radius of curvature of 120 mm. The calculated TEM_{00} beam diameter was about 400 µm in the Ho:YAP crystal. The radiation of Tm pump was focused to fill the mode volume of the Ho:YAP resonator. As a result, the good overlap of the pump-to-Ho-resonator mode was achieved. Using a knife edge, we measured the pump spot at the input surface of the Ho:YAP crystal to be approximately 450 µm in diameter, and the diameter of pump beam stayed nearly unchanged over the length of the Ho crystal. Q-switching experiments were 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 kHz to 50 kHz. To prevent Tm:YLF laser from being influenced by the feedback, a diaphragm was placed into the pump path, and the axis of Ho resonator was misaligned from the pump axis by approximately 10 mrad.

3 Experimental results

The power meter used in the experiment was Coherent PM30. For Tm:YLF laser, under incident LD power of 39.3 W, the maximum power of 15.0 W was achieved with the crystal temperature at 18°C. The beam quality factor was measured at 15 W output power, and the value of $M^2 \sim 1.1$ was estimated. For Ho:YAP laser, the output power as a function of the 1.91 µm pump power is illustrated in Fig. 2. The maximum CW output power was 6.8 W under the incident pump power of 13.4 W, corresponding to a Tm-to-Ho conversion efficiency of 50.7% and a slope efficiency of 65.6%. Operating at Q-switched mode, the Ho:YAP laser achieved 6.4 W average output power under the incident Tm pump power of 13.8 W at repetition rate of 5 kHz, corresponding to a conversion efficiency of 46.4% and a slope efficiency of 59.8%. The dependence of the CW output power of the Ho:YAP laser on the temperature of the crystal-holder at an incident pump power of 13.4 W has been measured as shown in Fig. 3. The output power decreased from 6.98 W to 6.0 W as the crystal-holder temperature was increased from 10°C to 30°C. The data show approximately 14% change in output within the temperature range

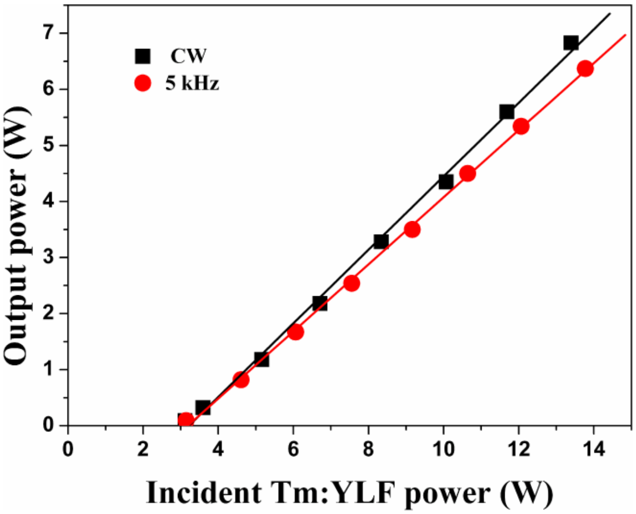

Fig. 2 The CW and 5 kHz repetition rate output power of Ho:YAP laser at room temperature

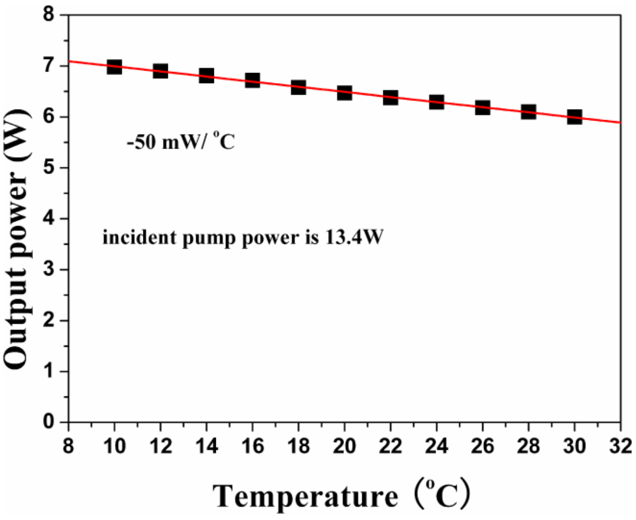

Fig. 3 Output power as a function of temperature of crystal-holder

measured. A simple linear fit to the data yields a slope of Ho:YAP laser output versus a crystal-holder temperature of −50 mW/°C, indicating that the 1.91 µm-pumped Ho:YAP laser possesses a very low sensitivity of output over room temperature.

The Q-switched laser pulse was detected by an InGaAs photodiode and recorded with a 350 MHz digital oscilloscope (wavejet 332, Lecroy). At the fixed repetition rate of 5 kHz, the dependence of laser pulse width on incident pump power was measured and is shown in Fig. 4. The pulse width shortens sharply when the incident pump power increases. As a result, the minimum pulse width was 31 ns at PRF of 5 kHz when the incident pump power was 13.4 W, the profile of which can be seen in Fig. 5. The energy per pulse was 1.28 mJ, corresponding to a peak power of approximately 41.3 kW.

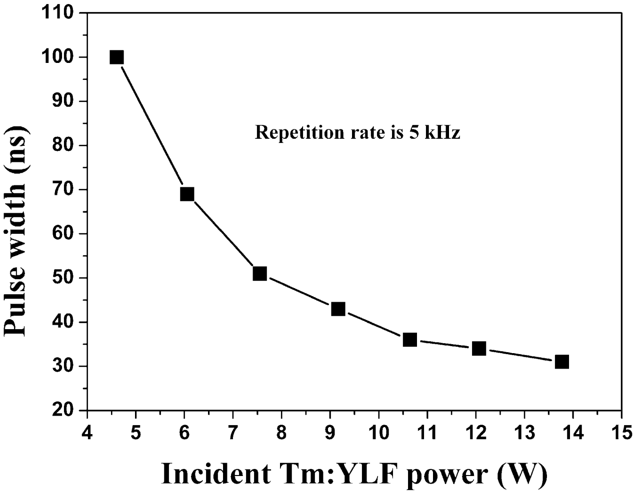

Fig. 4 The pulse width versus incident pump power at repetition rate of 5 kHz

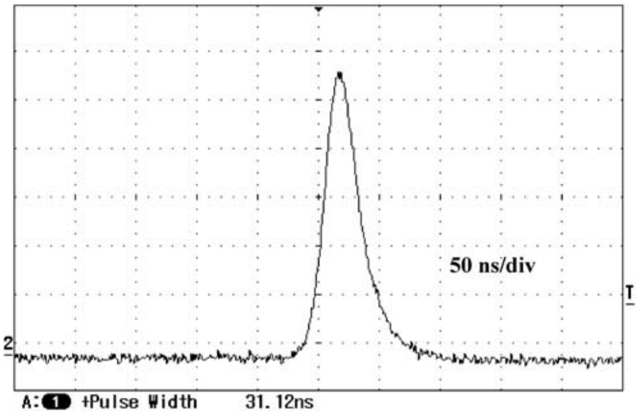

Fig. 5 Pulse profile of minimum pulse width at 5 kHz

The output wavelength of Ho:YAP laser was recorded with a spectrum analyzer (WA-650, EXFO) combined to a wavemeter (WA-1500, EXFO). As is shown in Fig. 6, the output laser wavelength was centered at 2118.25 nm with FWHM of about 0.5 nm. The output wavelength at different pump power levels and cooling temperatures was also investigated. No visible wavelength shifts were observed. It shows that the output wavelength is not sensitive to the change of laser crystal temperature. The output beam radius at 5 kHz was measured by a 90/10 knife-edge technique at several positions through a waist formed by a lens ($f = 200$ mm). By fitting the Gaussian beam standard expression to these data, we estimate the beam quality to be $M^2 \sim 1.3$.

An important application of 2-µm lasers is used for pumping $\mathrm{ZnGeP_2}$ (ZGP) optical parametric oscillators (OPOs) which generate mid-infrared sources. At room-temperature available pump sources for ZGP-OPO are the Q-switched Ho:YAG (2.09 µm) [16–18], Ho:YLF (2.05 µm)

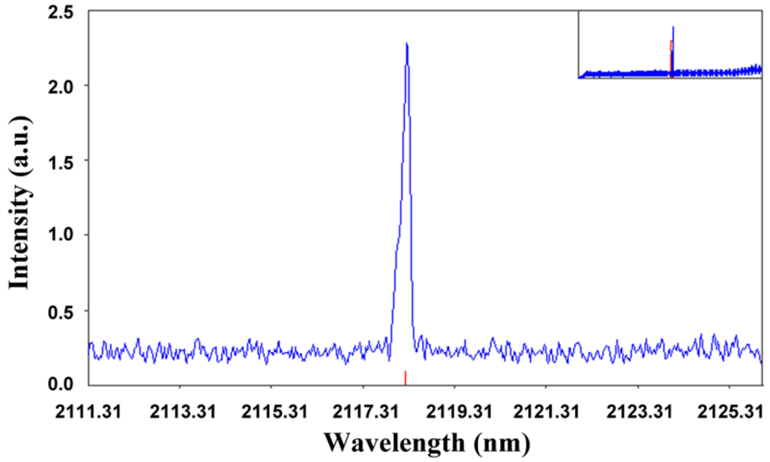

Fig. 6 Output spectrum of Ho:YAP laser at $T = 52\%$

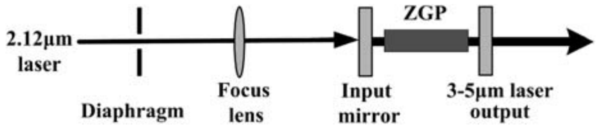

Fig. 7 Schematic of the ZGP-OPO pumped by Ho:YAP laser at room temperature

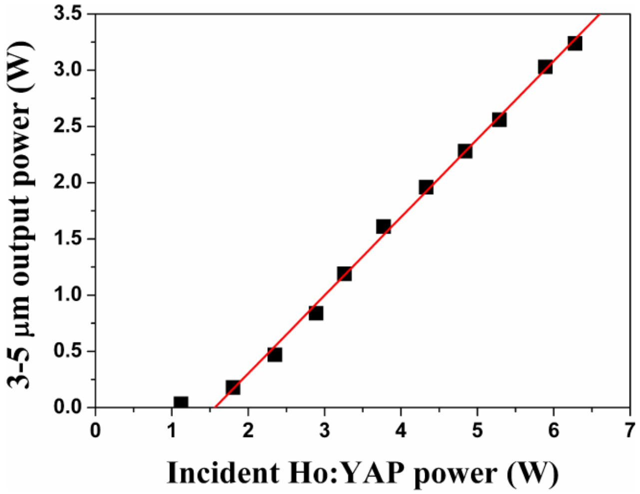

Fig. 8 Output power from ZGP-OPO as a function of pumping power

[19], and 2-μm fiber laser [20]. Emission wavelength of Ho:YAP laser is longer than for these lasers, resulting in lower background absorption of the ZGP crystal [21]. Using the Ho:YAP laser as a pumping source, we demonstrated a ZGP-OPO operating at room temperature. The experimental setup configuration of Ho:YAP laser pumping ZGP-OPO laser is shown in Fig. 7. The ZGP crystal (EKSPLA Ltd.) cut was type I phase matching at 55° in order to achieve the desired wavelengths. Both surfaces were antireflection coated at 2.1 μm and in the range of 3–5 μm, and the crystal dimensions were 6 mm × 8 mm × 15 mm. The measured absorption coefficient for o-light of the used ZGP crystal at output wavelength of Ho:YAP laser was about 0.06 cm^{-1}. The ZGP-OPO's resonator used two flat mirrors arranged as a linear cavity and configured as a doubly resonant oscillator (DRO); this provided simultaneous feedback for both signal and idler waves. The input dichroic mirror was coated HT at the 2.1 μm, and HR in the range of 3.5–4.5 μm. The output coupler was coated HR at the 2.1 μm and had reflectivity approximately 50% across the entire 3–5 μm region. The physical resonator length was approximately 23 mm. The output from the Ho:YAP laser was focused with a lens ($f = 150$ mm) to a diameter of approximately 0.7 mm inside the ZGP crystal. The OPO is thus doubly resonant and double-pass pumped. To prevent Ho:YAP laser from being influenced by the feedback, a diaphragm was placed into the pump path, and the OPO resonator's axis was misaligned from the pump axis by approximately 7 mrad.

Figure 8 shows the OPO output performance, output power is the combined sum of the signal (4.08 μm) and idler (4.41 μm), both in the mid-IR. At the pump power of 6.3 W incident upon the ZGP crystal, the maximum average output power reached 3.2 W with an overall optical-optical conversion efficiency of 50.8%, operating at 5.6 times the threshold. A linear fit to the data shows that a slope efficiency of 69.5%. The laser diode-to-mid-IR conversion was 9.0%. The fluctuation of the average output power at maximum output point was approximately 2.0% in the given 10 min. The spectral content of ZGP-OPO output was measured with a 300 mm monochromator and a HgCdTe detector. We observed a broad spectrum envelope with a FWHM of approximately 140 nm for the signal and 130 nm for the idler (shown in Fig. 9). Both signal and idler signatures contained a periodic structure, and we attribute the structure to the clustering effect [22] present in the DRO geometry. The M^2 values of the ZGP-OPO was measured by 90/10 knife-edge technique at maximum output power. We estimated that $M^2 \sim 6.6$ in the x-direction, and 3.7 in the y-direction (combined signal and idler beams). Appropriate adjusting of the input mirror of ZGP-OPO could reduce the difference

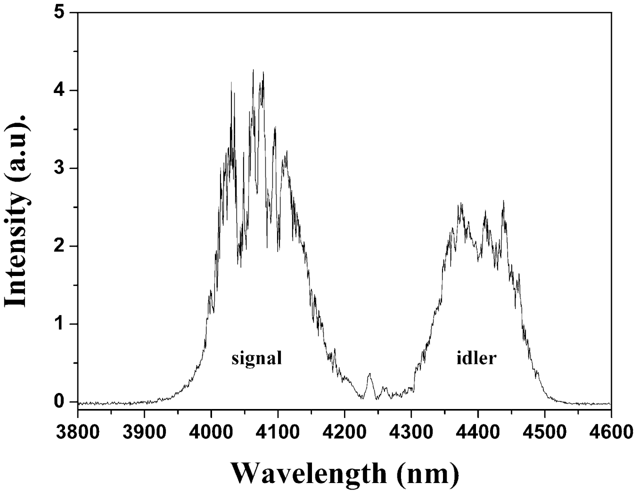

Fig. 9 Spectra of signal and idler from ZGP-OPO

between M_x^2 and M_y^2, but this may increase the threshold and reduce the efficiency of the laser. If the recycling pump beam could well overlap the incident pump beam, the beam quality in both directions and the efficiency of ZGP-OPO would be improved [17].

4 Conclusion

In conclusion, we have demonstrated a room temperature efficient continuous wave and Q-switched Ho:YAP laser double-pass pumped by a diode-pumped Tm:YLF laser. In the continuous wave mode, we achieved the maximum output power of 6.8 W and a slope efficiency of 65.6%. In the Q-switched mode with high PRF, we achieved the maximum 1.28 mJ energy per pulse at 5 kHz, and 6.4 W average output power with pulse width of 31 ns. The laser operated at a single mode (TEM_{00}) with a beam quality factor of $M^2 \sim 1.3$, which was demonstrated by a knife-edge method. In addition, our experiment shows that Ho:YAP laser is an excellent pumping source for the ZGP optical parametric oscillator.

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