Room temperature efficient actively Q-switched Ho:YAP laser

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Abstract: We report on efficient actively Q-switched Ho:YAP laser double-pass pumped by a 1.91-μm laser. At room temperature, when the incident pump power was 20.9 W, a maximum average output power of 10.9 W at 2118 nm was obtained at the repetition rate of 10 kHz, and this corresponds to a conversion efficiency of 52.2% and a slope efficiency of 63.5%. Moreover, a maximum pulse energy of ~1.1 mJ and a minimum pulse width of 31 ns were achieved, with the peak power of 35.5 kW.

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References and links


1. Introduction

Solid-state 2-μm lasers are useful for a variety of scientific and technical applications. Also, they are efficient pump sources for mid-infrared optical parametric oscillators[1,2]. The rare-earth-ion thulium (Tm³⁺) and holmium (Ho³⁺) co-doping materials, which work as quasi-three-level laser systems, are commonly used to obtain the 2-μm laser. However, in order to achieve a high power laser output, they need to operate at 77 K[3–6]. At present, 2-μm lasers based on holmium (Ho) ions have become prominent in these applications with the development of the 1.9-μm laser as an efficient pump source. Direct (in-band) pumping Ho⁵I⁷ manifold offers the advantages of high quantum efficiency, minimal heating due to low quantum defect between pump and laser of ~10%, and reduced upconversion losses caused by Tm sensitized. Budni et al. reported 18.8 W of continuous wave (CW) Ho:YAG output with an M²≈1.48 pumped by a Tm:YLF laser, corresponding to a Tm-to-Ho optical conversion efficiency of 56%[7]. Schellhorn reported a CW output power of 9.4 W Ho:YAG thin-disc laser with an M²≈5.2 pumped by a diode-pumped Tm:YLF laser, corresponding to a slope efficiency of 40% and an optical-to-optical efficiency of 36% with respect to the incident pump power[8]. Lippert et al. reported 9.8 W of Ho:YAG output at a 20 kHz pulse repetition rate with M²<1.1 pumped by a 15W thulium-doped fiber laser emitting at 1907 nm[9]. Dergachev et al. reported 25 W of CW Ho:YLF output pumped by a 60W thulium-doped fiber laser emitting at 1940 nm, corresponding to optical-to-optical efficiency of 42%[10]. In addition, Hart et al. demonstrated a room-temperature high efficient Ho: LuAG laser operating at 2.1 μm [11].

Among rare-earth doped host materials, Yttrium aluminium oxide (YAlO₃, YAP) was chosen for study as a promising efficient singly doped laser material. YAP is a biaxial crystal possessing orthorhombic structure. Its natural birefringence combined with good thermal and mechanical properties similar to those of YAG[12]. The spectral characteristics and laser actions of Ho:YAP was investigated, CW output power of 5.5W with 47% slope efficiency relative to the incident pump power of the 1 at.% Ho:YAP crystal was obtained [13].

In this paper, we present an efficient Q-switched Ho:YAP laser double-pass pumped by a diode-pumped Tm:YLF laser at room temperature. A slope efficiency of 65.3% and a conversion efficiency of 53.6% were obtained with CW output power of 11.2 W under the incident pump power of 38.5 W. With the same incident pump power, a maximum average output power of 10.9W was obtained at the repetition rate of 10 kHz, and this corresponds to a conversion efficiency of 52.2% and a slope efficiency of 63.5%.

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 is utilized as a pump source of Ho:YAP laser, since other high power lasers coinciding with the absorption peaks of Ho:YAP are not available to us. Tm:YLF crystal for the experiment is a-cut with dimensions of 3x3x12 mm³, and the doped concentration is 4 at. %. The pump source of Tm:YLF laser is 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 is imaged to 360 μm, which is positioned ~ 4mm inside the Tm:YLF crystal. Considering the transmission losses, nearly 90% of the pump power input to the Tm:YLF crystal. The Tm:YLF laser resonator is folded with a physical cavity length of 130 mm. The output coupler coated with...
22% transmittance at 1.91 μm is a plano-concave mirror with radius of curvature of 300 mm. A quartz etalon (0.1 mm in thickness) is used to tune the Tm:YLF lasing at 1.91μm.

Compared with our previous work, we used Ho crystal with lower dopand concentration in this paper. Low Ho\3+ concentrations result in lower rates of ETU (energy transfer upconversion), which has significant impact on the laser performance [14], as well as reducing thermal loading. YAP crystal with 0.5 at. % Ho\3+ concentration is grown by the Czochralski technique. The Ho:YAP crystal for the experiment is 35mm in length and 4x4 mm\2 in cross section. The laser-through faces of crystal are polished plane and coated at both 1.91 μm and 2.12 μm with reflectivity < 0.5%. The absorption coefficient of Ho:YAP at 1.91 μm is about 0.36 cm\1, implying nearly 92% double-pass pump absorption by the crystal. The 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 Ho:YAP laser resonator is folded with a physical cavity length of 100 mm. The flat mirror is high reflectivity (R >99%) in the wavelength range 1.9-2.2 μm. Flat 45° dichroic mirror is high reflection (R>99.5%) at 2.12 μm and high transmission (T>97%) at the p-polarized in the wavelength range 1.9-1.92μm. The output coupler coated with 52% transmittance at 2.12 μm is a plano-concave mirror with radius of curvature of 120 mm. The calculated TEM\00 beam diameter is about 400 μm in the Ho:YAP crystal. The pump spot at the input surface of the Ho:YAP crystal is approximately 450 μm in diameter. As a result, the good overlap of the pump-to-Ho-resonator mode is achieved. Considering the transmission losses, nearly 95% of the Tm power is injected into the Ho:YAP crystal. Q-switching experiments are achieved with a 46 mm long fused silica acousto-optical (A-O) Q-switch (QS041-10M-H17, Gooch & Housengo). 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 is placed into the pump path, and the Ho resonator’s axis is misaligned from the pump axis by approximately 10 mrad.

3. Results and discussion

The power meter used in the experiment was Coherent PM30. Under incident diode power of 55.1 W, the Tm:YLF laser output power of 22.3 W was achieved with M\2 ~1.2 when the crystal temperature was 18 °C. The output power of Ho:YAP laser as a function of the 1.91-μm pump power is illustrated in Fig. 2. The maximum CW output power was 11.2 W under crystal temperature was 18 °C. The output power of Ho:YAP laser as a function of the 1.91-μm pump power is illustrated in Fig. 2. The maximum CW output power was 11.2 W under crystal temperature was 18 °C. The output power of Ho:YAP laser as a function of the 1.91-μm pump power is illustrated in Fig. 2. The maximum CW output power was 11.2 W under crystal temperature was 18 °C. The output power of Ho:YAP laser as a function of the 1.91-μm pump power is illustrated in Fig. 2. The maximum CW output power was 11.2 W under crystal temperature was 18 °C. The output power of Ho:YAP laser as a function of the 1.91-μm pump power is illustrated in Fig. 2. The maximum CW output power was 11.2 W under crystal temperature was 18 °C. The output power of Ho:YAP laser as a function of the 1.91-μm pump power is illustrated in Fig. 2. The maximum CW output power was 11.2 W under crystal temperature was 18 °C. The output power of Ho:YAP laser as a function of the 1.91-μm pump power is illustrated in Fig. 2. The maximum CW output power was 11.2 W under crystal temperature was 18 °C. The output power of Ho:YAP laser as a function of the 1.91-μm pump power is illustrated in Fig. 2. The maximum CW output power was 11.2 W under crystal temperature was 18 °C. The output power of Ho:YAP laser as a function of the 1.91-μm pump power is illustrated in Fig. 2. The maximum CW output power was 11.2 W under crystal temperature was 18 °C.
and measured the beam radius along the propagation direction at full Q-switched laser power. By fitting Gaussian beam standard expression to these data, we estimate the beam quality to be $M^2 \sim 1.44$. Compared to Tm, Ho-codoped laser, this gives several advantages. First, with a low quantum defect, the laser’s slope efficiency could potentially be increased. Second, reduced the heat deposited in the laser medium, leading to increased beam quality and tolerance to high pump intensities. Third, reduced cooperative upconversion losses between Tm and Ho ions result in a significant increase in the effective upper level lifetime.

![Figure 2](image)

Fig. 2. The CW and 10 kHz repetition rate output power of Ho:YAP laser

![Figure 3](image)

Fig. 3. Output spectrum of Ho:YAP laser at $T = 52\%$. Inset, energy levels schematic of Ho:YAP

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. 3, the output laser wavelength was centered at 2118.25 nm with FWHM of about 0.5 nm. According to energy levels of Ho:YAP at 15 K[15], 2118 nm laser transfers from the 5187 cm$^{-1}$ level of $^3I_7$ manifold to 465 cm$^{-1}$ level of the $^3I_8$ manifold (illustrated in Fig. 3). This indicates Ho:YAP laser is a quasi-two-level system [16]. The laser was pumped at 1.91 µm and lased at 2118 nm, which yielded a very low quantum defect of ~11%. The slope efficiency relative to the absorbed power achieved represents value of quantum efficiency greater than 80%. One possible reason why the limit was not achieved is the photon avalanche upconversion process in Ho:YAP. The results of Ref. [15] revealed that the dominant green fluorescence in Ho:YAP crystal utilized a 584.3nm excitation source. In the experiment, we measured the upconversion spectrum of 2% and 1% Ho$^{3+}$ doped YAP crystal excited by a Tm:YLF laser from 400nm to 1000nm at room temperature. The spectrometer used was Ocean Optics HR-4000CG-UV-NIR. As is shown in Fig. 4, the spectrum exhibited low intensity signal centered around 545nm corresponding to the $^3S_2 \rightarrow ^1I_5$ transition, and intense emissions centered around 657 and 893nm corresponding to the $^3F_5 \rightarrow ^1I_6$ and $^3I_6 \rightarrow ^1I_8$ transitions, respectively. The upconversion excitation mechanism concerning the Ho$^{3+}$ excited-state levels is accomplished through a two/three-photon absorption, succeeded by cross-relaxation and excited-state absorption [17]. The 1.91µm pump photon nonresonantly excites Ho$^{3+}$ ions from the $^3I_7$ upper-level to the $^3I_8$ excited-state level which generates emission around 893nm. In this process, the participation of two/three host-phonons compensates for the energy mismatch of 850 cm$^{-1}$ between the
$^5\text{I}_7 \rightarrow ^5\text{I}_5$ transition and the pump photon energy. A second pump photon nonresonantly excites Ho$^{3+}$ ions from the $^5\text{I}_5$ to the $^5\text{F}_3$ excited-state level which generates the red emission around 657nm. Simultaneously, a 2118nm photon promotes some Ho$^{3+}$ ions from the $^5\text{F}_3$ level to the $^5\text{F}_3$ excited-state level, then relaxing to the $^5\text{S}_2$ level which generates the green emission around 545nm. In the experiment, we observed that the upconversion fluorescence intensity becomes weaker with the decrease of Ho$^{3+}$ concentration.

![Upconversion spectrum of Ho:YAP crystal at room temperature](image)

Fig. 4. Upconversion spectrum of Ho:YAP crystal at room temperature

The Q-switched laser pulse was detected by using an InGaAs photodiode and recorded with an oscilloscope (wavejet 332, Lecroy). At the fixed repetition rate of 10 kHz, the dependence of laser pulse width on incident pump power was measured and is shown in Fig. 5. The pulse width shortens sharply when the incident pump power increases. As a result, the pulse width was 31 ns at PRF of 10 kHz when the incident pump power was 20.9 W, the profile of which can be seen from Fig. 6. Furthermore, at the fixed incident pump power of 15.5W, we measured the dependence of laser pulse width on repetition rates. The pulse width increased greatly from 37 ns at 10 kHz to 133 ns at 50 kHz. Correspondingly, the peak power of the laser output decreased from 20.5 kW to 1.14 kW.

![Pulse width versus incident pump power at repetition rate of 10 kHz](image)

Fig. 5. Pulse width versus incident pump power at repetition rate of 10 kHz

![Pulse profile of minimum pulse width at 10 kHz](image)

Fig. 6. Pulse profile of minimum pulse width at 10 kHz
Fig. 7. Average output power of Ho:YAP laser as a function of temperature of crystal-holder. $P_{in}$, incident pump power.

The dependence of the output power (Q-switched at 10 kHz) of the Ho:YAP laser on the temperature of the crystal-holder at an incident pump power of 15.5 W has been measured as shown in Fig. 7. The average output power decreased from 8.1 W to 6.6 W as the crystal-holder temperature was increased from 5 °C to 30 °C. A simple linear fit to the data yields a slope of Ho:YAP laser output versus a crystal-holder temperature of −59 mW/°C, indicating that the 1.91 µm-pumped Ho:YAP laser possesses a low sensitivity of output over room temperature.

4. Conclusion

To summarize, we have demonstrated a room temperature efficient CW and Q-switched Ho:YAP laser double-pass pumped by a diode-pumped Tm:YLF laser. In CW mode, the maximum output power of 11.2 W and a slope efficiency of 65.3 % with respect to the incident pump power were achieved. In Q-switched mode with high PRF, we achieved the greater than 1 mJ energy per pulse at 10 kHz, and 10.9 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 $M^2$ ~ 1.44, which was demonstrated by a knife-edge method.

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