Continuous-wave operation of a room-temperature Tm:YAP-pumped Ho:YAG laser

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We report a continuous-wave (CW) 2.1-μm Ho:YAG laser operating at room temperature pumped by a diode-pumped 1.94-μm Tm:YAP laser. The maximum output power of 1.5 W is obtained from Ho:YAG laser, corresponding to Tm-to-Ho slope efficiency of 17.9% and diode-to-Ho conversion efficiency of 5.6%.

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High-power 2-μm lasers are useful for a variety of scientific and technical applications, including remote sensing and mid-infrared generation via pumping of optical parametric oscillators[1,2]. In addition, continuous-wave (CW) 2-μm lasers have significant potentials in laser welding of transparent plastic materials as well as laser surgery and therapy. Tm and Ho co-doped media with large emission cross section can meet the requirement of high peak power laser pulse operation at 77 K[3−6]. However, they also lead to very strong cooperative upconversion losses and hence a significant reduction in the effective upper level lifetime and increased thermal loading[7−9], so the Tm-Ho lasers are difficult to work at room temperature with high CW power. A diode pumped Tm(5.7%),Ho(0.36%):YAG laser with the maximum CW power of 0.42 W and slope efficiency of 19% was demonstrated by Galzerano *et al.*, but it suffered from the roll-off of slope efficiency and temperature sensitivity of the laser output[10]. One solution to this problem is to pump singly-doped Ho^{3+}:YAG in-band with a Tm-doped solid-state laser or fiber laser[11,12]. This approach has the advantage of very low quantum defect heating ($\sim$ 9% in Ho:YAG) with the result that high lasing efficiencies are attainable. In addition, the Ho storage lifetime is not affected by the pump intensity (gain)[13]. In 2000, a 33.7-W Tm:YLF laser pumped by a laser diode (LD) was used to generate 18.8-W Ho:YAG CW output, which represents a Tm:YLF to Ho:YAG optical-to-optical efficiency of 56%[14].

In this letter, we demonstrated a CW Ho:YAG laser pumped by a diode-pumped Tm:YAP laser at room temperature. The 1.94-μm Tm:YAP laser line was employed for reasonably pumping Ho:YAG in the $^5I_7$ and $^5I_8$ multifold. Tm:YAP crystal was grown by Laser and Optoelectronic Functional Material R and D Center, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences.

Absorption spectrum of Tm:YAP falls within the emission spectrum of commercially available laser diodes, emitting peak of 795 nm[15]. The emission spectrum of Tm:YAP (see Fig. 1) matches well with the absorption spectrum of Ho:YAG (Fig. 2). The peak emission cross-section lines (1.94 μm) of Tm:YAP are capable of pumping Ho:YAG efficiently.

The experimental setup is illustrated in Fig. 3. The Tm:YAP crystal for the experiment was c-cut with dimensions of 3 × 3 × 5 (mm), and had the dopant concentration of 4 at.-%. The end faces were polished plane and parallel, and anti-reflection (AR) coated at both 795 nm and 1.94 μm with reflectivity < 0.5%. The Tm:YAP crystal was end-pumped by a fiber-coupled LD array which delivered the maximum power of 25 W within the fiber with the core diameter of 200 μm and numerical apertures (NA) of 0.22. The emission wavelength of the

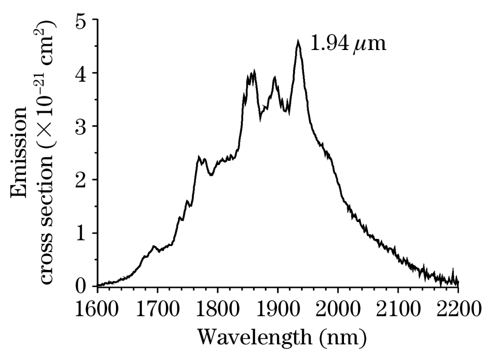

Fig. 1. Emission spectrum of 4%-Tm-doped YAP.

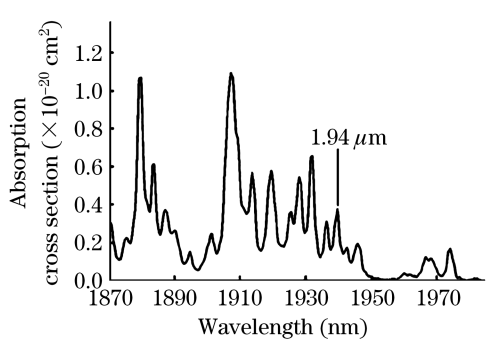

Fig. 2. Absorption spectrum of Ho:YAG.

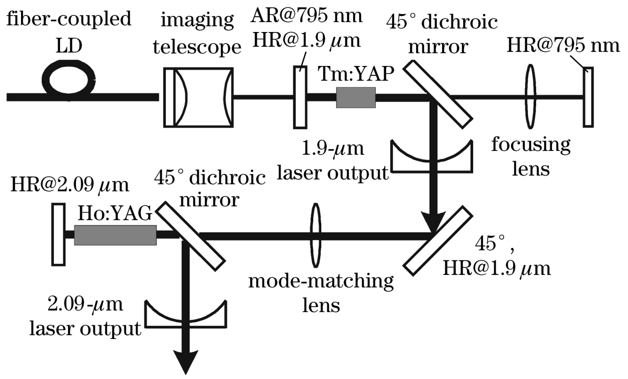

Fig. 3. Experimental setup of CW Ho:YAG laser pumped by a diode-pumped Tm:YAP laser at room temperature.

diode was 793.5 nm with full-width at half-maximum (FWHW) spectral width of 2 nm at 18 °C, and temperature tuned to 795 nm for optimal absorption and uniform thermal distribution along the length of Tm:YAP crystal. The resonator was a folded one with a cavity length of 30 mm. The output coupler was a plano-concave one with 250-mm radius of curvature, and was coated with 90% reflectivity at 1.94 μm. The depleted pump light transmitted through the 45° dichroic mirror ($R > 99.5\%$ at 1.94 μm and $T < 90\%$ at 795 nm), and was collected and refocused by the 55-mm focal length lens and high-reflection (HR) mirror at 795 nm.

With the focused pump beam size of 440 μm, the confocal distance ($2\pi n\omega_{\mathrm{p}}^2/M^2\lambda_{\mathrm{p}}$, where $n = 1.95$ is the refractive index of Tm:YAP, ω_{p} is the pump beam radius, $M^2 = 88$ is the pump beam quality factor, λ_{p} is the pump wavelength) is calculated to be 8.5 mm that is longer than the crystal length. The pump beam diameter is well mode-matched with the laser beam in the resonator, which is calculated to be 450 μm in diameter throughout the crystal length. Figure 4 shows the output power of Tm:YAP laser. Under the pumping power of 26 W available from the laser diode, the maximum power of 8.7 W was obtained with the crystal temperature kept at 18 °C. A linear regression fit to the data yielded a slope efficiency of 41%. A threshold pump power of 4 W was obtained.

The emission wavelength of Tm:YAP laser was measured with a WDG-30 monochrometer (300-mm focal length, 300 lines/mm grating blazed at 2 μm). The chopped light from exit slice was detected by a PbS detector connected with a TDS-3012B digital oscilloscope.

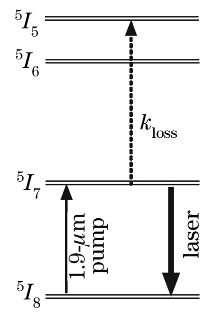

Fig. 5. Energy-level diagram for Ho:YAG laser.

The wavelength was located near 1935 – 1938 nm when a 10% transmission output coupler was used and the crystal temperature was kept at 18 °C during the measurement.

Ho:YAG is a quasi-two-level system at room temperature (see Fig. 5) whose upper lasing level is $^5I_7$ Ho manifold and the lower one is $^5I_8$ Ho manifold. The Ho:YAG laser crystal was 5 mm in diameter and 20 mm long, and doped with 1 at.-% holmium. The Ho:YAG laser resonator comprises an plane mirror with $R > 99.5\%$ at 2.1 μm, a 45° dichroic mirror with $R > 99.5\%$ at 2.1 μm and $T > 98\%$ at 1.94 μm, and an output coupler with $R = 95\%$ at 2.09 μm. The curvature radius of output coupler mirror is 200 mm, and the physical cavity length is about 116 mm, resulting in a TEM_{00} beam radius of 260 μm in the Ho:YAG crystal. The Ho laser crystal was mounted onto a copper heat sink, and the crystal-to-copper heat sink interface used was In foil. Cooling of the Ho:YAG crystal was carried out conductively at 10 °C. The Ho laser crystal was placed in the vicinity of the focus formed by the 200-mm focal length mode-matching lens used for the Tm:YAP laser brightness determination experiments (described above). The pump spot at the input surface of the Ho crystal was approximately 440 μm in diameter.

Figure 6 shows the Ho:YAG performance achieved during CW operation. The maximum output power was 1.5 W with 8.7-W Tm:YAP pump power. A linear fit to the data yields a slope efficiency of 17.9% with a threshold of approximately 0.8 W. The optical-to-optical conversion efficiency from Tm:YAP to Ho:YAG of 16.9% was obtained. Diode-to-Tm:YAP efficiency was approximately 33.4%, and diode-to-Ho:YAG efficiency was 5.6%. The lower efficiency was due to the weak absorption by

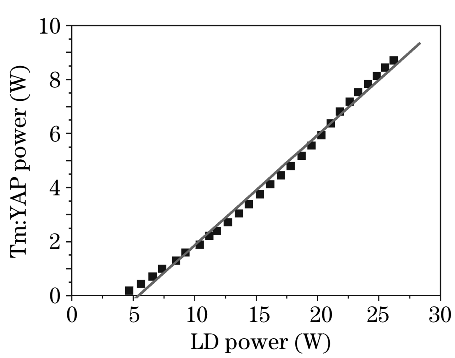

Fig. 4. Output power of Tm:YAP laser versus input LD power.

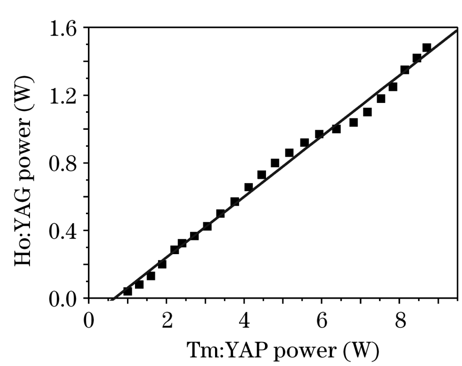

Fig. 6. Output power of Ho:YAG laser versus incident Tm:YAP power.

Ho:YAG at 1.94 μm, which is about 43%. A longer Ho crystal and double-pass pump configuration with an optical isolator could increase the conversion efficiency.

In summary, operation of a room temperature CW Ho:YAG laser pumped by a diode-pumped Tm:YAP laser was demonstrated. Output power greater than 1 W at 2.1 μm was achieved, corresponding to the diode-to-Ho laser efficiency of 5.6%. No roll-off of slope efficiency was observed in our experiment because of lower quantum defect between the wavelengths of Tm pumping absorption and Ho emission, which means that higher power from Ho laser can be obtained by simply increasing the Tm laser power.

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