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EVALUATION OF THE PERFORMANCE OF AN Ho:YAP LASER RESONANTLY PUMPED BY A THULIUM FIBER LASER

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Abstract

We investigate the continuous-wave performance of an Ho:YAP laser resonantly pumped by a Tm fiber laser at different output transmittance of 20%, 30%, and 50%. We use a 40 mm long a-cut crystal with 0.5 at.% Ho ion. Our experimental results show that the best power performance is obtained at an output transmittance of 30%. At an absorbed pump power of 12.1 W, we obtain a maximum output power of 6.1 W at 2118.1 nm with a slope efficiency of 63.4%. The laser operates at the TEM_{00} mode with a beam quality factor $M_2 \sim 1.5$ measured using a 90/10 knife-edge method.

Keywords: solid-state laser, resonant pump, Ho:YAP laser.

1. Introduction

Solid-state lasers at 2 μm have applications in remote sensing and medicine and also serve as pump sources for mid-infrared optical parametric oscillators. Since the 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. Tm,Ho co-doped laser materials can be high-power pumped by a commercial laser diode operating at 800 nm. However, cryogenic cooling must be used in these lasers to achieve high-efficiency laser output [1–3]. In recent years, with the development of the 1.9 μm laser as an efficient pump source, in-band pumped Ho lasers have avoided these drawbacks. The direct (in-band) pumping Ho $^5\mathrm{I}_7$ manifold offers several advantages, including high quantum efficiency, minimum heating and reduced up-conversion losses caused by sensitized Tm. To date, in-band pumping of singly-doped Ho lasers such as YAG [4–6], LuAG [7], YVO_4 [8], and YLF [9,10] have been reported.

Aside from these host materials, one of the most interesting crystals is yttrium aluminum oxide YAlO_3 (YAP, YAlO). YAP crystallizes in the orthorhombic space group, and this low symmetry (as compared to cubic YAG) has two important consequences: anisotropic luminescence and linearly polarized laser emission [11]. In addition, the properties of YAP are similar to those of YAG [12], and YAP is more suitable for 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 high-efficiency operation [13–17]. The broad absorption band of singly-doped Ho:YAP with multiple intense peaks at ∼1.9 μm [18] allows great flexibility in the selection of Tm-doped lasers for in-band pumping. Using a diode-pumped Tm:YLF laser operating at ∼1.9 μm as a pump source, the authors of [19–21] have demonstrated the laser performance

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of Ho:YAP crystal. Compared to the solid-state Tm:YLF laser, thulium-doped fiber lasers have many advantages, including high reliability, good beam quality, compact fabrication, wide tunable range, and heat dissipation. However, there is little information on the room-temperature Ho:YAP laser pumped by Tm-doped fiber lasers.

In this paper, using different output transmittances of 20%, 30%, and 50%, we demonstrate the continuous wave (CW) operation of an *a*-cut Ho:YAP laser in-band pumped by a thulium fiber laser at 1910 nm. Maximum output power of 6.1 W at 2118.1 nm was obtained under an absorbed pump power of 12.1 W, corresponding to a slope efficiency of 63.4%.

2. Experimental Setup

The experimental setup of the Ho:YAP laser pumped by Tm-doped silica fiber laser is schematically shown in Fig. 1. A Tm-doped fiber was pumped by a 60 W laser diode at 793 nm with a 200 μm pigtail fiber coupling output. The FBG is inscribed using a 248 nm excimer laser and a phase mask in hydrogen-loaded photosensitive fiber. The fiber is 25/250 μm, and the FBG wavelength is 1910 nm. The Tm-doped silica fiber used in the experiment is made by Nufern. The core diameter and numerical aperture of the Tm-doped silica fiber are 25 μm and 0.1, respectively. The length is about 2 m, and the Tm-doped concentration is 2.0 wt. %. The core diameter and numerical aperture of the fiber are 250 μm and 0.46, respectively.

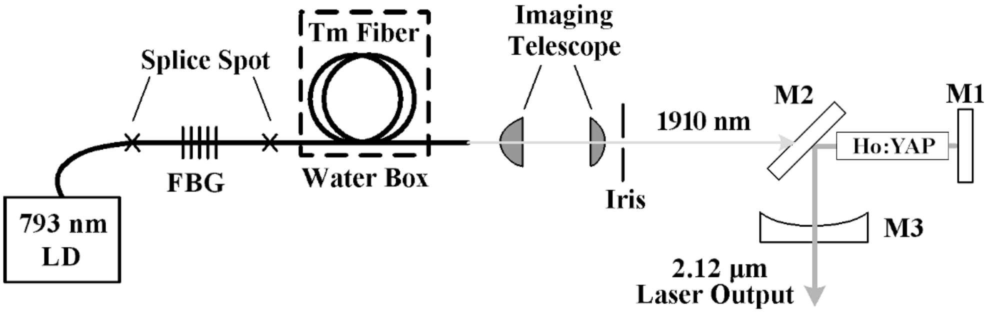

Fig. 1. Experimental setup of the Ho:YAP laser pumped by a thulium fiber laser.

The YAP crystal with 0.5 at. % Ho^{3+} concentration is grown by the Czochralski technique. The *a*-cut Ho:YAP crystal rod with 5 mm diameter has a length of 40 mm. Both end faces of the crystal are antireflection-coated for the laser and pump wavelengths. The laser crystal is wrapped in the indium foil and clamped in a copper crystal-holder held at a temperature of 20°C with a thermoelectric cooler. The actual fraction of the incident power absorbed by the Ho:YAP laser measured near threshold is 70%. 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 \approx$ 95%) at 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 cavity physical length is 65 mm. The calculated TEM_{00} beam diameter is $\sim$430 μm in the Ho:YAP crystal. The 1910 nm pumping light is focused onto the crystal with an approximate beam diameter of 500 μm using an imaging telescope. The pump-beam diameter is nearly unchanged over the Ho crystal length. As a result, a fairly good overlap of the pump-to-Ho-resonator mode is achieved. To shield the Tm fiber laser from the influence of feedback, an iris diaphragm is placed in the pump path, with the Ho-resonator axis misaligned from the pump axis by several mrad.

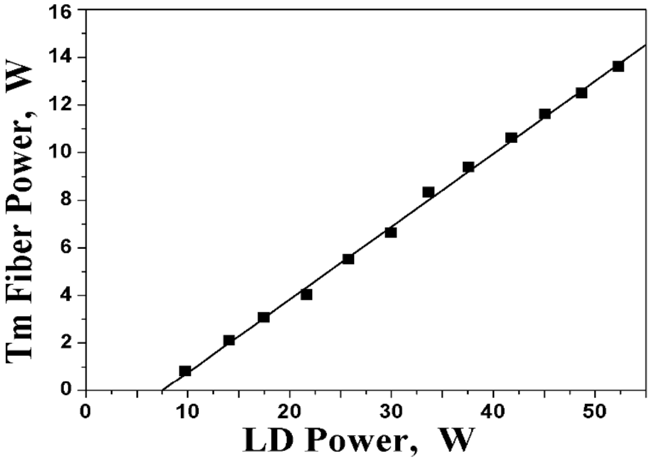

Fig. 2. Output power of Tm-doped fiber laser.

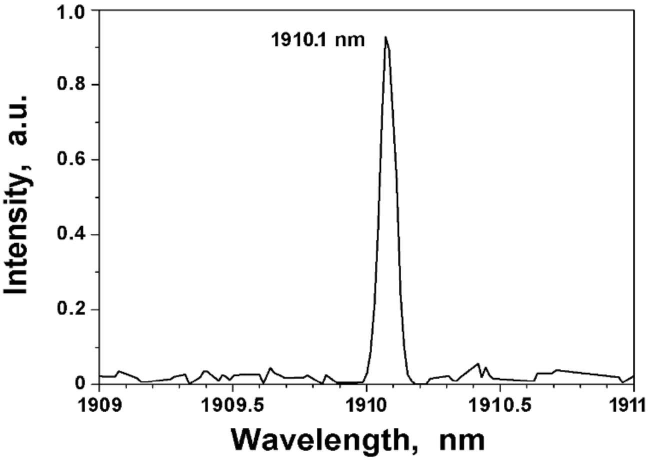

Fig. 3. Output spectrum of the Tm-doped fiber laser with a FBG.

3. Experimental Results

Figure 2 shows the Tm-doped fiber output power as a function of the diode-laser power. The Tm-doped fiber-laser maximum output power was 13.6 W when the diode pump power was 52.3 W, corresponding to a slope efficiency of 30.6% and a conversion efficiency of 26.0%. The spectrum was measured by a monochromator (300 lines/mm grating blazed for 2.0 μm). Figure 3 shows the output spectrum of the Tm-doped fiber laser with a FBG. The emission wavelength is centered at 1910.1 nm, and the FWHM is about 0.1 nm.

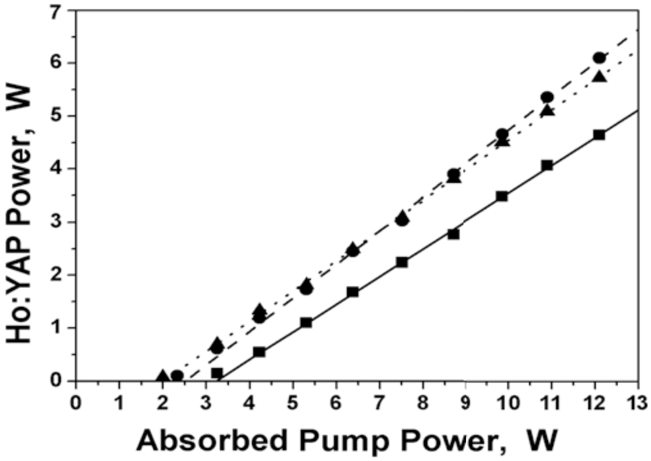

Fig. 4. The output power of the Ho:YAP laser with a transmissivity of 20% (▲), 30% (●), and 50% (■).

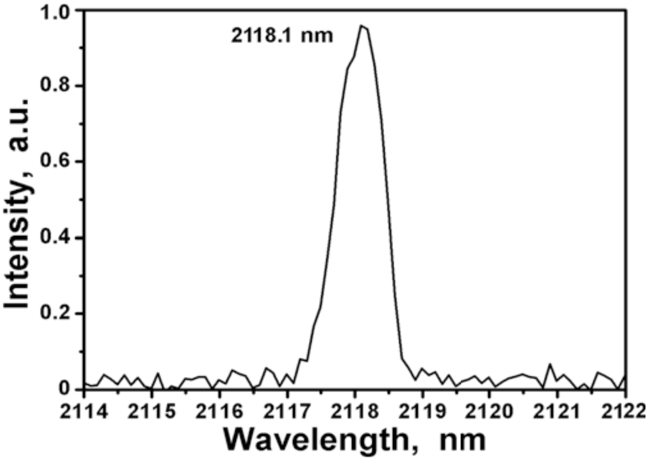

Fig. 5. The output spectrum of the Ho:YAP laser at a transmissivity of 30%.

Using different output transmissivities of 20%, 30%, and 50%, we investigated the continuous-wave laser performance of the *a*-cut Ho:YAP crystal. The output power as a function of the absorbed pump power is shown in Fig. 4. The highest efficiency operation was achieved at a transmissivity of 30%, which produced the maximum output power of 6.1 W with a slope efficiency of 63.4% at an absorbed pump power of 12.1 W. With a transmissivity of 20%, the maximum output power was 5.7 W when the absorbed pump power was 12.1 W, and the slope efficiency was 56.9%. With a transmissivity of 50%, at the same absorbed pump power, a maximum output power of 4.6 W with a slope efficiency of 52.4% was obtained.

The output wavelength of the Ho:YAP laser was measured by the monochromator. As is shown in Fig. 5, the output laser wavelength is centered at 2118.1 nm with FWHM of ∼0.6 nm. The Ho:YAP laser emission wavelength does not depend on the transmissivity of the output coupler, which was observed to be 20%, 30%, and 50%. The output-beam radius at the maximum output level was measured using a 90/10 knife-edge technique at several positions. By fitting the Gaussian-beam standard expression to these data, we estimate the beam quality as $M^2 \sim 1.5$.

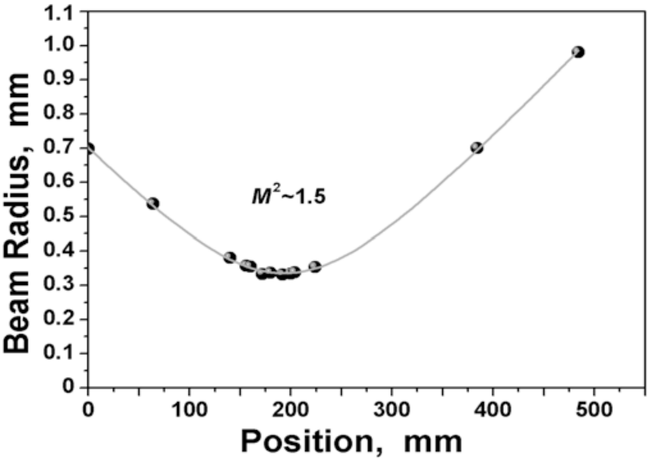

Fig. 6. Measured M^2-factor of the Ho:YAP laser at the maximum output level.

4. Conclusions

In conclusion, we investigated the continuous-wave performance of an *a*-cut Ho:YAP laser pumped by a Tm fiber laser at 1910 nm. Using a FBG, at a diode pump power equal to 52.3 W, we obtained a Tm fiber laser maximum output power of 13.6 W at a wavelength of 1910.1 nm. When the Tm fiber laser was employed as the pump source, the slope efficiency of the Ho:YAP laser was up to 63.4% at a transmittance of 30%. The output wavelength of the Ho:YAP laser was centered at 2118.1 nm with FWHM of ∼0.6 nm. The laser operated at the single TEM_{00} mode with beam quality factor $M^2 \sim 1.5$, which was demonstrated by a knife-edge method.

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