A narrow-linewidth continuous wave Ho:$YALO_3$ laser with Fabry–Perot etalons*

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A narrow linewidth continuous wave Ho:YAP laser with two Fabry–Perot etalons pumped by a Tm:YLF laser is reported. The maximum output power reaches 8.3 W when the incident pump power is 15.8 W, with 52.5% optical-to-optical conversion efficiency and 62.6% slope efficiency. A stable laser output at 2118.1 nm is achieved, with a linewidth less than 0.4 nm (full width at half maximum). The beam quality factor is $M^2 \sim 1.25$, measured by the traveling knife-edge method.

Keywords: solid state lasers, Tm:YLF, Ho:YAP, Fabry–Perot etalons

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1. Introduction

2-μm lasers are in the eye-safety wavelength regions, and have strong absorption lines of water and weak absorption lines of atmospheric gases. Therefore, 2-μm lasers are believed to have potential applications in a wide range of fields, such as atmospheric remote sensing, which includes Doppler radar wind sensing and water vapor profiling by differential absorption radar, spectroscopy, and basic research. Furthermore, high-power quasi-continuous wave (QCW) 2-μm lasers with high peak power are effective pump sources for optical parametrical oscillators (OPOs) and solid-state lasers further into the mid-infrared region.[1–5]

Tm and Ho co-doped media with a large emission cross section are beneficial to attain a high peak-power laser pulse, but they must be cooled to alleviate the up-conversion effects and energy transfer between Tm and Ho.[6–10] Another way to alleviate these effects is to put Ho and Tm in separate crystals. With the development of high power 1.9-μm lasers, which are efficient pump sources, 2-μm lasers based on Ho-doped crystals have become prominent in such applications. The host material for these Ho lasers is usually $Y_3Al_5O_{12}$ (YAG) or $LiYF_4$ (YLF).[11–14] Room-temperature Ho:LuAG and Ho:ZnS have also been demonstrated.[15,16] For the present study, $YAlO_3$ (YAP) is chosen as a promising efficient singly doped laser material.[17–19] The natural birefringence of YAP, combined with the mechanical properties similar to YAG, is beneficial to provide clean linearly polarized beams with virtually no depolarization loss. The Ho:YAP crystal is grown by the Czochralski method. The absorption spectrum of the Ho:YAP crystal reveals that many intense absorption peaks occur around 1871 nm, 1885 nm, 1907 nm, 1923 nm, 1931 nm, 1946 nm, 1970 nm, and 1983 nm.[16] The broad absorption of Ho:YAP around 2 μm makes it easy for a Tm-doped laser to pump. It is unlike that of Ho:YAG, which has a very narrow absorption peak at 1.91 μm. The output wavelengths of Ho:YAP lasers are always at 2118 nm. In this paper, we report a narrow linewidth less than 0.4 nm (full width at half maximum, FWHM), which is achieved by two Fabry–Perot (F–P) etalons in the laser cavity. A 8.3 W continuous-wave laser is obtained with 15.8 W pumped power. The optical-to-optical conversion efficiency and the slope efficiency are 52.5% and 62.6%, respectively.

2. Experimental setup

The experimental setup is shown in Fig. 1. The Tm:YLF crystal for the experiment was a-cut with dimensions of 3 mm×3 mm×12 mm, and its two end surfaces were anti-reflection-coated at both 792 nm ($R < 0.5\%$) and 1.91 μm ($R < 0.3\%$). The doped concentration was 4 at.%. The Tm:YLF crystal was wrapped in an indium foil and held in a copper heat sink bonded on a thermal electric cooler (TEC) with precise temperature control, and the temperature of the Tm:YLF crystal was held at 15 °C. The pump source was a 60 W laser diode (MIF4S22-793.3-60C-H200H, DILAS), output with a 400 μm core-diameter pigtail fiber. The pump light was divided into two equal power beams to pump the two ends of the Tm:YLF crystal. The coupling lenses, with 25 mm and 45 mm focuses, were used to refocus the pump laser into the laser crystal. The pump-beam diameter was nearly 720 μm at the laser crystal location. The depleted pump light transmitted through the 45° dichroic mirror ($R > 99.5\%$ at 1.9 μm and $T \sim 95\%$ at 792 nm). Considering the transmission losses, nearly 90% of the pump power was input to the Tm:YLF crystal. The Tm laser resonator was a folded cavity with a

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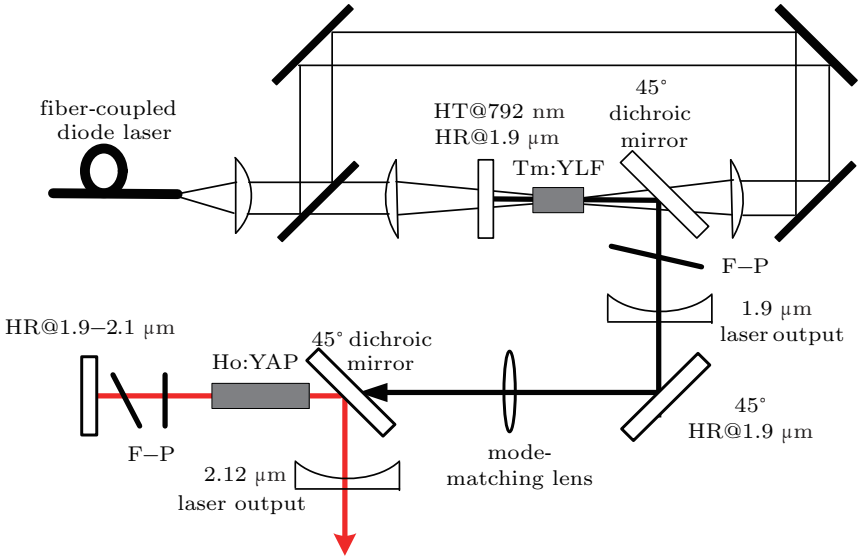


Fig. 1. (color online) Schematic diagram of the experimental setup.

length of 64 mm. The output coupler was a plano-concave lens with a 300 mm radius of curvature, and it was coated with 74% reflectivity at 1.91 μm. The F–P etalon (0.1 mm thick) tuned the Tm:YLF lasing at 1.91 μm. By tuning the F–P etalon, the Tm:YLF laser could operate at 1908 nm with an FWHM of about 1.0 nm, as shown in Fig. 2. The beam quality factor was measured at the maximum power output, resulting in a value of $M^2 \sim 1.2$.

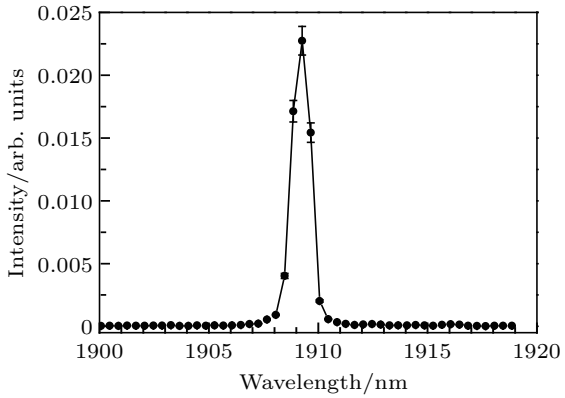


Fig. 2. Output spectrum of F–P tuned Tm:YLF laser.

The Ho:YAP crystal, c-cut along the grown direction, doped with 0.5 at.%, had dimensions of 4 mm×4 mm (section) × 35 mm (length), and its two end surfaces were anti-reflection-coated at both 1.91 μm ($R < 0.5\%$) and 2.12 μm ($R < 0.5\%$). This Ho:YAP crystal was wrapped in an indium foil and held in a copper heat-sink bonded on a thermal electric cooler for precise temperature control. In this experiment, the temperature of the Ho:YAP crystal was held at 15 °C. The Ho:YAP crystal was placed in the vicinity of the focus formed by the 200 mm focal length mode-matching lens used for the Tm:YLF laser brightness determination experiments. The pump spot at the input surface of the Ho:YAP crystal was approximately 260 μm in diameter. The Ho:YAP laser resonator had a concave output coupler of 100 mm radius in curvature, with 30% transmission. Two etalons (0.5 mm thick quartz and 0.1 mm thick YAG) with no coating were inserted in the cavity to restrict the wavelength of the Ho:YAP laser.

3. Experimental results

Figure 3 shows the output characteristics of the diode-pumped Tm:YLF laser. The maximum CW output power obtained is 18.1 W with an incident pump power of 49.5 W, corresponding to an optical efficiency of 36.5%. A slope efficiency of 45.9% is determined by a linear fit of the experimental data with respect to the incident diode power. The laser emission is linearly polarized along the $E//\sigma$ direction.

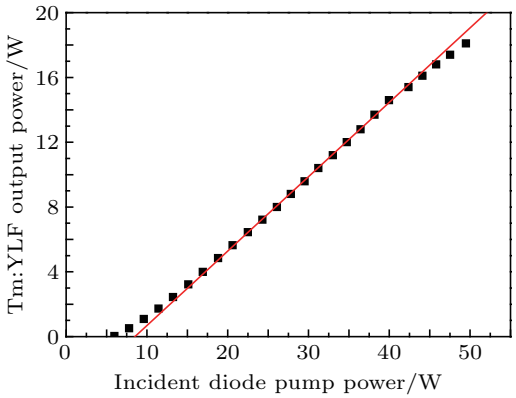


Fig. 3. (color online) Output characteristics of the diode-pumped Tm:YLF laser at 15 °C.

Figure 4 shows the output characteristics of the Ho:YAP lasers (with the etalons set up and without the etalons set up). The two laser setups perform very similarly with respect to threshold, efficiency, and output power. The threshold with the etalons is 282 W with 62.6% slope efficiency, which yields a

maximum output power of 8.3 W at a pump power of 15.8 W and approximately 52.5% optical-to-optical conversion efficiency at the maximum power level. Without the etalons, the threshold is 2.72 W with 63.2% slope efficiency. The difference of slope efficiencies in the two cases is slight, and the maximum powers and the maximum efficiencies of the setups with etalons differ only a little, which indicates that the etalons do not substantially affect the losses. The slightly lower output power and efficiency with the etalons may result from the resonator's actual reflectivity being lower than the design value. In addition, the etalons with no coating also brought some additional losses.

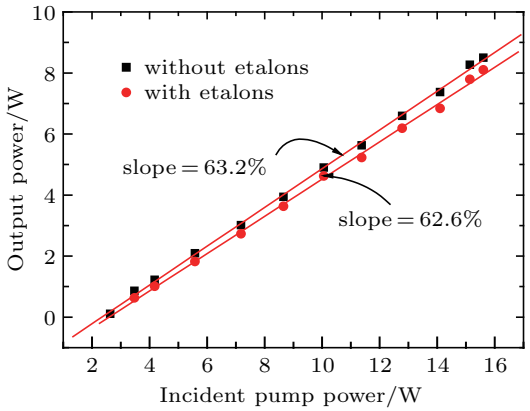


Fig. 4. (color online) Output power of Ho:YAP laser.

The output wavelength of the Ho:YAP laser was measured with a monochrometer (300-mm focal length, 600 lines/mm grating blazed at 2.0 μm). The lasing radiation was monitored by an InGaAs detector with an SR830 lock-in amplifier for signal extraction. The output laser spectrum of the Ho:YAP laser without the etalons is shown in Fig. 5. The output laser wavelength is centered at 2118 nm with an FWHM of about 1 nm. In contrast, the setup with the etalons has a narrow linewidth due to the selection of wavelength, with an FWHM of about 0.4 nm, as is shown in Fig. 6.

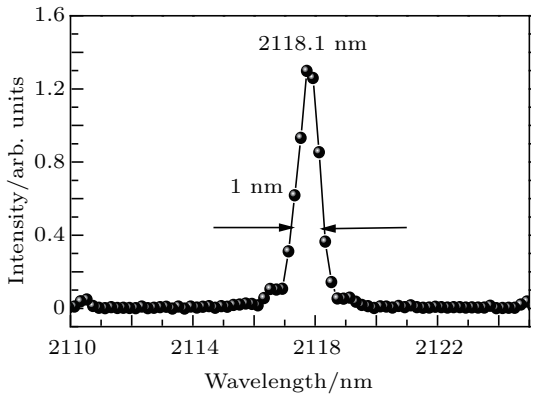


Fig. 5. (color online) Output spectrum of Ho:YAP laser without etalons.

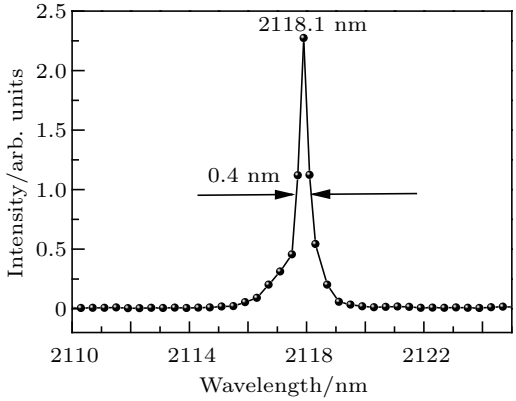


Fig. 6. (color online) Output spectrum of Ho:YAP laser with etalons.

The beam radius for the Ho:YAP laser with two etalons at the 8.0 W output power level was measured by the 90/10 knife-edge method. The lens ($f = 200$ mm) was located 305 mm away from the output coupler. Figure 7 shows the measured beam radii at different distances from the lens. We estimate the beam quality to be $M^2 = 1.25 \pm 0.02$, clearly indicating nearly diffraction-limited beam propagation.

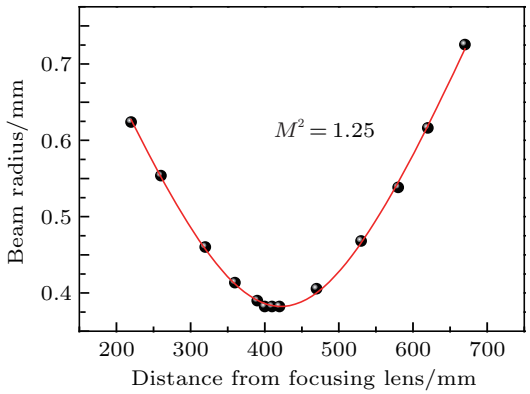


Fig. 7. (color online) Beam radius for the Ho:YAP laser at the 8.0 W output power level.

4. Conclusion

In summary, a narrow linewidth CW Ho:YAP laser with two etalons is demonstrated. The maximum output power reaches 8.3 W when the incident pump power is 15.8 W with optical-to-optical conversion efficiency and slope efficiency of 52.5% and 62.6%, respectively. A stable output and a narrow linewidth less than 0.4 nm FWHM at 2118.1 nm are achieved. The beam quality factor is $M^2 \sim 1.25$, measured by the traveling knife-edge method. The laser performance of the Ho:YAP laser with two etalons makes it suitable for use as an effective pump, improving OPO by 3–5 μm, which will be investigated in the future.

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