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A Continuous-Wave Ho:$YAlO_3$ Laser with Output 8.5 W Pumped by a 1.91 μm Laser at Room Temperature *

YAO Bao-Quan(姚宝权)**, YANG Xiao-Tao(杨晓涛), DUAN Xiao-Ming(段小明), WANG Tian-Heng(王天衡), JU You-Lun(鞠有伦), WANG Yue-Zhu(王月珠)

National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150001

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A cw high efficient Ho:$YAlO_3$ laser pumped by 1.91 μm diode-pumped Tm:YLF laser at room temperature is realized. The maximum output power reaches 8.5 W when the incident pump power is 15.6 W. The slope efficiency is 63.7%, and the Tm:YLF to Ho:YAP optical conversion efficiency is 54.5%. The laser wavelength is 2118.3 nm when the transmission of output coupler is 30%. The beam quality factor is $M^2 \sim 1.39$ measured by the traveling knife-edge method.

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Solid state lasers emitting in the 2 μm region are of great interest for eye-safe applications in Doppler radar wind sensing,[1] range finding or water vapor profiling.[2] With the fast development of high power 1.9 μm laser as an efficient pump source, the 2 μm lasers based on Ho-doped crystals have become prominent in these applications, and the host materials for these Ho lasers are usually $Y_3Al_5O_{12}$(YAG) and $LiYF_4$(YLF).[3–5] The room-temperature Ho:LuAG laser has also been demonstrated by Hart *et al.*[6] Of all the rare-earth ion doped laser host materials, $YAlO_3$ (YAP) was chosen for study as a promising efficient singly doped laser material.[7–9] The natural birefringence of YAP, combined with similar mechanical properties to YAG, is beneficial ro the capability of providing clean linearly polarized beams with virtually no depolarization loss. The absorption spectrum is not as keen as YAG,[10] so that the need of the Tm laser is not very rigorous. In this Letter, we report on the room-temperature Ho:YAP lasing at 2118.3 nm end-pumped by a 1.91-μm Tm:YLF laser. The maximum output power reaches 8.5 W when the incident pump power is 15.6 W. The slope efficiency is 63.7%, and the optical-optical efficiency is 54.5%. The beam quality factor is $M^2 \sim 1.39$ measured by the traveling knife-edge method.

The experimental setup is shown in Fig. 1. The Tm:YLF crystal for the experiment is *a*-cut with dimensions of $3 \times 3 \times 12\,\mathrm{mm}^3$, whose two end surfaces were AR-coated at both 792 nm ($R < 0.5\%$) and 1.91 μm ($R < 0.3\%$). The doped concentrations is 4 at.%. Tm:YLF crystal is wrapped in indium foil and held in a copper heat-sink bonded on a thermal electric cooler (TEC) with precise temperature control, and Tm:YLF crystal was held at 18°C. The pump source is a 60 W laser diode (MIF4S22-793.3-60C-H200H, DILAS), with output by a 400-μm core-diameter pigtail fiber. The temperature of the laser diode is tuned to match well with the peak absorption wavelength of laser crystal. The pump light is 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 are used to refocus the pump laser into the laser crystal. The pump-beam diameter is nearly 720 μm at the laser crystal location. The depleted pump light transmits through the 45° dichroic mirror ($R > 99.5\%$ at 1.9 μm and $T \sim 95\%$ at 792 nm). Considering the transmission loss, nearly 90% of the pump power inputs to the Tm:YLF crystal. The Tm laser resonator is folded with a cavity length of 130 mm. The output coupler is a plano-concave lens with 300-mm radius of curvature, and is coated with 74% reflectivity at 1.91 μm. The F-P etalon (0.1 mm thickness) tunes the Tm:YLF lasing at 1.91 μm.

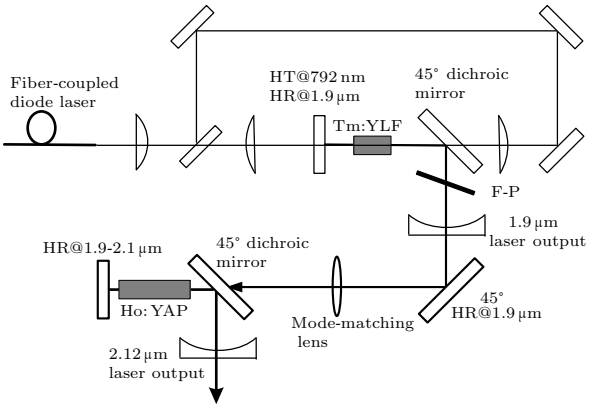

Fig. 1. Experimental setup of room-temperature Ho:YAP laser.

The output characteristics of diode-pumped Tm:YLF laser are shown in Fig. 2. The maximum cw output power obtained was 18.1 W with incident pump power of 49.5 W, corresponding to the optical conversion efficiency of 36.5%. A slope efficiency of

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**Email: yaobq08@hit.edu.cn
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45.9% was yielded by linear fit of the experimental data with respect to the incident diode power. Laser emission was linearly polarized along the $E//\sigma$ direction. Tuning the F-P etalon, the Tm:YLF laser can operate at 1910 nm with FWHM of about 1.0 nm. The beam quality factor was measured at maximum output power, resulting in a value of $M^2 \sim 1.2$.

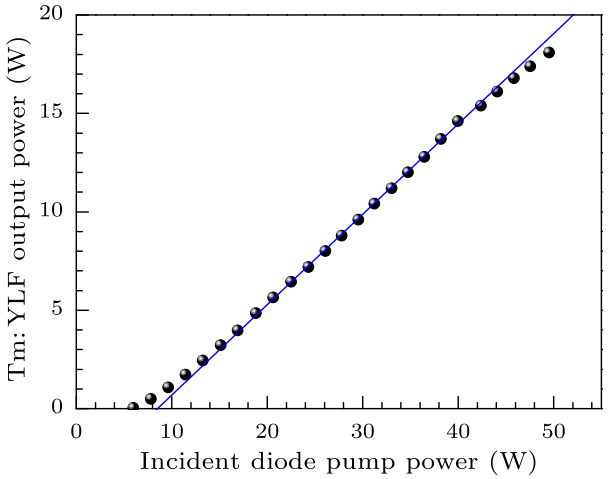

Fig. 2. Output characteristics of the diode-pumped Tm:YLF laser at 18°C.

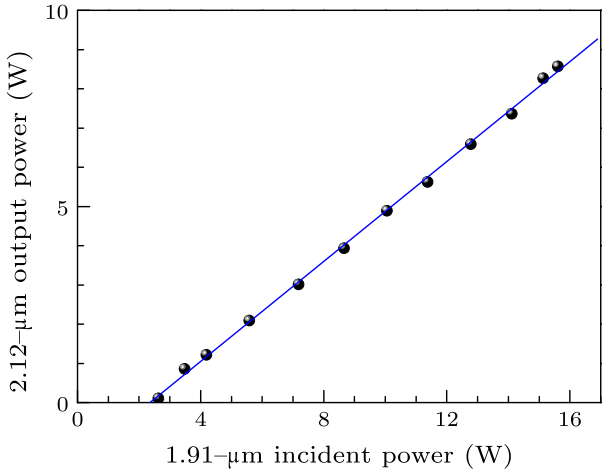

Fig. 3. Output power of Ho:YAP laser.

The Ho:YAP crystal, b-cut along the grown direction, doped with 0.5 at.%, has dimensions of $4 \times 4 \times 35\,\mathrm{mm}^3$ (in length), whose two end surfaces were AR-coated at both 1.91 μm ($R < 0.5\%$) and 2.12 μm ($R < 0.5\%$). This Ho:YAP crystal was wrapped in indium foil and held in a copper heat-sink bonded on a thermal electric cooler (TEC) 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 is plano-concave with a 100 mm radius of curvature concave output coupler, whose transmission is 30%. The high reflector mirror is a plane mirror highly reflecting at both the pump and laser wavelengths. The 45° dichroic mirror provides both high reflection (HR) at 2.12 μm ($R > 99.5\%$) and high transmission (HT) at 1.91 μm ($T > 94\%$). The physical length of the resonator was about 80 mm.

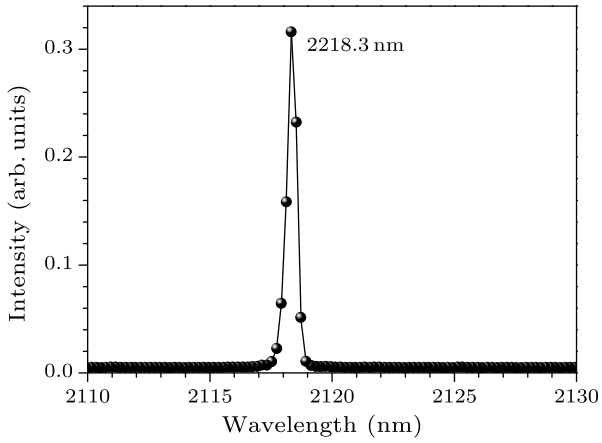

Fig. 4. Output laser spectrum of the Ho:YAP laser.

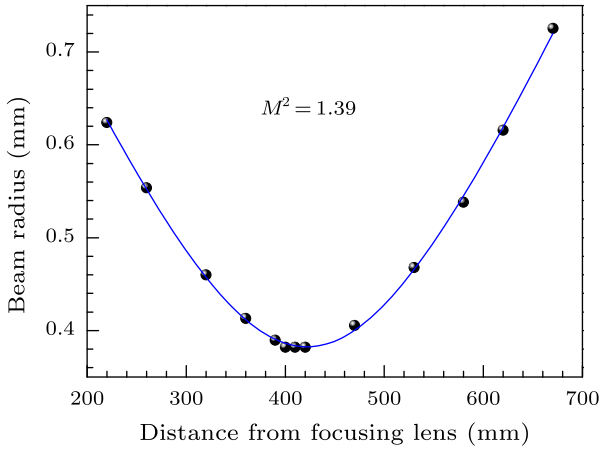

Fig. 5. Beam radius for the Ho:YAP laser at the 8.0 W output power level.

Figure 3 shows the output characteristics of the Ho:YAP laser. The maximum continuous wave output power obtained was 8.57 W with incident pump power of 15.6 W, corresponding to the optical conversion efficiency of 54.5%. A slope efficiency of 63.7% was yielded by linear fit of the experimental data with respect to the incident pump power. Laser emission was linearly polarized and the polarization degree was measured up to larger than 20 dB. 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 a SR830 lock-in amplifier for signal extraction. The output laser spectrum of the Ho:YAP laser is shown in Fig. 4. The

output laser wavelength was centered at 2118.3 nm with FWHM of about 0.8 nm. The beam radius for the Ho:YAP laser at the 8.0 W output power level is also measured by the 90/10 knife-edge method. The lens ($f = 200$ mm) is located at 305 mm away from output coupler. Figure 5 shows the measured beam radius at different distances from the lens. We estimate the beam quality to be $M^2 = 1.39 \pm 0.02$, clearly indicating nearly diffraction-limited beam propagation.

In summary, a cw high efficient Ho:YAP laser pumped by a diode-pumped Tm:YLF laser at room-temperature is demonstrated. The maximum output power reaches 8.5 W when the incident pump power is 15.6 W. The slope efficiency is 63.7%, and the Tm:YLF to Ho:YAP optical conversion efficiency is 54.5%. The wavelength is 2118.3 nm when the transmission of output coupler is 30%. The beam quality factor is $M^2 \sim 1.39$ measured by the traveling knife-edge method. Because Ho^{3+} has relatively long upper-level life and larger stimulated emission cross section, the Ho:YAP laser is very suitable to generate nanosecond pulse laser output by Q-switching. The high repetition rate Q-switched Ho:YAP laser can be a good pump source optical parametric oscillator in mid-infrared radiation generation.

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