Experimental study of continuous-wave and Q-switched laser performances of Ho:YVO_4 crystal

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In this letter, we report a Ho:YVO_4 laser pumped by a 1.94-μm laser in both continuous-wave (CW) and Q-switched modes. The output performance of the Ho:YVO_4 laser is compared with different output coupler transmissions. By use of the output coupler transmissions of T=30%, we obtain the maximum CW output power of 3.9 W at 2052 nm, with beam quality factor of M^2=1.09 for the absorbed pump power of 12.5 W. For the Q-switched mode, we achieve maximum output energy per pulse of 0.38 mJ and the minimum pulse width of 25 ns, corresponding to the peak power of 15.2 kW.

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The 2-μm lasers operating in the eye-safe region have applications in a number of areas, including remote sensing, medical applications, and as the pump source of optical parametric oscillators (OPOs)[1−3]. Holmium-doped materials are commonly used to obtain the 2-μm laser output because of the significantly high emission cross-section around the 2-μm region. The pumping of Ho^{3+} doped crystals by narrow-band laser radiation lead to a considerable increase in the laser power and efficiency, as well as to a better beam quality. And narrow-band pumping of singly Ho-doped oxides and fluorides crystal has been widely demonstrated[4,5].

In recent years, YVO_4 crystals have become increasingly attractive as a potential excellent 2-μm laser host, including both Tm^{3+}singly doped and Tm^{3+} Ho^{3+} co-doped[6,7]. YVO_4 is a tetragonal uniaxial crystal belonging to a space group D_{4h} with unit cell parameters a = b=0.712 nm and c=0.629 nm[8]. The crystal has higher thermal conductivity, better mechanical properties, and stabilized chemical properties. Compared to Ho-doped oxides and fluorides crystal, Ho:YVO_4 crystal has a wider pump light absorption bandwidth, comparable upper state life time, and the larger pump laser emission section[9,10]. Especially, Ho:YVO_4 has a main absorption cross-section around 1940 nm which is just the main emission wavelength of Tm:YAP laser[11]. The reports on Ho:YVO_4 lasers were fewer so far. Most recently, our group achieved the efficient continuous wave (CW) mode Ho:YVO_4 lasers at room temperature pumped by 1.91 and 1.94 μm, respectively[12,13]. However, to our knowledge, Q-switched Ho:YVO_4 laser has not been reported. The experimental setup achieved a room-temperature Ho:YVO_4 laser pumped with a Tm:YAP laser at 1.94 μm in both CW and Q-switched modes. In the CW mode, we obtained the maximum 3.9-W output power at 12.5-W absorbed pump power, with beam quality of M^2=1.09. For the Q-switched mode, we achieved maximum output energy per pulse of 0.38 mJ and the minimum pulse width of 25 ns, corresponding to the peak power of 15.2 kW.

The experimental setup of CW and Q-switch Ho:YVO_4 laser is shown in Fig. 1. In this experiment, Tm:YAP slab laser pumped by two fiber-coupled diodes lasers as the pump source evaluated the lasing performance of Ho:YVO_4 crystal. We selected a 2.2 at.% doped, a-cut Tm:YAP crystal with the dimension of 1×6×22 (mm) as the oscillator crystal and the crystal was set at 17°. By use of flat-concave geometry and dual-end pumped configuration, Tm:YAP crystal strong thermal lens effect was controlled in the high-power operation. The pump sources of Tm:YAP laser were two fiber-coupled laser diodes setting temperature to obtained 793-nm emission wavelength and the maximal output power was 60 W for each. The output mirror selected R=200 mm which had transmittance of 23% around 1.94 μm. The flat 0° and 45° dichroic mirrors had high reflectivity (R >99.97%) around 1.94 μm and high transmission at the pump wavelength (T ∼98.6%). The 0.5-mm-thickness and 0.1-mm-thickness YAG etalons were inserted into the cavity to restrict the laser wavelength at 1938 nm, avoiding spiking in the Tm:YAP laser output caused by the water absorption lines near 1.94 μm. The Ho:YVO_4 crystal was 30 mm in length and 3×3 (mm) in cross section, doped with 0.5 at.% Ho and a-cut along the growth direction. Both end faces of the Ho:YVO_4 crystal were antireflection coated at the laser wavelength and the pump wavelength. The crystals with silver foil mounted and held in the copper heat sink were controlled at a temperature of 15° by a thermoelectric cooler. The Ho:YVO_4 laser resonator was folded with a physical cavity length of 112 mm, including a flat mirror with high reflectivity at the 2.1 μm and high transmission at the 1.9 μm, a flat 45° dichroic mirror with high reflectivity at 2.1 μm and high transmission at 1.9 μm and an output coupler with a radius of curvature of 200 mm. The Q-switched experiment was achieved by use of a 35-mm-long acousto-optic Q-switched with high transmission for 2.1-μm operation, and the rated radio frequency power was 20 W. By use of a 75-mm focal length mode-matching lens, the mode radius of the Ho:YVO_4 laser in the crystal was calculated to be about 0.17 mm, which was well match with the pump spot.

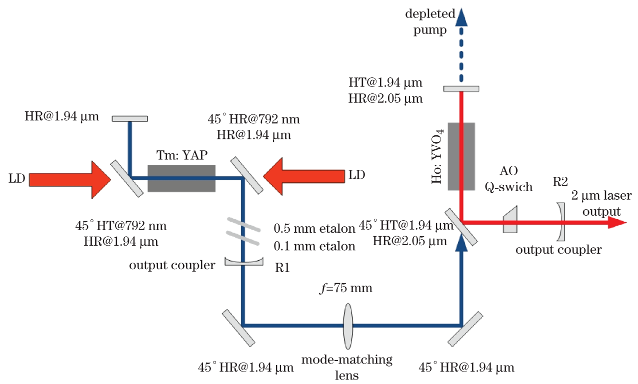

Fig. 1. Schematic diagram of a Ho:YVO_4 laser pumped by a Tm:YAP laser.

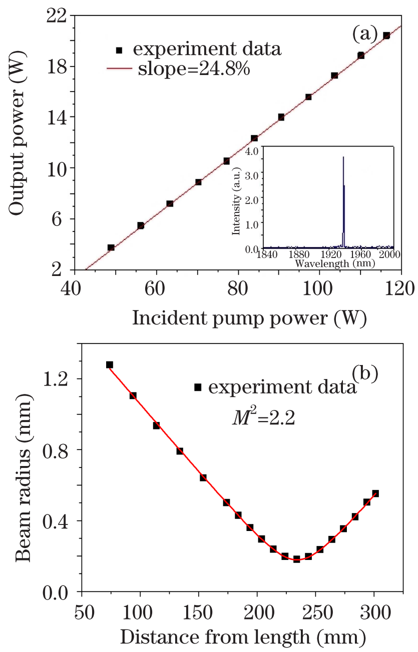

Fig. 2. (a) Output power (wavelength at the maximum output level). (b) M^2 measurement at the 10-W output power level.

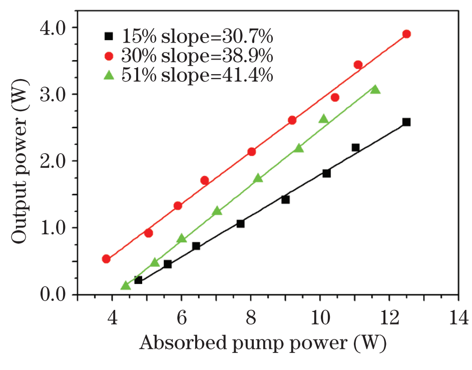

Fig. 3. CW output power of Ho:YVO4 laser at output coupler transmissions of T=15%, 30%, and 51%.

Figures 2(a) and (b) shows the output power with respect to the incident pump power and the beam quality factor of M^2 measurement in 10-W output power of the Tm:YAP laser. The maximum output power was 20.4 W at the incident pump power of 116.5 W, corresponding to the optical-to-optical efficiency of 17.5% and slope efficiency of 24.8%. The output wavelength was 1938.4 nm in the maximum output power. By use of a 150-mm focal length lens, we calculated the beam quality of M^2 was about 2.2 in the output power of 10 W.

The CW output of Ho:YVO_4 laser with respect to absorbed pump power in a single-pass pumping configuration is shown in Fig. 3 for output coupler transmissions of T=15%, 30%, and 51%, respectively. It was found that about 50% of the pump power was absorbed in the single-pass pumping configuration. By use of the output coupler transmissions of T=30%, we obtained greater CW output power of 3.9 W at 12.5-W absorbed pump power in a single-pass pumping configuration, corresponding to the optical-to-optical efficiency of 26.3% and slope efficiency of 38.9%. The linearly polarized output along crystallographic c-axis of Ho:YVO_4 laser was suitable for acousto-optic Q-switch generating high PRF Q-switched output.

The output pulse energy and pulse width of the Q-switched Ho:YVO_4 laser in different output coupler transmissions when the pulsed repetition frequency is 10 kHz are shown in Figs. 4(a) and (b). The pulse temporal behavior was recorded by a Lecroy digital oscilloscope (Wavesurfer 64 Xs, 2.5 Gs/s, 600-MHz bandwidth) with an InGaAs detector. We obtained maximum output energy per pulse and the shortest pulse width by using an output coupler of T=30%, the output energy per pulse was 0.38 mJ and the pulse width was 25 ns (shown in Figs. 5(a) and (b)) when the absorbed pump power was 10.4 W. And a peak power of approximately 15.2 kW was obtained in the Q-switched Ho:YVO_4 laser. In the case of T=15% and 51%, output energy per pulse of 0.21 and 0.30 mJ we achieved with a pulse width of 35.4 and 31.2 ns, corresponding to the peak power of 5.93 and 9.62 kW, respectively. The pulse width shortened sharply when the incident pump power increased, as we expected.

The laser output wavelength in 3.9 W of CW output power for output coupler transmissions of T=30% is shown in Fig. 6. We utilized EXFO WA-1500 wavemeter and WA-650 digital display device to measure the Ho:YVO_4 laser output wavelength of continuous operation. The output wavelength was about 2052 nm with a linewidth less than 0.2 nm. The Ho:YVO_4 cavity laser output wavelength was shifted to 2053 nm when the output transmission was 15% and only 2052 nm emission line was observed.

Figure 7 shows the output beam profile and the measured beam radius at 3.9 W of CW output power at different distances. By use of the pyroelectric camera, we observed the 2-μm laser beam profile (inset in Fig. 7), and the second moment beam diameter could not be

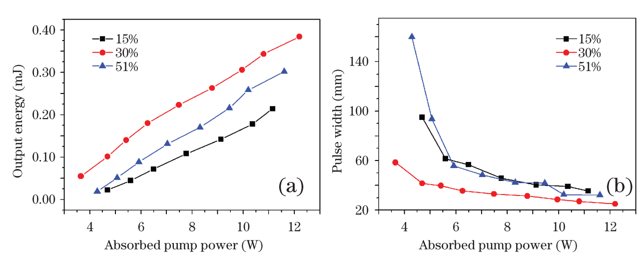

Fig. 4. (a) Output pulse energy and (b) pulse width versus incident pump power in output coupler transmissions of

T=15%, 30%, and 51% at a repetition rate of 10 kHz.

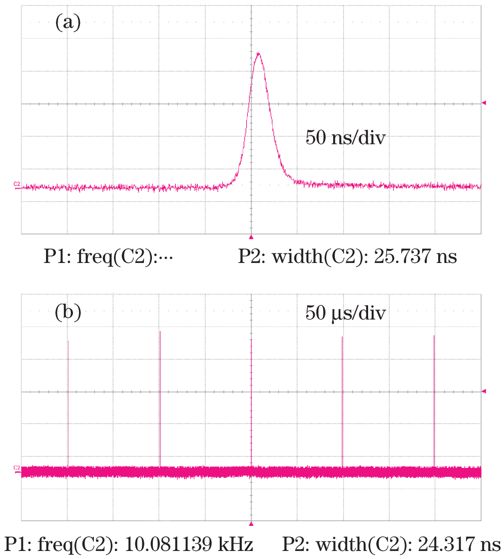

Fig. 5. (a) Typical oscilloscope trace of expanded shape of a single pulse. (b) A train of output pulses.

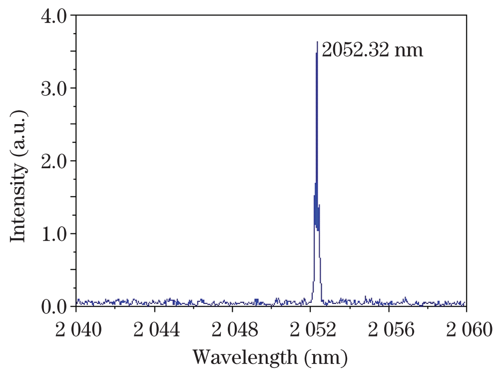

Fig. 6. Ho:YVO_4 laser output wavelength in 3.9 W of output power.

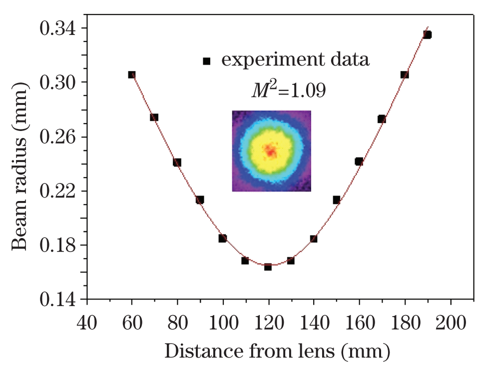

Fig. 7. M^2 measurement of the Ho:YVO_4 laser output at the maximum output power of 3.9 W and typical two-dimensional beam profiles.

accurately measured as Ref. [14]. Using the 90/10 knife edge method with a f=100 mm of focal length lens positioned about 215 mm after the output mirror, we fitted Gaussian beam standard expression to these data and the beam quality of M^2 =1.09 was inferred, which clearly indicated nearly diffraction-limited beam propagation.

In conclusion, CW and repetitively Q-switched operation of a Ho:YVO_4 laser pumped by a 1.94-μm Tm:YAP laser at room temperature is demonstrated. The Tm:YAP laser maximum output power is 20.4 W at the incident pump power of 116.5 W, the output wavelength is 1938.4 nm and the beam quality of M^2 is about 2.2 in output power of 10-W level. The maximum CW output power is 3.9 W at 12.5-W absorbed pump power in a single-pass pumping configuration with output coupler transmissions of T=30%, corresponding to the optical-to-optical efficiency of 26.3% and slope efficiency of 38.9%. A beam quality of M^2 = 1.09 and the emission line centering on 2052 nm is obtained at the output power of 3.9 W. For the Q-switched mode, we achieve maximum output energy per pulse of 0.38 mJ and the pulse width of 25 ns, corresponding to the peak power of 15.2 kW in the output coupler transmissions of T=30%.

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