Diode-pumped high-efficiency broadband tunable Tm:YAP laser

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A laser diode-pumped high-efficiency widely tunable Tm:YAP laser with excellent comprehensive properties is reported. The output power is stable at a given pump power. Under the absorbed pump power of 12.95 W, the maximum output power at 2,010 nm is 5.16 W, corresponding to a slope efficiency of 45.5%. The generated beam profile is close to the Gaussian TEM$_{00}$ near the maximum pump power. Furthermore, the laser working wavelength can be continuously tuned through optimization from 1,894 to 2,066 nm, which is the widest tunable range for Tm:YAP lasers to date.

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All-solid-state lasers with emission wavelength near 2 μm have a great application prospect in medicine[1], optical commutation, atmospheric sensing[2], and fundamental research[3] due to their strong water absorption. The 2-μm laser can also be used as a useful pump source for Ho-ion-based and Cr-ion-based lasers[4,5], and optical parametric oscillators of 3–5 μm and 8–12 μm. In addition, Tm-doped lasers have peak absorption around 800 nm, thus it can be pumped by commercial laser diode with high efficiency. Therefore, thulium-ion-based lasers have attracted great attention over the recent years[6−10]. An attractive laser host for thulium is the yttrium aluminum perovskite (YAP), which is a negative biaxial crystal with the orthorhombic $\mathrm{D}_{2\mathrm{h}}^{16}$ space group, the yttrium ions in the sites of C_s (monoclinic) symmetry[11]. With the combination of good thermal conductivity and mechanical properties, broad tunability, and natural birefringence that dominates any thermally induced birefringence, Tm:YAP crystal has shown great advantages for the development of high-efficiency tunable diode-pumped lasers[10−14]. In 2004, Sullivan *et al.* demonstrated 50-W output power from a free-running Tm:YAP laser at 1,940 nm and Q-switched operation with 7-mJ/5-kHz output[13]. To date, it is the best result of Tm:YAP laser performance. In 2006, Černy *et al.* obtained a maximum tunable range from 1,869 to 2,036 nm with a birefringence filter (BF)[12].

In this letter, we have develope a Tm:YAP laser pumped by a fiber-coupled laser diode with excellent comprehensive properties. The maximum continuous wave (CW) output power of 5.16 W at 2,010 nm was obtained under 12.95-W absorbed pump power. The generated beam profile is close to the Gaussian TEM$_{00}$ near the maximum pump power. Moreover, the tunable wavelength range by optimization with an inserted quartz plate in the cavity is 1,894–2,066 nm, which is the widest tunable range for Tm:YAP laser to date.

The 4 at.-% Tm-doped YAP crystal in this study was grown along the crystalline b-axis, provided by the Shanghai Institute of Optics and Fine Mechanics (SIOM), with the Czochralski method. The Tm:YAP crystal was cut off along the crystalline c-axis with dimensions of 3 × 3 (mm) in the cross section and 5 mm in length. The Tm:YAP crystal (polished with parallel end faces, uncoated) was wrapped with indium foil and mounted in a water-cooled copper block; the water temperature was maintained at 15 °C.

The crystal was end-pumped by a fiber-coupled laser diode with emission wavelength of around 793 nm and controlled by a temperature regulation. The diameter and numerical aperture of the fiber core were 400 μm and 0.22, respectively. The pump laser beam was shaped and focused by the 1:1 lens system into the Tm:YAP crystal. The focused spot in the Tm:YAP crystal was about 200 μm. In the experiment, two types of resonator were adopted. Plano-concave cavity was used for continuous wave output and three-mirror folded cavity for tuning output. Both resonators were designed to support only TEM$_{00}$ oscillation, and the focused laser beam radius in the crystal was ∼200 μm.

The setup for the continuous wave output experiment is schematically shown in Fig. 1. The resonator consisted of a plane dichroic input mirror high transmission (HT) at 793 nm and high reflection (HR) at 1,850–2,050 nm and a spherical output coupler with different transmittances (R = 200 mm, T = 1%, 4%, and 7%).

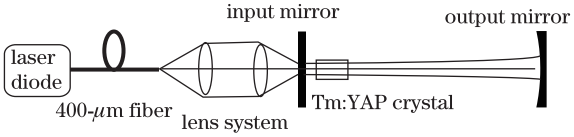

Fig. 1. Schematic diagram of the CW Tm:YAP laser.

The CW output power of the Tm:YAP laser near 2,010 nm under different output transmissions (1%, 4%, and 7%) was investigated, and the best performance was obtained with transmittance of 7%. The maximum laser output power of 5.16 W for 12.95-W absorbed-pump-power was obtained, corresponding to a slope efficiency of 45.5%, and the corresponding threshold was about 1.6 W. The result from the measured dependence of the laser output generated on the absorbed pump power is illustrated in Fig. 2. During the experiment, the output coupler with transmittance of 1% was damaged for the low damage threshold when the pump power was over 15.5 W. Predictably, if the crystal is coated and the output coupler has larger transmission, the maximum output power and the corresponding slope efficiency should be higher for the same pump condition. In addition, the stability of the output power has been observed. At a given pump power, the power fluctuation (the difference between the maximum and the minimum) is about 2% of the average power. The observation time is about one to two hours.

With the output coupler of $T = 4\%$, we measured the beam profile of the laser under different pump power by using an infrared(IR)-sensitive camera (Pyrocam III, Spirion). The results are shown in Fig. 3. The generated beam structure mode was perfect Gaussian TEM_{00} with 67-mW output power of 1.5-W absorbed pump power (Fig. 3(a)). However, a slight distortion in the beam profile appeared due to the thermal effect[15] when the pump power further increased (4.2-W output power with 12.2-W absorbed pump power in Fig. 3(b) and 6.7-W output power with 14.7 W absorbed pump power in Fig. 5(c)). As the heat dissipation in a thin slab gain material is much better than that in a bulk gain material, a slab Tm:YAP laser will be developed to reduce the thermal effect.

Furthermore, the tunability of Tm:YAP was tested. The wavelength tuning setup used in the experiment is schematically shown in Fig. 4. The folded resonator comprised a plane dichroic input mirror (HT at 793 nm and HR at 1,850–2,050 nm), a spherical mirror (R = 500 mm, HR at 1,850–2,050 nm), and a plane output coupler with transmittance of 1% and 4%.

To perform wavelength tuning, a 2-mm-thick quartz plate was inserted into the three-mirror folded cavity at the Brewster angle for lower insertion loss (Fig. 4). The quartz plate was chosen because of its high damage resistance in comparison with blazed diffractive gratings, low insertion losses in comparison with prism, and its relative simplicity in terms of overall arrangement. By using the output couplers with different transmittances of 1% and 4%, we demonstrated wavelength tuning. With optimized pump power, the widest tunable range was obtained at the absorbed pump power of 11.5 W, and the wavelength can be tuned at an extended range from 1,894 up to 2,066 nm with the maximum output power of 1.84 W at 2,010 nm. The results are shown in Fig. 5. Further wavelength tuning was restricted by the coating of the mirrors used.

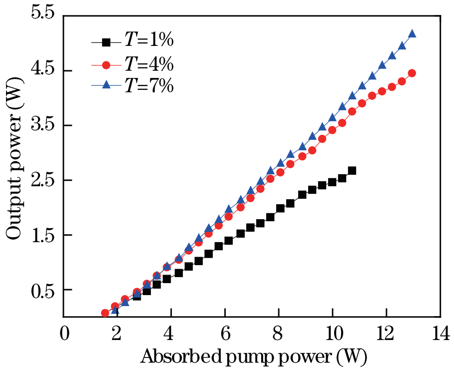

Fig. 2. Output characteristic of the Tm:YAP laser.

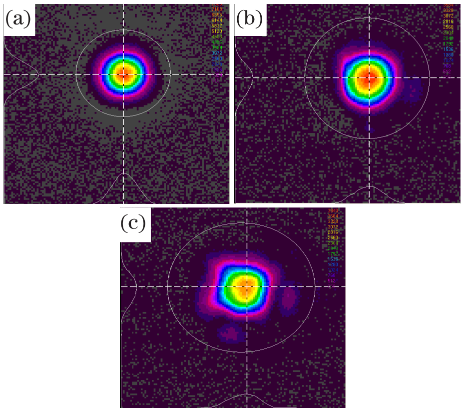

Fig. 3. Tm:YAP laser-generated beam profile under different output power: (a) 67 mW; (b) 4.2 W; and (c) 6.7 W.

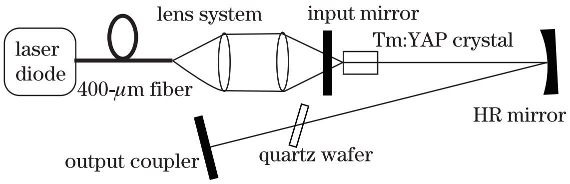

Fig. 4. Schematic diagram of the tunable Tm:YAP laser.

In conclusion, we develope a diode-pumped high-efficiency widely tunable Tm:YAP laser. The laser output performance is demonstrated with different output coupler transmittances of 1%, 4%, and 7%. The conversion efficiency is 29.5% and the maximum slope efficiency can reach 45.5% with T = 7%. The generated beam profile is close to the Gaussian TEM_{00} near the maximal pump power, and a slight distortion of the beam profile is observed as the pump increases. Wavelength tuning is achieved by inserting a quartz plate into the folded cavity. The widest tunable range

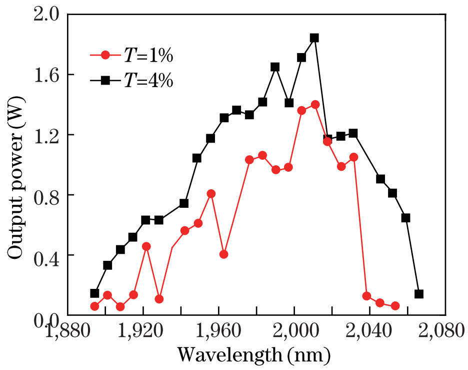

Fig. 5. Tuning curve of the Tm:YAP laser.

extended from 1,894 to 2,066 nm with the maximum output power of 1.84 W at 2,010 nm. Compared with previous reports on Tm:YAP lasers, the Tm:YAP laser demonstrate in this letter shows great advantages. In the future, we plan to optimize the Tm:YAP laser as the pump source for Cr:ZnSe lasers[5,16], providing widely tunable range from 2.1 to 3 μm.

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