Diode-pumped high-efficiency Tm:YLF laser at room temperature

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High-efficiency continuous-wave (CW) Tm:YLF laser by the dual-end-pumping configuration is presented. Under the total input pump power of 24.0 W, the highest output power reaches 9.8 W in the wavelength range of 1910 − 1926 nm by use of 10% output coupling, corresponding to optical conversion efficiency of 40.9% and slope efficiency of 51.4%. The free-running laser spectrum of Tm:YLF is measured.

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Thulium-doped laser materials are suitable to be pumped by diode laser[1−6]. The emission lies in the eye-safe region and includes strong absorption lines of water. Thus, thulium laser sources are of interest for many applications in the remote sensing and medical fields. Tm-doped $YLiF_4$ (YLF) has many attractive properties as a promising material for development of a solid-state laser source with radiation wavelength of 1.9 − 2.0 μm, and for avalanche upconversion lasers[7]. YLF is a very attractive choice as the host medium when it is used for pumping the 2.1-μm Ho:YAG laser[8−10].

There is an efficiency-enhancing cross-relaxation mechanism between $^3H_4$ and $^3F_4$ levels of Tm:YLF that produces two excitation ions in the upper laser level $^3F_4$ with one pump photon, as shown in Fig. 1. This makes the laser potentially very efficient with a quantum efficiency approaching two. The absorption band between $^3H_6$ and $^3H_4$ levels in the 792 − 793 nm spectral region[11] can be easily accessible with available high-power AlGaAs laser diodes. In addition, its naturally occurring birefringence is beneficial to the capability to provide clean linearly polarized beams with virtually no depolarization loss. Now, there have been many experimental reports about the high-power Tm:YLF laser around 1.9 μm. Pomeranz *et al.* reported a 21.8-W continuous-wave (CW) output power corresponding to optical-to-optical conversion efficiency of 37% from a Tm:YLF laser[12]. Budni *et al.* reported a 36-W CW Tm:YLF output power pumped by 120-W diode-laser[11]. Kieleck *et al.* reported a 22-W CW output power corresponding to optical-to-optical conversion efficiency of 39%[13]. In addition, So *et al.* reported a CW output power of ∼ 70 W corresponding to a 31% optical-to-optical conversion efficiency from a slab geometry Tm:YLF laser[14].

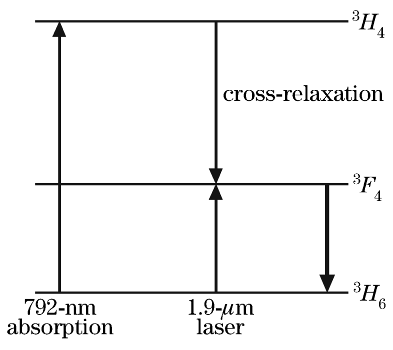

Fig. 1. Energy level diagram for Tm:YLF.

In this letter, we demonstrate a high-efficiency CW diode-pumped Tm:YLF laser. The maximum CW output power of 9.8 W is obtained by double-end-pumping method, corresponding to optical conversion efficiency of 40.9% and slope efficiency of 51.4%.

The Tm:YLF laser cavity is L-shaped with double-end-pumping geometry, as shown in Fig. 2. Compared with the single-end-pumping method commonly used, double-end-pumping method has uniform thermal distribution and good mode matching between pump mode and oscillating mode, which leads to high efficiency and good beam quality of the laser output.

The Tm:YLF crystal is a-cut with the dimensions of 3 × 3 × 8 (mm), and the dopant concentration is 4 at.-%. Both ends of the crystal are anti-reflection (AR) coated at 792 nm and 1.9 μm, and the crystal is mounted in a copper heat sink that is set at room temperature. The pump source is a 792-nm 26-W laser diode (LD) coupled by a fiber with core diameter of 200 μm and numerical aperture (NA) of 0.22. The LD output is divided into two equal power beams. The coupling lenses with 25 and 55 mm focal lengths are used to re-focus the pump light on the end facets of the laser crystal. Combined diode-pump transmission losses through the dichroic mirror and condenser lenses allow approximately 90% of the diode light as pump input to the Tm:YLF crystal. The pump diode light is focused into the crystal with a spot size of 440 μm

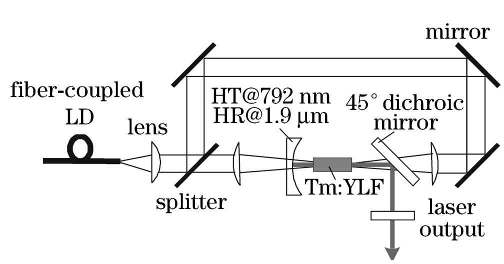

Fig. 2. Experimental setup.

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in diameter.

The resonator used is of plano-concave geometry. The high reflector acts as a resonator mirror with a 250-mm radius of curvature and also transmits the pump radiation. The reflectivity at 1.9 μm is approximately 99.8%, and the transmission at the pump wavelength is 98%. The dichroic mirror provides both high reflection (HR) at the resonating wavelength (99.8%) and high transmission (HT) at the pump wavelength (95%). The flat output coupler (OC) is coated for $\sim$ 10% transmission at 1.9 μm. The cavity has a physical length of 33 mm.

Figure 3 shows the output characteristics of the Tm:YLF laser. The lasing threshold is 2.5 W. Under pump power of 24.0 W available from the LD, the maximum power of 9.8 W is achieved with the crystal temperature of 15 °C. A linear fit to the data yields a slope efficiency of 51.4%. The optical-to-optical conversion efficiency at the maximum power level is approximately 40.9%.

The slope efficiency η is given by

$$\eta = \eta_a \eta_q \frac{T}{T+L} \frac{\nu_l}{\nu_p}, \quad (1)$$

where η_a is the pump absorption efficiency, η_q is the quantum efficiency, T is the OC transmissivity, L is the intracavity round-trip loss, ν_l is the laser frequency, and ν_p is the pump frequency. The L value is estimated to be 2% according to the reflective loss on both crystal ends and transmissive loss. According to Eq. (1) and the measured 51.4% slope efficiency, the quantum efficiency is up to 1.6, compared with the theoretically calculated value of 1.9 by Petros *et al.*[15].

The optical-to-optical conversion efficiency versus input pump power is shown in Fig. 4. From the figure, we can see that the efficiency increases rapidly in low-pump-power region. When the pump power is higher than 9.6 W, the efficiency increases slowly. At the maximal output power of 9.8 W, the optical-to-optical efficiency is up to 40.9%, which is much higher than the previously reported data.

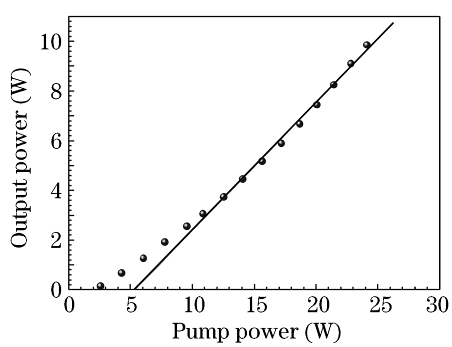

Fig. 3. Output power of Tm:YLF laser versus incident pump power.

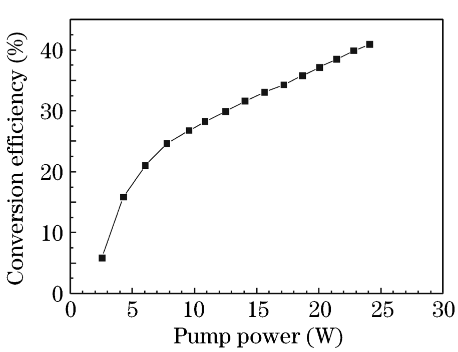

Fig. 4. Optical-to-optical conversion efficiency versus input pump power.

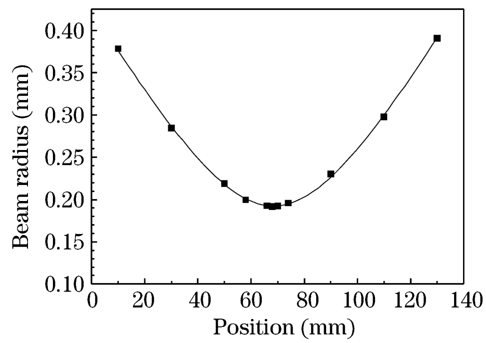

Fig. 5. Beam radius for the Tm:YLF laser at the 6.0-W output power level.

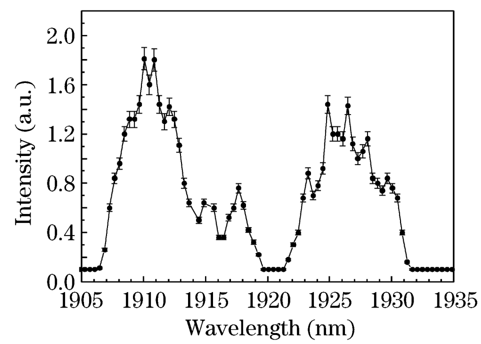

Fig. 6. Free-running output spectrum of Tm:YLF laser with the OC transmissivity of 10%.

The beam radius for the Tm:YLF laser at the 6-W output power level is also measured by the 90/10 knife-edge method. The lens (f = 200 mm) is located at the position 370 mm away from the OC. Figure 5 shows the measured beam radius at different positions after the lens. We estimate the beam quality to be $M^2 = 1.69 \pm 0.02$ by Gaussian fitting.

The wavelength of Tm:YLF laser is measured with a monochrometer (300-mm focal length, 300-line/mm grating blazed at 2000 nm). The chopped input laser is detected by a PbS detector connected with a TDS-3012B digital oscilloscope. Figure 6 shows the measured laser spectrum of the Tm:YLF laser. With a 10% transmission OC, the emission oscillates at 1910 nm with full-width at half-maximum (FWHM) of 4 nm and also at 1926 nm with FWHM of 7 nm.

In summary, we have reported a high-efficiency diode-pumped Tm:YLF laser at room temperature. The maximum CW output power is 9.8 W and the slope efficiency is 51.4%, corresponding to an optical conversion efficiency of 40.9%. The high efficiency is realized by the double-end-pumping method. In the future, the Ho:YAG laser pumped by Tm:YLF will be investigated.

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