Efficient Tm:YAG Ceramic Laser at 2 μm *

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We demonstrate a high-efficiency continuous-wave Tm:YAG ceramic laser pumped with a Ti:sapphire laser. The output power up to 860 mW is obtained under the absorbed pump power of 2.21 W at 785 nm, corresponding to a slope efficiency of 42.1% and optical to optical efficiency of 22%. The measured central wavelength is 2012 nm.

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Solid-state lasers operating in the 2 μm spectral region are very useful due to their many applications in medical, remote sensing and military technologies. As most gain media used at this eye-safe laser wavelength, the Tm^{3+}-doped crystals have shown high efficiency and output power in the cw and Q-switched laser operation. Diode pumped Tm:YAG, Tm:BaY_2F_8, Tm:$LiLuF_4$ and Tm:YLF lasers have been reported.[1−4] The highest slope efficiency of 44% was reported for the Tm:YAG crystal laser.[5] Compared with the laser crystals, the laser ceramic media have many remarkable characteristics. In particular, the ceramic laser medium can be easily fabricated in a large size, which is extremely difficult for single crystals. The short fabrication period and mass production result in lower cost than that of single crystals. Furthermore, the fracture toughness of the YAG ceramics was three times more than that of the YAG single crystal.[6] Therefore, the ceramics have a higher resistance to thermal shock than the single crystals. As the laser media, ceramic laser materials show a promising high efficiency performance in laser operation. Recently a diode-pumped Tm:YAG ceramic slab laser was reported for the first time.[7] Output power of 4.5 W was obtained with an absorbed pump power of 31.2 W, corresponding to a slope efficiency of 20.5%.

In this work, we report a high-efficiency cw Tm:YAG ceramic laser pumped with a cw Ti:sapphire laser at wavelength 785 nm. The laser characteristics were studied by using three different output couplers. For the output coupler (OC) of 3% transmission, high output power of 860 mW was obtained at the central wavelength of 2012 nm, with a slope efficiency of 42.1%. It is demonstrated that the ceramic Tm:YAG can be a promising laser material for laser operating at 2 μm spectral region due to its high efficiency, low cost and easy fabrication.

Because of the quasi-three-level laser properties of Tm^{3+} ions at room temperature and high doping concentration of Tm^{3+}, the cross-relaxation energy transfer [Tm ($^3H_4 - {}^3F_4$)-Tm ($^3H_6 - {}^3F_4$)] can occur to produce two excitations in the $^3F_4$ upper laser state for every pump photon.[1] The quantum efficiency of the $^3F_4$ state could reach nearly two. However, if the Tm^{3+}-doping concentration is too high, the oscillation threshold and the re-absorption loss will increase and cause the decreasing of the slope efficiency. Therefore, it is important to choose the proper doping concentration of Tm^{3+}. We employed a 6 at.% doped Tm:YAG ceramic (provided by the Shanghai Institute of Ceramics, Chinese Academy of Sciences) with size of 5 mm × 5 mm × 3.5 mm for our experiment. Figure 1 presents the absorption spectrum and fluorescence spectrum of the Tm:YAG ceramic.[8]

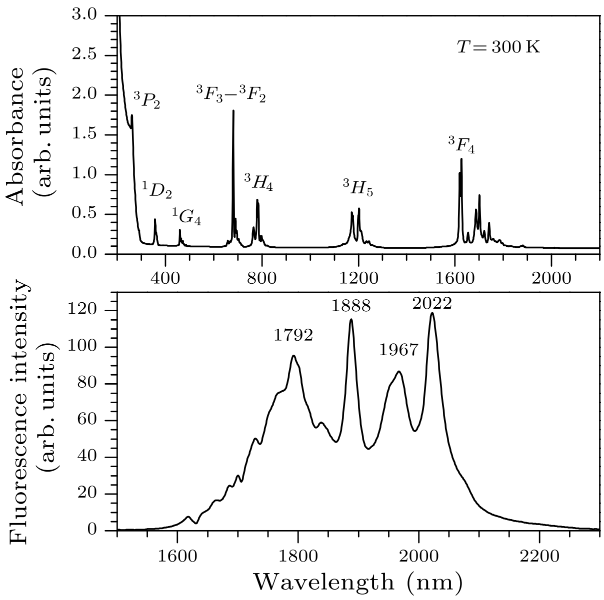

Fig. 1. The spectra of absorption and fluorescence of Tm:YAG ceramic at 6 at.%.

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To realize the laser operation in the spectral region of 2 µm, the typical Z-shape cavity was designed as depicted in Fig. 2. Two end facets of the Tm:YAG ceramic were coated with anti-reflection films at both 785 nm and 2000 nm. A pair of two concave mirrors, M1 and M2, with a radius of curvature (ROC) of 100 mm, were coated with a special dichroic film for high reflection (HR) in the region of 1900–2100 nm ($R > 99.9\%$) and anti-reflection at 785 nm. A 785 nm cw Ti: Sapphire laser was employed as a pump source to provide a maximum output power of 4.70 W. The pump beam was focused on the ceramic by a lens of 100 mm focal length. The temperature of the ceramic was maintained at 12°C by a water cooling system. The total length of the cavity was about 790 mm.

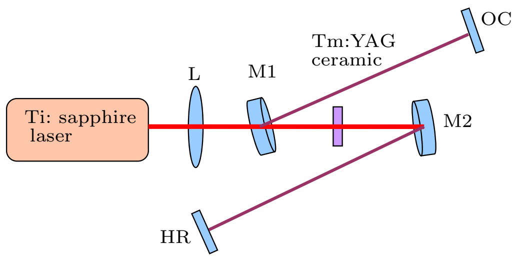

Fig. 2. Schematics of the Tm:YAG ceramic laser setup. M1, M2, concave mirrors with ROC of 100 mm; HR, plane high reflection mirror; OC, output coupler; L, lens.

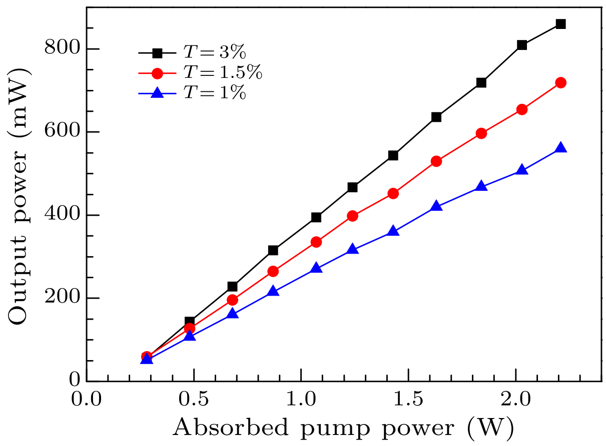

Fig. 3. Tm:YAG ceramic laser power output versus absorbed pump power with three output couplers.

Because of the loss in the optical coupling system, only 83% pump laser was focused on the Tm:YAG ceramic. In the measurement, 2.21 W was absorbed by the ceramic with a absorption of 56.7% under an incident pump power of 3.9 W. To optimize the lasing efficiency, three output couplers with transmissions of 3%, 1.5% and 1% were used in our experiments respectively. Figure 3 shows the output power of the Tm:YAG ceramic laser versus the absorbed pump power with three different output couplers. The highest output power of 860 mW was reached by using the 3% OC under an absorbed pump power of 2.21 W. The corresponding maximum slope efficiency was 42.1% and the optical conversion efficiency was 22%. For the 1.5% OC, the achieved output power was 719 mW and the slope efficiency was 34.2%. For the 1% OC, the output power and the slope efficiency were 560 mW and 26.2%, respectively. By decreasing the pump laser power, we measured the lasing threshold as 140 mW (absorbed pump power). The nearly linear increasing characteristics of the output power indicated that even higher output power should be possible if a higher power pumping source is used.

Noticing the laser power increasing with the transmission of OC within the whole pumping range in our experiment, it is obviously shown that the optimized transmission of OC should be larger than 3%. According to the rate equation for a longitudinally pumped quasi-three-level system, the output power as a function of pump power can be calculated theoretically by[9]

$$F = \frac{1 + \frac{B}{fS}\ln(1 + fS)}{f\int_0^\infty \frac{\exp[-(a^2+1)x]}{1+fS\exp(-a^2x)}dx}, \tag{1}$$

where a is the ratio of pump-beam to laser-beam waists, B is the ratio of the reabsorption loss to fixed cavity loss, F is a normalized variable proportional to pump power, and S is a normalized variable proportional to internal laser power. The expressions of the parameters a, x, f, B, F and S are shown in reference.[9] Then, in longitudinally pumped configuration, the output power and the slope efficiency can be written as[10]

$$p_{\rm out} = \frac{\pi\omega_l^2 h\nu_l T}{4\sigma\tau}S, \tag{2}$$

$$\eta = \frac{T}{T+L}\frac{\nu_l}{\nu_p}\eta_a\eta_q\frac{dS}{dF}, \tag{3}$$

where ω_l is the laser-beam waist, ν_l and ν_p are the laser and pump frequencies, respectively. T is the transmission of output coupler, L is the round-trip loss of the laser cavity, σ is the emission cross section, τ is the fluorescence lifetime of the upper manifold, η_a is the absorption efficiency of pump power, η_q is the quantum efficiency of pumping into the $^3F_4$ state. When $L = 0.006$, $\sigma = 3.04 \times 10^{-21}$ cm^2, $\tau = 11$ ms, and $a = 1$, the optimized transmission of OC is 14% (unavailable at present in our lab) for 4 W of the incident pump power. With the 14% OC, the calculated output power is 1.61 W and the slope efficiency is 73.8% (for absorbed pump power). Therefore, by employing an improved cavity configuration and optimized output coupler, higher output power and efficiency can be achieved.

The wavelength of the Tm:YAG ceramic laser was measured by a monochrometer with a resolution of 1.6 nm (Omni-λ150, 150-mm focal length, 300 lines/mm, grating blazed at 1250 nm). The chopped-input laser was detected by an HgCdTeZn infrared detector (PCI-3TE-10.6), and the signal from the detector was amplified by a lock-in amplifier (SR 830). The measured spectrum of the Tm:YAG ceramic laser is shown in Fig. 4. The central wavelength is 2012 nm with a spectral linewidth of 3 nm.

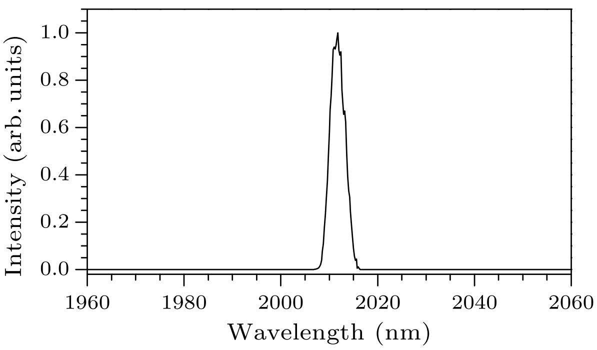

Fig. 4. Laser spectrum of the Tm:YAG ceramic.

In conclusion, we have demonstrated a high-efficiency cw Tm:YAG ceramic laser by using three different output couplers. The maximum output power of 860 mW is achieved with the slope efficiency of 42.1% when using 3% OC. The central wavelength is 2012 nm. It is believed that even higher power and efficiency should be possible by using an improved laser cavity and optimized transmission OC. It is suggested that the Tm:YAG ceramic is competitive with the single crystal and will be a promising laser medium for laser operation at 2 μm.

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