Highly efficient 2 μm Tm:YAG ceramic laser

W. L. Gao,[1] J. Ma,[1] G. Q. Xie,[1,5] J. Zhang,[2,6] D. W. Luo,[3] H. Yang,[4] D. Y. Tang,[3] J. Ma,[2,4] P. Yuan,[1] and L. J. Qian[1]

[1]*Department of Physics, Key Laboratory for Laser Plasmas (Ministry of Education), State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China*

[2]*Temasek Laboratories, Nanyang Technological University, Singapore 639798*

[3]*School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798*

[4]*School of Materials Science and Engineering, Nanyang Technological University, Singapore 639798*

[5]*e-mail: xiegq@sjtu.edu.cn*

[6]*e-mail: JianZhang@ntu.edu.sg*

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We have experimentally demonstrated a highly efficient diode-pumped Tm:YAG ceramic laser operating at 2 μm wavelength. The maximum output power of 6.05 W was realized with a slope efficiency as high as 65%. As far as we know, it is the highest slope efficiency reported for Tm:YAG ceramic laser. The wavelength tuning experiment of Tm:YAG ceramic laser was carried out and the results suggest that Tm:YAG ceramic laser could operate simultaneously at multiple wavelengths in a wide range of 1884–2017 nm.

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Tm^{3+}-activated laser materials have attracted much attention for the 2 μm eye-safe wavelength regions because of their potential applications in atmospheric, medicinal, and space applications [1–3]. The Tm^{3+}-doped materials generally exhibit strong absorption bands near 790 nm, thus it can be pumped efficiently by AlGaAs laser diodes. The laser performance of thulium-doped Yttrium aluminum garnet ($Y_3Al_5O_{12}$, YAG) single crystal has been widely studied [4–9]. The highest slope efficiency of 59% has been reported for the Tm:YAG single crystal laser pumped by Ti:sapphire laser, while the highest slope efficiency of 44% was also realized with laser diode (LD) pumping [5,6].

Transparent ceramic materials combine the advantages of single crystals and glasses. They not only possess good optical and thermal properties as fine as single crystals, but also can be fabricated with large size and high concentration. Furthermore, they also have other superiorities, such as short fabrication period, less cost, mass production, multilayers, and multifunctional samples [10,11]. In recent years, high quality Tm^{3+}-doped YAG laser ceramic materials have been fabricated with the nanocrystalline technology and vacuum sintering method. The efficient continuous wave and Q-switching operations of Tm:YAG ceramic have been reported [11–15]. For 6 at. % Tm:YAG ceramic laser, the slope efficiency of 42.1% was realized with Ti:sapphire laser pumping [12]. The output power of 17.2 W with a slope efficiency of 36.5% was also reported by diode pumping [13]. For 4 at. % Tm:YAG ceramic, an output power of 7.1 W was obtained with diode pumping, but the slope efficiency was only 10.7% [14].

In this Letter, the absorption spectrum, the fluorescence spectrum, and the laser performance of the 4 at. % Tm:YAG ceramic were investigated. The maximum output power of 6.05 W and the slope efficiency of 65% was realized in the Tm:YAG ceramic laser with 5% output coupler. With the 2% coupler, the highest output power was 5.82 W and the slope efficiency was 61%. The wavelength tuning characteristics of the Tm:YAG ceramic laser has also been investigated.

A sample of the 4 at. % Tm:YAG ceramic with dimensions of $3 \times 3 \times 4$ mm^3 was cut and the two 3 mm × 3 mm faces were optically polished. The transmission spectrum was recorded by a UV/visible/IR spectrophotometer (Cary 5000, Varian). The optical path length of transmission light was 4 mm in Tm:YAG ceramic. Figure 1 shows the transmission spectrum of Tm: YAG ceramic over the wavelength range of 200–2000 nm at room temperature. The Tm:YAG ceramic have an optical transmittance of ~85% in the nonabsorption regions. The scattering coefficient of the fabricated YAG ceramic was measured to be <0.2%/cm at 1 μm wavelength. There exist six strong Tm^{3+} absorption bands located at about 356, 458, 684, 781, 1202, and 1626 nm, which correspond to the transitions of Tm^{3+} from ground state $^3H_6$ to its excited state, $^1D_2$, $^1G_4$, $^3F_{3,2}$, $^3H_4$, $^3H_5$, and $^3F_4$, respectively. Among the measured range, the two strong absorption bands

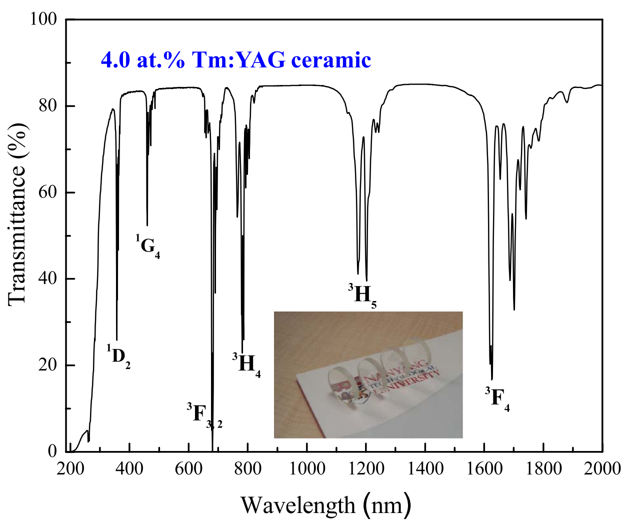

Fig. 1. (Color online) Transmittance spectrum of Tm:YAG ceramic.

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at 684 nm and 781 nm are suitable for laser diode pumping.

The absorption spectrum of the Tm:YAG ceramic from 750 nm to 810 nm at room temperature is shown in Fig. 2. There are two strong absorption bands located at 781 nm and 786 nm, which well match the emitting wavelength of high-power AlGaAs laser diodes. In the laser experiment, we used a high-power fiber-coupled laser diode as the pump source. In order to sufficiently absorbing the pump light, the wavelength of LD is fixed at 786 nm by controlling the temperature of LD module (Fig. 2).

The fluorescence spectrum of the Tm:YAG ceramic at room temperature is shown in Fig. 3. As 5 s and 5 p outer shell of Tm ions shield the transition $^3F_4 - {}^3H_6$ manifolds, the emission spectrum of Tm:YAG ceramic was characterized with a nonsmooth multiple-spike structure. The strong emission peaks are at wavelengths of 1626, 1702, 1746, 1785, 1882, 1960, and 2016 nm, respectively. The fluorescence characteristic of ceramic was generally identical to the corresponding single crystal [16]. Tm:YAG single crystal has an emission cross section of 2×10^{-21} cm^2 at 2 μm wavelength. [1]. As a quasi-three level system, the laser emission below 1.9 μm is difficult to achieve due to the reabsorption effect in the Tm-ion lasers.

Firstly, CW laser experiment was carried out with the Tm:YAG ceramic rod. The laser setup is shown schematically in Fig. 4. A high-power fiber-coupled LD at 786 nm was used as the pump source (S50-790-2, Nlight Instruments). Through focusing optics (N.A. = 0.22), the pump light was focused into the laser ceramic with a spot radius of 140 μm. The input plano–plano mirror M1 was coated with a high reflection (>99.7%) in a range of 1850–2100 nm and high transmission (>95%) at 780–810 nm. M2 mirror was plano–plano output coupler. In the experiment, two output couplers were used with a transmission of 5% and 2%, respectively. An Tm:YAG ceramic rod with Tm^{3+} concentration of 4 at. % was used as the gain media. The Tm:YAG ceramic was prepared and fabricated at Nanyang Technological University in Singapore. The ceramic rod had a dimension of 3 mm × 3 mm in cross section and 4 mm in length and was antireflectively coated at pump and laser wavelengths.

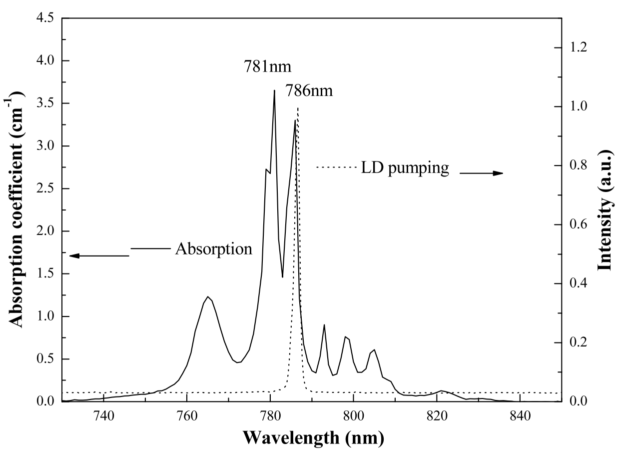

Fig. 2. Absorption spectrum of Tm:YAG ceramic (dotted line) and emission spectrum of LD (solid curve).

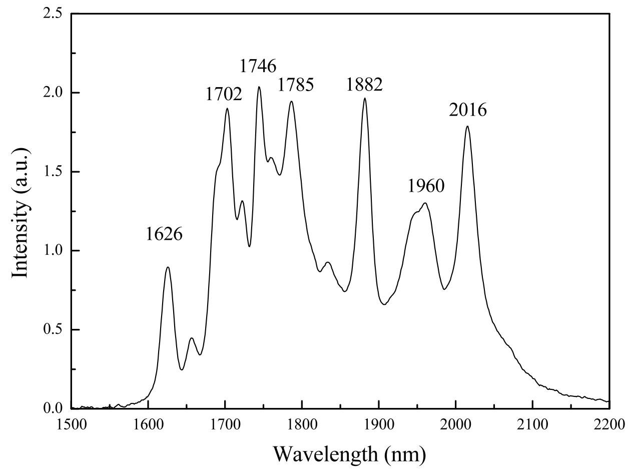

Fig. 3. Fluorescence spectrum of 4 at. % Tm:YAG ceramic.

To remove the generated heat under pumping, the ceramic rod was wrapped with indium foil and tightly mounted in a water-cooled copper block. The temperature of cooling water was maintained to be 8°C. In the experiment, the laser output power was measured by a thermal-sensor power meter (PM3201, THORLABS). The laser spectrum was recorded by an optical spectrum analyzer with a resolution of 0.22 nm (SIR-5000, SANDHOUSE).

The output power dependence on absorbed pump power is shown in Fig. 5 with different output couplings. From Fig. 5, we can see that more efficient operation was achieved by using 5% coupling in this experiment. The maximum output power of 6.05 W was obtained under an absorbed pump power of 10.68 W, with a slope efficiency of 65%. To our best knowledge, it is the highest slope efficiency reported for Tm:YAG ceramic[11–15]. The M^2 factor of the beam was measured to be around 2.5. The lasing threshold was 1.921 W of incident pump power. With the 2% coupling, the highest output power was 5.82 W and the slope efficiency was 61%. In this case, the lasing threshold was 1.428 W of incident pump power. The spectrum of Tm:YAG laser was centered at 2016 nm, which corresponds to one of fluorescence spectrum peaks of Tm:YAG ceramic. The slope efficiency of 65% achieved corresponds to a photon quantum efficiency of 1.67, which implies an efficient cross relaxation process occurs in the Tm:YAG ceramic laser [6].

The high slope efficiency operation in the laser could be explained as follows: we measured the thermal focal lengths in different pump powers according to the method reported in [17]. According to the calculation results by ABCD matrix method, we found that the laser mode in the ceramic was about 150 μm in radius and almost insensitive to thermal focal length, which is close to the pump spot size in the ceramic rod. The Rayleigh length

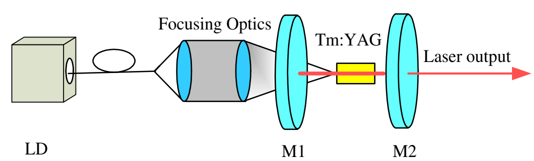

Fig. 4. (Color online) Experimental setup of Tm:YAG ceramic laser.

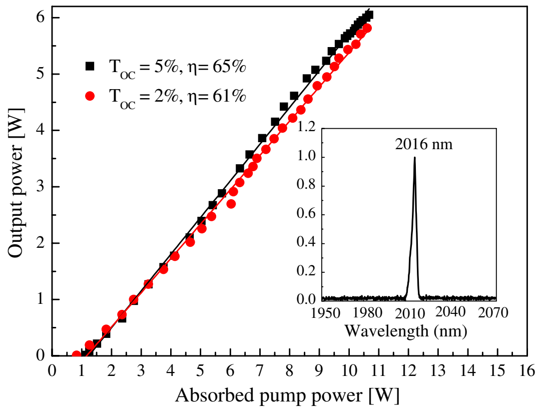

Fig. 5. (Color online) The output power versus absorbed pump power with different output couplings. Inset: the laser spectrum of Tm:YAG ceramic laser.

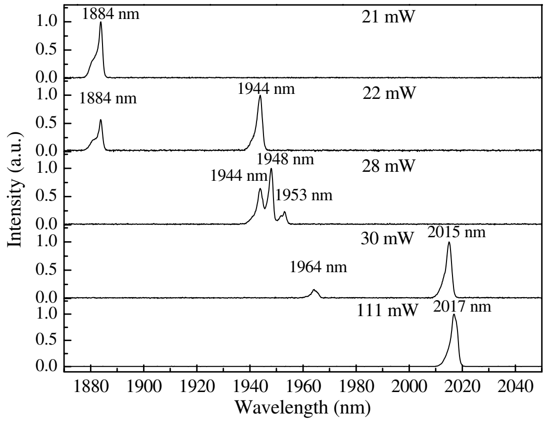

Fig. 6. Wavelength tuning operation of the Tm:YAG ceramic laser.

of focused pump light is measured to be about 2.5 mm by the knife-edge method, which is slightly shorter than the length of Tm:YAG ceramic. Thus, a good mode matching between pump light and laser mode could be achieved. On the other hand, a high quality ceramic sample with low scattering loss should be responsible for the high-efficiency operation of the laser.

In order to explore the potential of ultrashort pulse generation in the Tm:YAG ceramic, we also studied the wavelength tuning performance of the Tm:YAG ceramic. In the tuning experiment, a high-brightness single-emitter LD was used as the pump source and an X-folded cavity with an output coupling of $T = 0.5\%$ was employed. A CaF_2 prism with Brewster angle cut was used as a wavelength tuning element in the cavity. The output laser wavelengths could be tuned by rotating the angle of the output coupler. The tunable spectra and the corresponding output power of the Tm:YAG ceramic laser is shown in Fig. 6 under fixed pump power. It shows that the output laser wavelength is not continuously tunable with rotating the angle of the output coupler, which could be attributed to the multiple-spike structure of the fluorescence spectrum in the ceramic. Simultaneous multiwavelength emission of the ceramic laser was observed as shown in Fig. 6. The simultaneous dual-wavelength or three-wavelength emission is very useful for generation of THz emission and Doppler lidar. The laser has a low output power when tuned to short wavelength due to the reabsorption loss. The laser output power was only 21 mW at 1884 nm wavelength. The output power increased as the emission wavelength was tuned to long wavelength. The simultaneous dual-wavelength emission of 1884 nm and 1944 nm, 1964 nm and 2015 nm were achieved, respectively. Even three-wavelength emission at 1944, 1948, and 1953 nm was also realized when the output power was changed to 28 mW. Ultimately, the laser wavelength was tuned to 2017 nm and remained unchanged, even the output power varied from the highest value of 111 mW to 8 mW. In the wavelength tuning operation, the output laser has a round TEM_{00} mode.

In conclusion, we have experimentally demonstrated a highly efficient diode-pumped Tm:YAG ceramic laser operating at 2 μm wavelength. The maximum output power of 6.05 W was realized with a slope efficiency of 65%. As far as we know, it is the highest slope efficiency reported for Tm:YAG ceramic lasers. The wavelength- tuning experimental results suggest that Tm:YAG ceramic laser could simultaneously emit dual wavelengths or three wavelengths, which could have potential applications in THz radiation generation and Doppler lidar.

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