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High-efficiency diode-pumped Tm:YAG ceramic laser

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ABSTRACT

A high efficient Tm:YAG ceramic laser at 2007 nm pumped by a diode laser was demonstrated. The laser performances with Tm^{3+} doping concentrations of 4 at.% and 6 at.% were comparatively analyzed. The continuous-wave (CW) laser powers up to 2.11 W and 1.68 W have been obtained for Tm:YAG ceramics at 6 at.% and 4 at.% doping levels, corresponding to the slope efficiencies of 43.6% and 53.8% respectively.

1. Introduction

Diode-pumped thulium doped solid-state lasers operating in the eye-safe 2 μm spectral region have potential applications in medicine, laser radar and remote sensing, etc [1,2]. The absorption bands around 800 nm in Tm^{3+} doped materials make them can be pumped with commercially available diode lasers. Due to efficient cross-relaxation, two Tm^{3+} ions will be excited for each absorbed 785 nm pump photon [3]. Among Tm-doped materials, Tm:YAG has better thermo-mechanical properties and higher fracture limit. Thus significant research efforts have been dedicated to Tm:YAG crystal lasers and the efficiency of 49% for incident pump power by using a Thermoelectric Cooler (TEC) cooling system has been achieved [4–6].

Recently transparent ceramics have attracted great interest due to their possible application as media for high power and high energy laser operation with many significant advantages compared with single crystal materials [7–9]. For example, large ceramics with a high doping concentration can be easily fabricated, and mass production is available within a shorter fabrication period. With the progress of fabrication technology, the scattering losses of ceramics have been reduced significantly to be comparable with single crystals [10]. Furthermore, the fracture toughness and the thermal performance of ceramics are even better than those of single crystals. In 2004, an Nd^{3+} doped YAG ceramic laser with the efficiency higher than single crystals was reported by Lu et al. [11]. By using Yb^{3+}:Sc_2O_3 and Y_2O_3 composited ceramic the ultrafast laser pulse has been obtained with obviously higher output power and laser efficiency than Yb^{3+} doped crystals [12].

Following the extensively researches on Nd^{3+} and Yb^{3+} doped YAG ceramic lasers, more and more studies on the Tm:YAG ceramic laser performances have been reported in recently [13–16]. Zhang et al. demonstrated a diode-pumped CW Tm:YAG ceramic laser with 17.2 W output power corresponding to a slope efficiency of 36.5% (for the absorbed pump power) under the absorbed pump power of 53.2 W [15]. Wang et al. obtained 7.3 W output power from a CW Tm:YAG ceramic laser pumped by an Er:YAG laser at 1617 nm and the slope efficiency was as high as 62.3% [16]. However, the pumping source they used is not a common diode laser.

In this letter, we report the CW laser operation of Tm:YAG ceramic pumped by a 786 nm diode laser. The effect of Tm^{3+} doping concentration on the laser operation was studied by using two Tm:YAG ceramics to be doped 4 at.% and 6 at.% respectively. The maximum output power of 2.11 W at 2007 nm was achieved with 6 at.% doped Tm:YAG ceramic, corresponding to a slope efficiency of 43.6% (for the absorbed pump power). The highest slope efficiency of 53.8% was obtained by using 4 at.% doping. Although current result is not very high, it lights the way to use Tm:YAG ceramics for 2 μm laser operation at high level as expected.

2. Experimental setup

Two Tm:YAG ceramics with doping concentrations of 4 at.% and 6 at.% were produced by Nanyang Technological University, Singapore. Commercial Al_2O_3 power and co-precipitated Y_2O_3 and Yb_2O_3 powders were used as the starting materials, and the vacuum reactive sintering method, similar to the method described by Luo et al. [17], was used to fabricate the laser ceramics. For laser operating, two ceramic rods have same cross section of 3 mm × 3 mm but different lengths. The facets of the ceramics were all polished and antireflection coated at 786 nm and 1900–2100 nm ($R < 0.2\%$).

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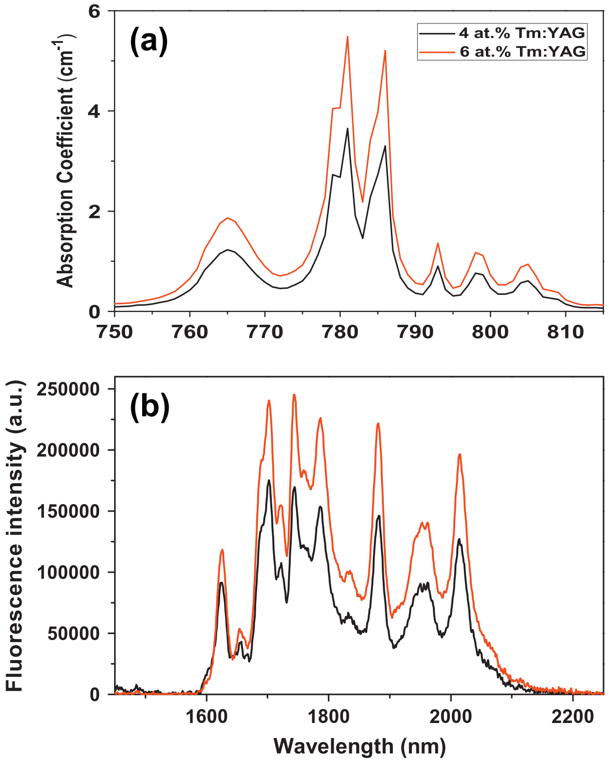

Fig. 1. Room-temperature absorption and emission spectra of Tm:YAG ceramics.

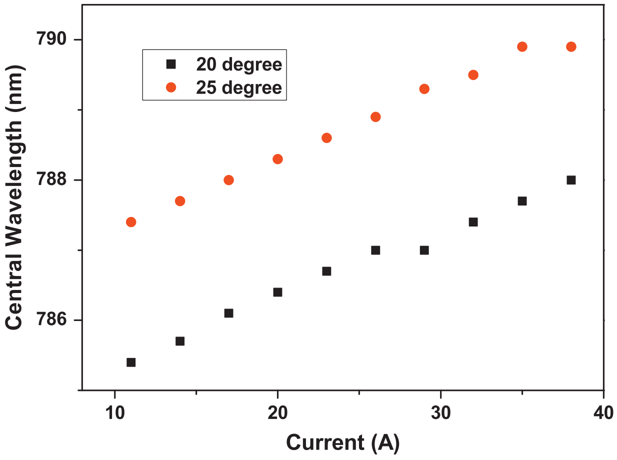

Fig. 2. Central wavelength of the diode laser under different temperatures and operating currents.

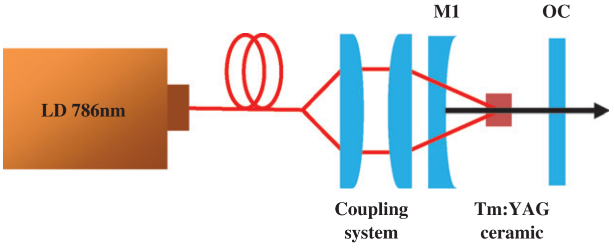

Fig. 3. Experimental setup of continuous wave Tm:YAG ceramic laser.

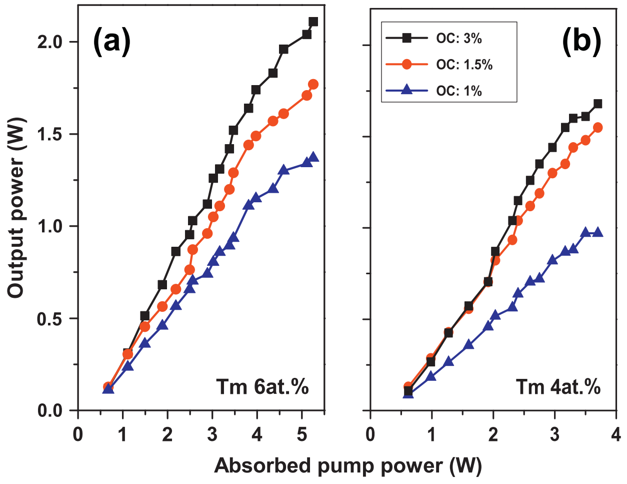

Fig. 4. Relationship between output power and absorbed pump power for Tm:YAG ceramic laser. (a) Laser output of 6 at.% Tm:YAG ceramic. (b) Laser output of 4 at.% Tm:YAG ceramic.

Wrapped with indium foil and mounted tightly in a water-cooled copper heat sink, the ceramics were considered to have efficient heat dissipation, and the water temperature was maintained at 9 °C during the experiment.

The absorption spectra of two Tm:YAG ceramics were measured by a spectrometer (Cary 5000 Spectrophotometer, Varian, USA) with a resolution of 0.5 nm at room-temperature as shown in Fig. 1a. From Fig. 1a we can see that the features of two absorption curves are similar and both have a maximum absorption band centered at 786 nm. Because the absorption coefficients of two Tm:YAG ceramics are 3.30 cm^{-1} and 5.21 cm^{-1} respectively, the lengths of two rods were chosen to be 3.9 mm and 2.7 mm for the 4 at.% and 6 at.% doping Tm:YAG ceramics in order to have the same pump absorbance during laser operating. Fig. 1b shows the fluorescence of two Tm:YAG ceramic samples.

The pump source is a fiber-coupled diode laser (LD) with a core diameter of 200 μm and a numerical aperture of 0.22 from Beijing GK laser Technology Co., Ltd. and the operating temperature range of LD is limited from 20 °C to 28 °C. The central wavelength varies with temperatures and operating currents as shown in Fig. 2. For operating at higher power or higher energy the operating current must be higher, and then the central wavelength will be higher. To match the maximum absorption band centered at 786 nm of the ceramics, the setting of operating parameters is in extremely hard condition. At the lowest operating temperature, 20 °C, the central wavelengths of the LD are 788 nm and 785 nm for the pump power at the highest and near the threshold respectively. In other words, the operating wavelength of the diode laser does not match the absorption peak (786 nm) of Tm:YAG ceramic very well. For the 6 at.% Tm:YAG ceramic, about 57.9% and 20.5% of pumping power could be absorbed at the low pumping level (about 2 W), and the high pumping (about 25 W) respectively. For the 4 at.% Tm:YAG ceramic, 45.1% and 14.4% of pumping powers could be absorbed at the low and high pumping levels, respectively.

The pump laser beam was reimaged and focused into the laser medium using a coupling system with a magnification of 0.8. The schematic of the pumping geometry and laser cavity are depicted in Fig. 3. A simple two-mirror cavity was employed. The input concave mirror M1 with a radius of curvature of 100 mm was antireflection coated at 786 nm on the both faces and high-reflection coated for a spectral range of 1900–2100 nm. The output couplers (OC) with 1%, 1.5% and 3% transmissions at 1900–2100 nm spectral regions were tested. The cavity length was 16 mm. A piece of germanium plate was used to filter the residual pump light to assure

Table 1
The CW output power characteristics of two Tm:YAG ceramics.

Ceramic doped (at.%)	OC (%)	Maximum output (W)	Optical-to-optical efficiency (for absorbed pump power) (%)	Slope efficiency (for absorbed pump power) (%)	Threshold (incident pump power) (W)
6	1	1.37	26.1	28.1	0.476
	1.5	1.77	33.7	36.6	0.476
	3	2.11	40.2	43.6	0.635
4	1	0.97	26.2	29.9	0.498
	1.5	1.55	41.9	47.6	0.429
	3	1.68	45.4	53.8	0.640

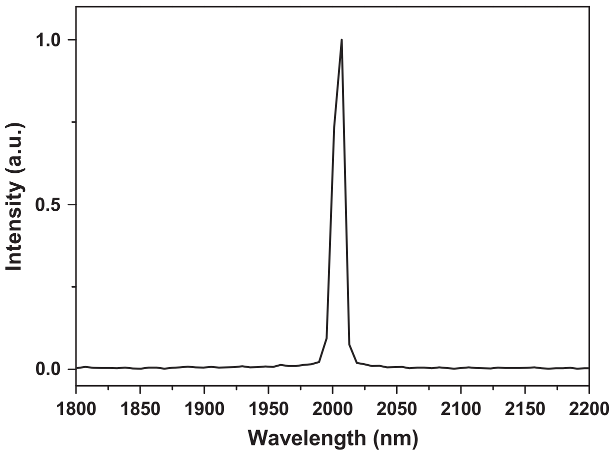

Fig. 5. Laser spectrum of Tm:YAG ceramic laser.

accuracy measuring of the laser output power by a power meter (PM30, Coherent, Inc.).

3. Results and discussion

The laser performances were carried out for both 4 at.% and 6 at.% Tm:YAG ceramics with three different output couplers (OCs). The results are shown in Fig. 4a, b and Table 1. The absorbed pump power was measured by subtracting the transmitted pump power from the incident pump power under non-lasing condition. From Table 1, we can see that the highest output power 2.11 W was given by 6 at.% Tm:YAG ceramic. The output power of 1.68 W, corresponding to a slope efficiency of 53.8% or an optical conversion efficiency of 45.4%, was given by 4 at.% Tm:YAG ceramic using the 3% OC. The slope efficiency of 4 at.% doping is higher than that of 6 at.% doping and may be resulted from the reduced upconversion of the 4 at.% doped ceramic.

The germanium used to filter the residual pump light was coated for antireflection (AR) from 2 μm to 4 μm. However, there still is a part of laser beam reflected. The loss of the germanium plate at 2 μm laser was measured to be 13%. Thus the actual laser output was even higher. It is undoubted that the mismatch between the wavelength of pumping diode and the absorption peak of Tm:YAG ceramic effects strongly on the lasing efficiency. We believe that higher output power and slope efficiency could be achieved if the pumping source has more suitable operating wavelength.

The output laser spectrum was measured by an optical spectrum analyzer with a resolution of 6 nm (NIRQUEST, Oceanoptics). The center wavelength was 2007 nm for both 4 at.% and 6 at.% doped ceramics (see Fig. 5), the bandwidth reached the resolution limit of the optical spectrum analyzer.

4. Conclusions

In conclusion, efficient 2007 nm Tm:YAG ceramic lasers pumped by a diode laser were demonstrated. The effect of doping concentration on the laser operating was experimentally observed. The 6 at.% Tm:YAG ceramic gave the maximum output power of 2.11 W with the slope efficiency of 43.6%. The highest slope efficiency of 53.8% was given by the 4 at.% Tm:YAG ceramic. As is well known, the optimization of the laser output power for a given pump power usually involves a compromise between high slope efficiency and low threshold pump power. There is a potential improvement over the reported experimental result by choosing the various parameters (including cavity structure and crystal parameters).

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