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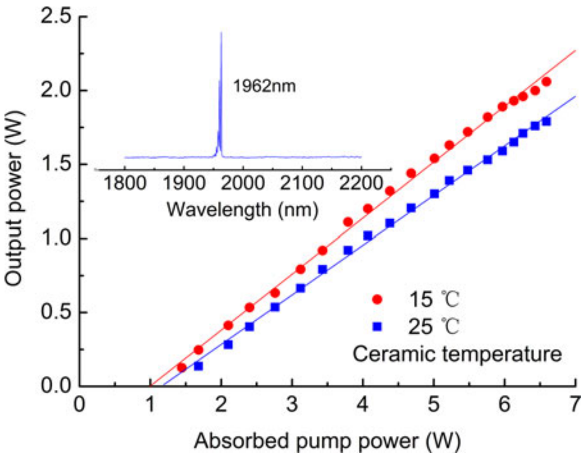

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1.96-μm Tm:YAG Ceramic Laser

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Abstract: We have demonstrated an efficient diode-end-pumped continuous-wave Tm:YAG ceramic laser at 1962 nm using a compact two-mirror cavity. The laser oscillation at 1962 nm was realized by increasing the cavity loss at 2016 nm to limit oscillation with the strongest laser gain. For comparison, two different output couplers were used to build single wavelength lasers operating at 1962 and 2016 nm. A laser output power of 2.06 W at 1962 nm was achieved for an absorbed pump power of 6.59 W with the laser ceramic temperature maintained at 15 °C. The corresponding slope efficiency and conversion efficiency were calculated to be 37.8% and 31.3%, respectively. In contrast, the maximum output power at 2016 nm was approximately 3.47 W under the same conditions. The 1962 nm laser has potential application in the analysis of CO_2 and HBr molecular gases.

Index Terms: Tm:YAG laser, laser ceramic, 1962 nm.

1. Introduction

Thulium-ion (Tm^{3+}) lasers operating in the 1.9-2.1 μm spectral region, which has the characteristics of eye-safe, atmospheric transparency, and overlap with the absorption bands of molecular gases, are widely used in remote sensing, medical treatment, atmosphere monitoring, and laser radar [1]–[4]. The lasing wavelength varied as the Tm^{3+} doped into different host materials. The typical Tm^{3+}-doped laser materials are Tm:YLF, Tm:KLu$(WO_4)_2$,Tm:YAP, and Tm:YAG. YAG was recognized as an excellent laser host material due to its attractive thermal and optical properties. In comparison with other laser materials (such as YLF), YAG is mechanically harder and chemically more stable. This finding results in easier machining and polishing of YAG. The higher thermal conductivity and hardness of the YAG crystal contribute to sustain a much higher heat load, and, hence, a higher laser output power can be expected. In 1965, Johnson *et al.* first reported the spectrum and continuous oscillation of Tm^{3+} ions in YAG [5]. In 1997, Honea *et al.* obtained a laser output power of 115 W at a wavelength of 2.01 μm using a 360 W, 805 nm scalable diode-end-pumped YAG/Tm:YAG/YAG diffusion-bonded crystal laser system [6]. Liu *et al.* reported a 100 W Tm:YAG slab laser at a wavelength of ~2015 nm using an incident pump power of 350 W with a slope efficiency of 33.6% [7]. Recently, efficient Q-switched Tm:YAG lasers operating at a wavelength of

2 μm have also been reported [8], [9]. Most work surrounding Tm:YAG lasers has been focused on the laser emission above 2.0 μm. In contrast, the typical Tm^{3+}-doped laser materials such as Tm:YLF [10]–[12], Tm:KLu$(WO_4)_2$ [13], [14], and Tm:YAP [15]–[17] can offer different laser emission wavelengths below 2.0 μm. It is well known that Tm:YAG also shows a wide fluorescence spectrum from 1500 to 2200 nm at room temperature. Using a birefringent plate, Stoneman *et al.* reported a wavelength tunable Ti:sapphire laser pumped Tm:YAG emission from 1.9 to 2.1 μm [18]. Though the main feature of Tm:YAG has been the emission above 2.0 μm, the potential for laser emission below 2.0 μm and possible differences compared to other typical Tm^{3+}-doped laser materials is also interesting. The absorption bands of many molecular gases (such as CO_2 and HBr) are centered at 1.96 μm [18], therefore, laser emission at 1962 nm also has potential application in the analysis of molecular gases.

YAG ceramic is superior to crystal given that it can be prepared with a large size at low cost [19]–[21]. Furthermore, the flexibility in the doping concentration of transparent ceramics is higher than that of single-crystal materials [22]. The fracture toughness and thermal performance of ceramics are even better than that of crystals. As a lasing medium, ceramic laser materials have attracted much attention because of their excellent performance [23], [24]. In 2009, Zhang *et al.* manufactured highly transparent Tm:YAG ceramic with an in-line transmittance of 84.0% at 2015 nm [25]. A maximum output power of 4.5 W was obtained with a maximum absorbed pump power of 31.2 W and a slope efficiency of 20.5%. Gao *et al.* reported the highest slope efficiency for a Tm:YAG ceramic of up to 65% [26], which is higher than the best result of 59% obtained using a single-crystal [6]. Wang *et al.* reported a Tm:YAG ceramic laser band pumped by an Er:YAG laser at 1617 nm with a slope efficiency of 62.3% [27]. Liu *et al.* also reported a wavelength tunable Tm:YAG ceramic emission from 1956 to 1995 nm [28]. A maximum output power of 1.51 W at 1990.5 nm had been achieved with 37.8 W absorbed pump power.

In this paper, Tm:YAG ceramic lasing at a single wavelength of 1962 nm was demonstrated using a compact two-mirror cavity. Lasing characteristics for the Tm:YAG ceramic at 1962 nm and 2016 nm were investigated with two different output couplers. The maximum output power of 2.06 W at 1962 nm was obtained for an absorbed pump power of 6.59 W, corresponding to a slope efficiency of 37.8%.

2. Spectral Characteristics of Tm:YAG Ceramic

The laser transition of Tm:YAG is a quasi-three level system at room temperature, with the 1.9-2.1 μm laser operation based on the $^3F_4 \rightarrow {}^3H_6$ transition in Tm^{3+}-ions. The upper laser level ($^3F_4$) is excited through the cross-relaxation process $^3H_4 + {}^3H_6 \rightarrow {}^3F_4 + {}^3F_4$, which means that two Tm^{3+}-ions are excited into the $^3F_4$ level with each photon (of wavelength of approximately 786 nm) absorbed by the $^3H_4$ level [29]. Due to this cross-relaxation, the Tm^{3+}-ion-doped laser has a high quantum efficiency (of nearly 2). In actual operation, the cross-relaxation in Tm^{3+}-ions is a "two-for-one" process, leading to highly efficient laser operation with a slope efficiency well above the Stokes limit (39%) [30], [31]. High Tm^{3+}-doping concentration generates a short fluorescence lifetime and larger thermal effect [6], [32]. In contrast, low concentration doping causes a reduction in the population probabilities of atoms. In our experiments, we investigated Tm:YAG ceramic samples with a Tm^{3+}-ion-doping concentration of 3.0, 4.0, and 6.0 at.% that were fabricated using the solid-state sintering method under high vacuum conditions.

The absorption and emission cross-section spectra of Tm:YAG ceramic from 1500 nm to 2200 nm are shown in Fig. 1. The data show strong emission peaks due to Tm^{3+} ions at wavelengths of 1702, 1746, 1785, 1882, 1962, and 2016 nm. The cross-section spectra of Tm:YAG ceramic and crystal have been compared to each other in a study by Zhang *et al.* [8], which shows that the spectrum of Tm:YAG ceramic is not exactly the same as that of Tm:YAG crystal. The emission peak intensities at 1882 and 1962 nm are higher in Tm:YAG ceramic than in Tm:YAG crystal. This higher intensity makes laser emission at 1.96 μm more favorable in Tm:YAG ceramic than in Tm:YAG crystal. From Fig. 1, we can see that the emission peaks below 1900 nm show strong overlap with the absorption spectrum. Therefore, it is difficult to achieve laser emission

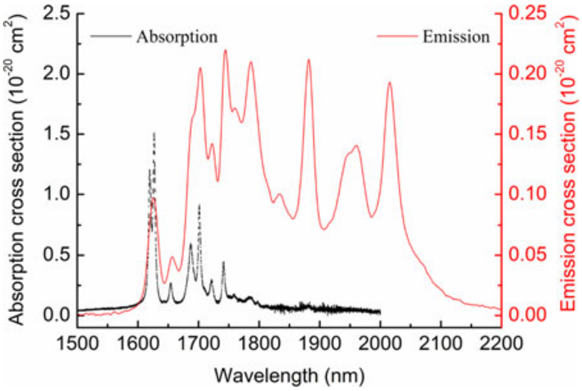

Fig. 1. The absorption and the emission cross-section spectra of the Tm:YAG ceramic between 1500 nm and 2200 nm.

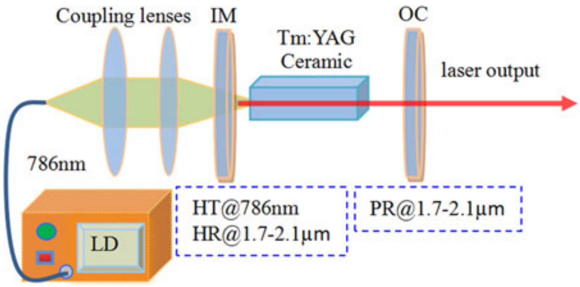

Fig. 2. Schematic diagram of LD end-pumped Tm:YAG ceramic laser setup.

below 1900 nm in the Tm^{3+}-ion laser with a quasi-three level system due to the reabsorption effect. The emission intensity and cross-section of Tm:YAG ceramic at 2016 nm is stronger than that at 1962 nm. Consequently, laser operation at a wavelength of 2016 nm is easier to achieve than at 1962 nm. According to the theory of simultaneous dual-wavelength lasing, single wavelength laser operation is only realized in the case of a sufficiently large difference between the thresholds of two single wavelength lasers [33]. Therefore, we must increase the lasing threshold at 2016 nm by increasing cavity loss to achieve oscillation at the weak-gain wavelength of 1962 nm.

3. Experimental Setup Design

The schematic diagram of the experimental setup is shown in Fig. 2. Tm:YAG ceramic samples with a Tm^{3+}-ion-doping concentration of 3.0, 4.0, and 6.0 at.% and of dimensional size of $2 \times 3 \times 5.8$ mm^3, $2 \times 3 \times 6$ mm^3, and $2 \times 3 \times 4$ mm^3, respectively, were used as the gain medium. Both end faces of the ceramic rods were polished and coated with an anti-reflection coating from 1.7 to 2.1 μm. Up-conversion and the reabsorption effect in Tm:YAG will inevitably result in a decrease in efficiency of the laser. By holding the Tm:YAG ceramics at a low temperature one can effectively reduce the up-conversion and reabsorption effect [21]. Therefore, to avoid negative thermal effects, Tm:YAG ceramic samples were wrapped with indium foil and tightly mounted in a water-cooled copper heat sink.

A fiber-coupled laser diode (LD) operating at 786 nm with a core diameter of 100 μm and a numerical aperture of 0.22 was used as the pump source for the Tm:YAG ceramic laser. The laser beam was focused onto the laser medium using two coupling lenses with focal lengths of 30 mm and 100 mm. The focused beam spot diameter was approximately 330 μm. A simple compact two-mirror linear cavity was used. The input concave mirror (M1) with a radius of curvature of 200 mm was coated on one side with an anti-reflection ($T > 98\%$) coating at 786 nm and on the op-

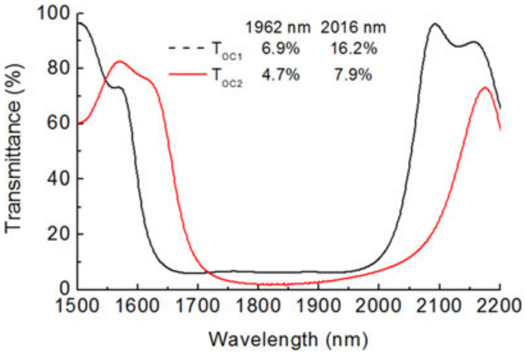

Fig. 3. Transmittance for both output couplers OC1 and OC2.

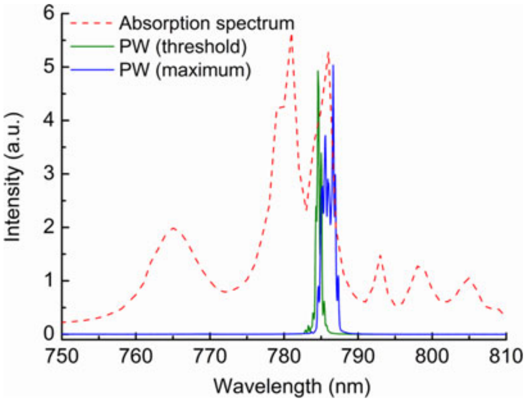

Fig. 4. The absorption spectrum of Tm:YAG ceramic and the pump laser wavelengths at the threshold and maximum output currents.

posite side with a high-reflection (R > 99.8%) coating from 1.7 to 2.1 μm. To obtain a laser output at 1962 nm, we increased the transmittance loss at 2016 nm. Two different output mirrors (OC1 and OC2) were used for laser operation; the transmittance of OC1 and OC2 at 1962 nm and 2016 nm is shown in Fig. 3. The transmittance at 1962 nm of both output concave mirrors was lower than that at 2016 nm. In particular, the transmittance of OC1 at 1962 nm and 2016 nm was 6.9% and 16.2%, respectively and that of OC2 at 1962 nm and 2016 nm was 4.7% and 7.9%, respectively.

4. Results and Discussions

The laser performance for Tm:YAG ceramic with three different Tm^{3+}-doping concentrations was comparatively investigated at different cooling temperatures. For the 4.0 at.% Tm^{3+}-doped sample held at a temperature of 15 °C, maximum output powers of 2.06 W and 3.47 W were obtained using an incident pump power of 13.2 W with OC1 and OC2, respectively. However, lower maximum output powers of 1.71 W and 1.43 W were obtained with OC1 for the 3.0 at.% and 6.0 at.% Tm:YAG ceramic samples, respectively. Therefore, the 4.0 at.% Tm:YAG ceramic demonstrated a much higher output power and was the main focus of further work. Upon increasing the temperature of the 4.0 at.% Tm:YAG ceramic to 25 °C, maximum output powers of 1.79 W and 3.27 W were obtained using OC1 and OC2, respectively.

The slope efficiency of the laser output at both 1962 nm and 2016 nm with respect to the incident pump power decreased after the incident pump power exceeded a certain value. This decrease was caused by deviation in the pump laser wavelength away from the peak absorption of Tm:YAG ceramic. Fig. 4 shows the absorption spectrum of Tm:YAG ceramic from 750 to 810 nm and the

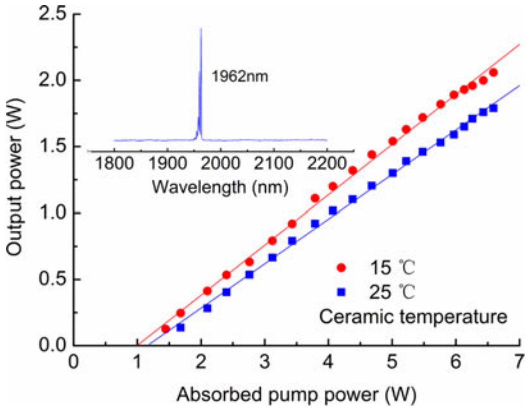

Fig. 5. Laser output power versus absorbed pump power with OC1; inset shows the laser spectrum.

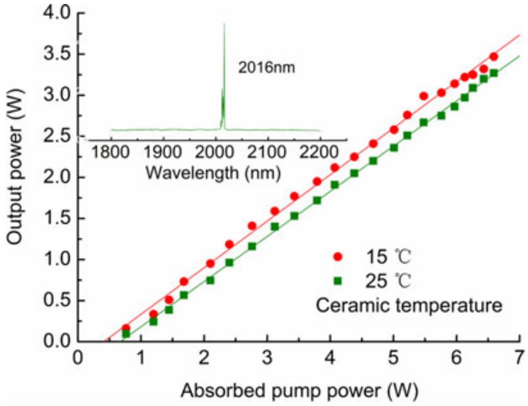

Fig. 6. Laser output power versus absorbed pump power with OC2; inset shows the laser spectrum.

practical pump laser wavelength at the threshold and maximum output currents. The pump laser wavelength deviated from the absorption peak at 786 nm of the Tm:YAG ceramic for LD current operation at maximum laser output. Although the pump wavelength was not well matched with the Tm:YAG peak absorption wavelength, we found that the laser output power increased with the absorbed pump power and maintained a linear relationship. The laser output power versus the absorbed pump power for each of the two output couplers OC1 and OC2 are shown in Figs. 5 and 6, respectively. The insets show the laser output spectrum measured by a monochromator with a resolution of 0.05 nm. Over the wavelength range from 1800 to 2200 nm, laser wavelengths of 1962 nm and 2016 nm were detected for OC1 and OC2 output mirrors, respectively.

Figs. 5 and 6 also show the laser output power as a function of the absorbed pump power for different ceramic temperatures held at 15 and 25 °C. The data show that higher output power was achieved at the lower temperature of the laser ceramic, which is a typical characteristic of quasi-three level system laser operation. We can also see that the 1962 nm laser output is more sensitive to the ceramic temperature, which may be caused by a more severe reabsorption effect compared to laser operation at 2016 nm. The laser oscillation at 2016 nm has a higher threshold compared to that at 1962 nm because of the higher transmittance of OC1 at 2016 nm than at 1962 nm. Therefore, the upper laser level population was consumed by the transition at 1962 nm rather than that at 2016 nm. Although the transmittance of OC2 at 2016 nm was slightly higher than at 1962 nm, the laser oscillation at 2016 nm, with its large cross-section, still showed a lower threshold compared to that of laser oscillation at 1962 nm, resulting in the observed laser output at 2016 nm. Therefore, we can understand that the higher efficiency and output power obtained using OC2 compared to that for OC1 was caused by strong-gain laser oscillation at 2016 nm. The 1962 nm laser has a threshold of approximately 1.0 W, which is higher than the 2016 nm laser threshold of approximately 0.5 W. For the 1962 nm laser, the maximum output power of 2.06 W was achieved at the maximum available absorbed pump power of 6.59 W. The slope efficiency and the conversion efficiency calculated with respect to the absorbed pump power were 37.8% and 31.3%, respectively. In contrast, the 2016 nm laser has a slope efficiency of 56.3% and a conversion efficiency of 52.7%. Therefore, the 1962 nm laser with its small cross-section shows relatively lower efficiency and output power compared to the 2016 nm laser.

5. Conclusion

Tm:YAG ceramic lasing at wavelength below 2.0 μm was demonstrated using a compact two-mirror cavity and laser diode end-pumped system. Laser oscillation at 1962 nm was realized by increasing the cavity loss at 2016 nm to limit oscillation with the strongest laser gain. The Tm:YAG ceramic laser performance at both 1962 nm and 2016 nm was investigated using two different output couplers. Ceramic samples with different Tm^{3+}-doping concentrations that were held at different cooling temperatures were compared. The laser operation at 1962 nm with its more severe reabsorption was more sensitive to the ceramic temperature than laser operation at 2016 nm. Maximum output power of 2.06 W at 1962 nm was achieved for an absorbed pump power of 6.59 W and an incident pump power of 13.2 W with the laser ceramic temperature maintained at 15 °C. The corresponding slope efficiency and optical conversion efficiency with respect to the absorbed pump power were calculated to be 37.8% and 31.3%, respectively. The 1962 nm laser has potential application in the analysis of molecular gases.

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