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Efficient continuous wave and acousto-optical Q-switched $Tm:Lu_2O_3$ laser pumped by the laser diode at 1.7 μm

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ABSTRACT

A resonantly-pumped continuous wave and acousto-optical (AO) Q-switched $Tm:Lu_2O_3$ laser was demonstrated in this paper. In the continuous-wave regime, with absorbed pump power of 15.4 W, the $Tm:Lu_2O_3$ laser delivered a maximum output power of 6.1 W and a slope efficiency of 66.4% with respect to the absorbed pump power. With a pulse repetition frequency of 10 kHz, the AO Q-switched $Tm:Lu_2O_3$ laser produced maximum average output power of 3.87 W. At the pulse repetition frequency of 5 kHz, the AO Q-switched $Tm:Lu_2O_3$ laser reached the maximum pulse energy of 0.74 mJ and the minimum pulse width of 46 ns, resulting in a peak power of 16.1 kW.

1. Introduction

The diode-pumped solid-state lasers (DPSSL) operating at 2 μm have many applications in medicine, remote sensing, material processing and pumping of mid-infrared optical parametric oscillators. Until now, many hosts doped by Tm-ions have been investigated as the laser medium to generate the 2-μm laser radiations. Among these mediums, the sesquioxides (such as $Tm:Y_2O_3$, $Tm:Lu_2O_3$ and $Tm:Sc_2O_3$) have high thermal conductivity and wide luminescence band in the 2-μm spectral range, bring about a new chance to achieve the efficient laser output with longer than 2.05 μm wavelength.

Based on the $^3H_6 \rightarrow ^3H_4$ transition, the common pumping wavelength of Tm-doped laser is about 800 nm, which has high pump quantum efficiency owing to the cross-relaxation process. There is another pumping choice which is located at around1.2 μm based on the $^3H_6 \rightarrow ^3H_5$ transition. Nowadays, the continuous wave (CW) and pulsed Tm-doped sesquioxides have been demonstrated with the pumping wavelength of near infrared 800 nm or 1.2 μm [1–6]. Tens watts output power was already obtained under 800 nm pumping [2]. However, high thermal loading was accompanied with near infrared pumping due to high quantum defect, which limits the improving of output power and efficiency in Tm-doped sesquioxide lasers.

An alternative way to overcome this issue is to pump Tm-ions by 1.6–1.7 μm wavelengths based on the $^3H_6 \rightarrow ^3F_4$ transition. This pumping approach was called resonantly-pumping or in-band pumping scheme. In 2001, Cornacchia et al. demonstrated the first Tm,Ho:YLF laser by this scheme [7]. Presently, resonantly-pumped Tm:YAG ceramic, $Tm:KY(WO_4)_2$, $Tm:CaYAlO_4$, $Tm:CaGdAlO_4$, Tm:YLF and Tm-fiber lasers have been widely investigated [8–13]. There is less research on the resonantly-pumped Tm-doped sesquioxide lasers. In 2014, Larin et al. demonstrated an efficient 1940 nm $Tm:Lu_2O_3$ ceramic amplifier pumped by 1678 nm [14]. In 2015, Tokurakawa et al. reported a 1611.5 nm pumped $Tm:Sc_2O_3$ laser with slope efficiency of 74% [15]. In 2016, Ntipov et al. demonstrated a 1670 nm pumped $Tm:Lu_2O_3$ ceramics laser with an output power of 23 W at 2.06 μm and an optical conversion efficiency of 51% [16]. In above works on resonantly-pumped Tm-doped sesquioxide lasers, the pump source is Raman-shifted fiber laser, so they are not real "all solid-state".

In this paper, to the best of our knowledge, a LD-resonantly-pumped $Tm:Lu_2O_3$ laser was demonstrated for the first time. Two LDs with central wavelength of 1725 nm were employed as the pump source, with dual end-pumping architecture, the output power of 6.1 W at 2.06 μm was obtained with absorbed pump power of 15.4 W, corresponding to a slope efficiency of 66.4% with respect to the absorbed pump power. In addition, the M^2 factor of diode-pumped $Tm:Lu_2O_3$ laser was estimated to be about 1.7 at maximum output level. Under AO Q-switched regime, the average output powers of 3.87 W and 3.71 W were obtained at PRFs of 10 kHz and 5 kHz, respectively. The minimum pulse width of 46 ns was achieved.

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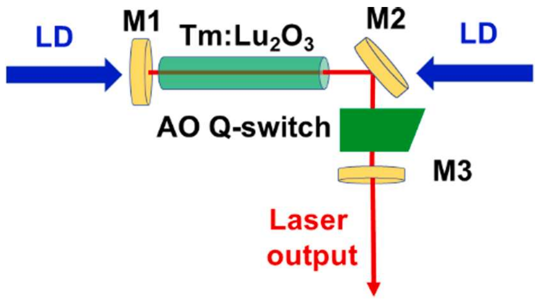

Fig. 1. The experimental setup of $Tm:Lu_2O_3$ laser dual-end-pumped by the LD at 1.7 µm.

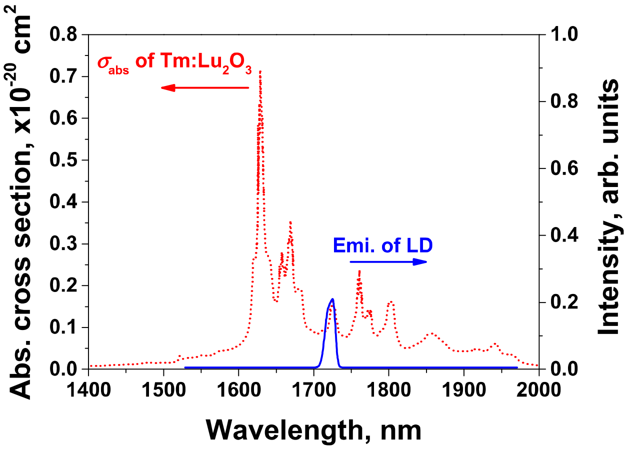

Fig. 2. Absorption cross sections [1] of $Tm:Lu_2O_3$ and output wavelength of LD.

2. Experimental setup

In order to realize the dual-end-pumping architecture, a three-mirrors folded cavity was used in this work, which was schematically shown in Fig. 1. The $Tm:Lu_2O_3$ crystal which has 2 at.% doping concentration was employed in this experiment. The cross section of laser crystal was 3 × 3 mm^2, and the doping length was 14 mm. Both end-faces of $Tm:Lu_2O_3$ crystal were antireflection coated for pump and laser wavelength. The laser crystal was sandwiched by two cooper heat sinks, which was controlled at 15 °C by the thermoelectric cooler. Two 1.7-µm fiber coupled LDs were used as the pump source, which has core diameter of 400 µm, numerical aperture of 0.22, and maximum output power of 20 W. We used simple 1:1 telescope to collimate and refocus the pump beam into the laser crystal. The pump spot radius was about 400 µm in the laser crystal. The operating temperature of LDs was controlled by cooled water. A wavemeter (Bristol 721A) was used to record the variation of wavelength of LD depending on its output power at operating temperature of 25 °C. The output spectrum at maximum output level was depicted with the absorption cross sections of $Tm:Lu_2O_3$ crystal in Fig. 2. It can be seen that good overlap was achieved between pump spectrum and absorption peak of 1725 nm. However, the spectrum overlap is not always optimal owing to the unstable central wavelengths of LD with different output levels. In order to evaluate the actual pump absorption of $Tm:Lu_2O_3$ crystal, we have measured it with different LD powers under nolasing conditions. As a result, the single-pass absorption efficiency increased from 56% to 72% with increasing of LD power from threshold to maximum.

A three-mirrors folded cavity was used in the experiment. The 0° plane input mirror M1 was coated for high transmission at 1.7 µm and high reflective at 2.06 µm. A 45° dichromatic mirror M2 was used to separate the pump and laser. The plano-concave output coupling M3 with radius of curvature of 500 mm was used in this experiment. As we know, there are two lasing wavelengths of 1.96 µm and 2.06 µm in $Tm:Lu_2O_3$ crystal. In order to inhibit the 1.96 µm oscillation, the M3 mirror was also coated with transmittance of 70% for 1.96 µm. A quartz acousto-optical (AO) Q-switch (SGQ41-2000-1QC, CETC) with length of 35 mm and aperture of 1.8 mm was employed for Q-switching operation. The diffraction efficiency was more than 45%. The rated radio frequency power was 20 W at a frequency of 41 MHz.

3. Experimental results

Firstly, without AO Q-switch, we investigated the efficient CW output characteristics of $Tm:Lu_2O_3$ laser. The physical cavity length was about 20 mm. In the experiment, three output transmittances of 5%, 10% and 15% were used to investigate the output characteristics of $Tm:Lu_2O_3$ laser, as shown in the Fig. 3(a). With T = 5% and absorbed pump power of 15.4 W, the best output performance was obtained with maximum output power of 6.1 W and slope efficiency of 66.4% with respect to the absorbed pump power. With T = 10% and the same pump power, the $Tm:Lu_2O_3$ laser yielded the 5.4 W output power and 59.2% slope efficiency. At T = 15%, the maximum output power and slope efficiency decreased to 4.8 W and 55.4%, respectively. For T = 5% and 10%, the pump threshold was same 6.2 W. With T = 15%, the pump threshold increased to be about 6.8 W. In this work the pump absorption is low. The conversion efficiency could be improved with increasing of pump absorption, which was accomplished by using of longer crystal and wavelength-locked LDs. In addition, with optimizing of ratio between the pump and laser radii, the conversion efficiency also could be improved. The output spectra of $Tm:Lu_2O_3$ laser were measured by the

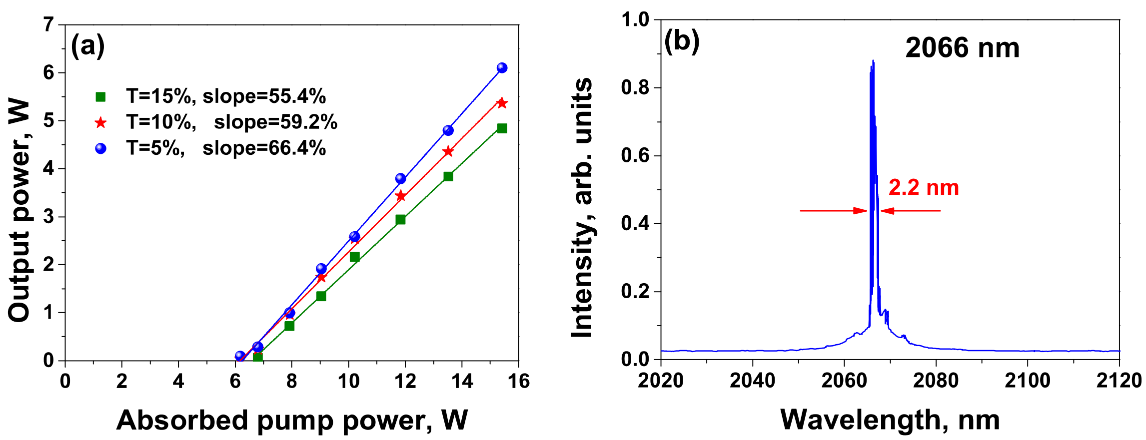

Fig. 3. The output powers and spectrum of dual-end-pumped $Tm:Lu_2O_3$ laser.

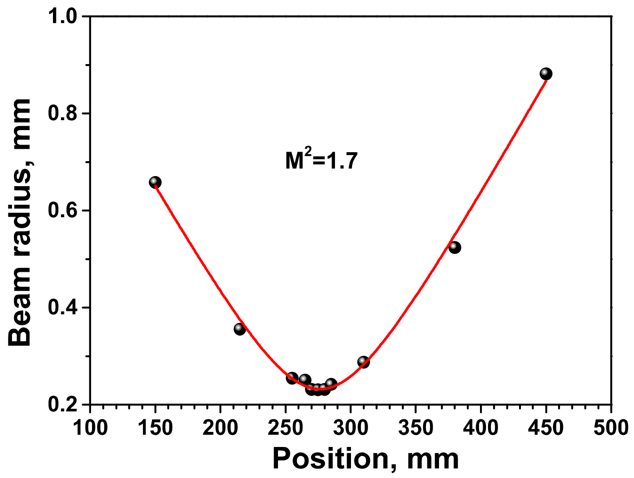

Fig. 4. . The measurement of M^2 factor of $Tm:Lu_2O_3$ laser at maximum output.

wavemeter (Bristol 721 A) under above mentioned three output transmittances. One oscillation line was observed in the experiment, which has central wavelength of 2066 nm with full width at half maximum linewidth of about 2.2 nm, as shown in Fig. 3 (b).

The M^2 factor of $Tm:Lu_2O_3$ laser at maximum output level was estimated by the 90/10 knife-edge method. A lens with long focal length of 150 mm was served to transform the output beam. The beam radii were recorded at different positions along the beam propagation direction, as shown in Fig. 4. The parametric of output beam was achieved by fitting of measured data. As a result, the M^2 factor was calculated to be about 1.7.

With inserting of AO Q-switch, the physical cavity length was extended to be about 60 mm. By using the output coupler with T = 5%, the AO Q-switching performance of $Tm:Lu_2O_3$ laser was investigated. Fig. 5(a) shows the output powers depended on the absorbed pump power. When the RF driver is power off, the $Tm:Lu_2O_3$ laser produced 4.12 W CW output power at absorbed pump power of 15.4 W. With PRF of 10 kHz, at same absorbed pump power, a maximum average output power of 3.87 W was obtained with a slope efficiency of 44.4%. With decreasing the PRF to 5 kHz, average output power of 3.71 W was realized with a slope efficiency of 42.5%.

Fig. 5 (b), (c) and (d) depict the pulse energies, pulse widths and peak powers of AO Q-switched $Tm:Lu_2O_3$ laser, respectively. With the PRF of 10 kHz, the pulse width decreased from 260 ns to 79 ns and the pulse energy increased from 0.05 mJ to 0.39 mJ, corresponding to calculated peak power from 0.04 kW to 4.9 kW. At PRF of 5 kHz, the minimum pulse width was decreased to be 46 ns, corresponding to a maximum pulse energy of 0.74 mJ and a maximum peak power of 16.1 kW. The profile of the minimum pulse width was given in Fig. 6.

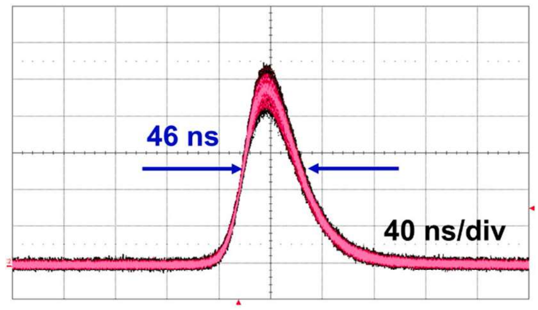

Fig. 6. The profile of minimum pulse width of AO Q-switched $Tm:Lu_2O_3$ laser.

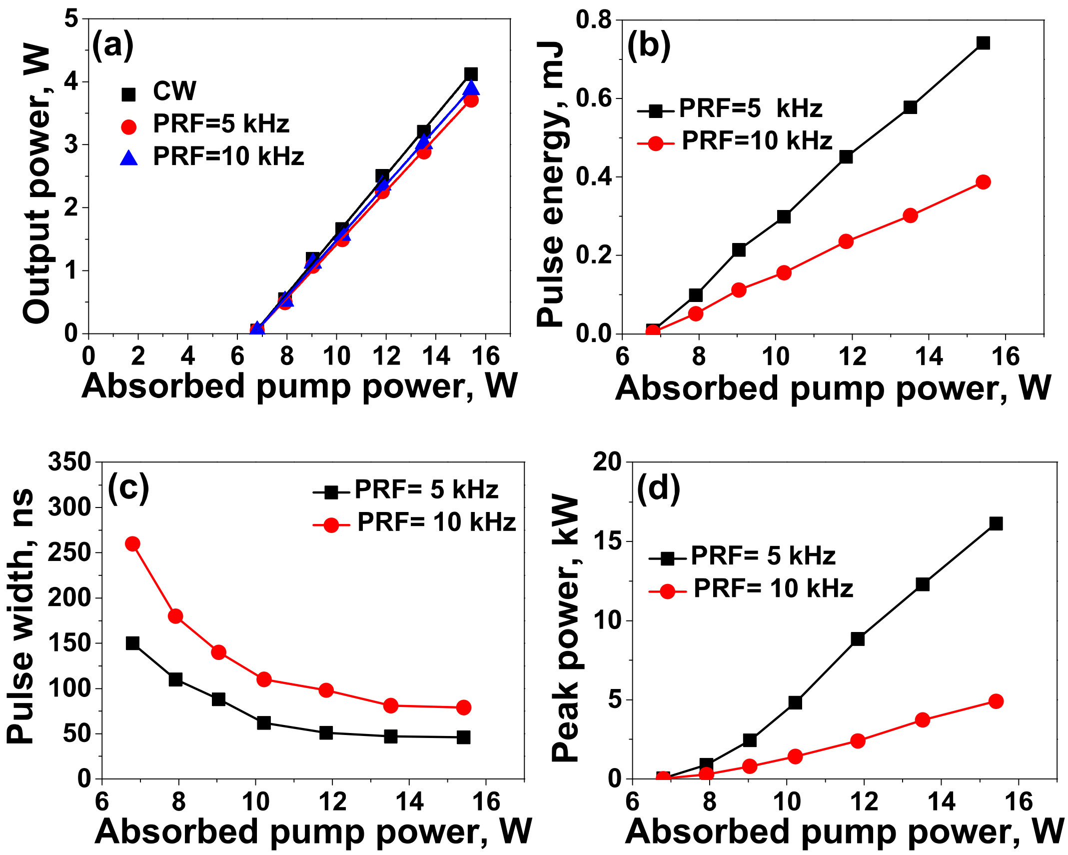

Fig. 5. The output powers (a), pulse energies (b), pulse widths (c) and peak powers (d) of AO Q-switched $Tm:Lu_2O_3$ laser.

4. Summary

In summary, a CW and AO Q-switched $Tm:Lu_2O_3$ laser resonantly-pumped by the laser diode at 1.7 μm was presented in this work. Without AO Q-switch, a maximum CW output power of 6.1 W and slope efficiency of 66.4% with respect to the absorbed pump power were achieved. With PRF of 10 kHz, AO Q-switched $Tm:Lu_2O_3$ laser delivered the average output power of 3.87 W and pulse width of 79 ns. At PRF of 5 kHz, the minimum pulse width of 46 ns and maximum pulse energy of 0.74 mJ were obtained, corresponding to a peak power of 16.1 kW. This work provides an efficient acousto -optical Q-switched 2.1 μm laser with high peak power, which can be utilized as the pump source of mid-infrared and long-wave infrared optical parametric oscillators.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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