



Full length article

## Diode-pumped continuous wave Tm:Lu<sub>2</sub>SiO<sub>5</sub> laser with narrow linewidth output

Haijun Guan <sup>a,b</sup>, Yunqing Liu <sup>a,\*</sup><sup>a</sup> College of Electronic and Information Engineering, Changchun University of Science and Technology, Changchun 130022, China<sup>b</sup> Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

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## ABSTRACT

A room-temperature narrow linewidth continuous wave (CW) Tm:Lu<sub>2</sub>SiO<sub>5</sub> laser is investigated by using a Volume Bragg grating and a Fabry-Perot etalon. The output wavelength of 2054.24 nm and a linewidth of 0.12 nm were obtained experimentally, and 1.64W of output power was achieved under an absorbed pump power of 9.2W, corresponding to an optical-to-optical conversion efficiency of 17.8% and a slope efficiency of 23.6%. The laser beam quality was optimized and measured to be M<sup>2</sup> ~ 1.2 in the x-axis direction and 1.3 in the y-axis direction, respectively.

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### 1. Introduction

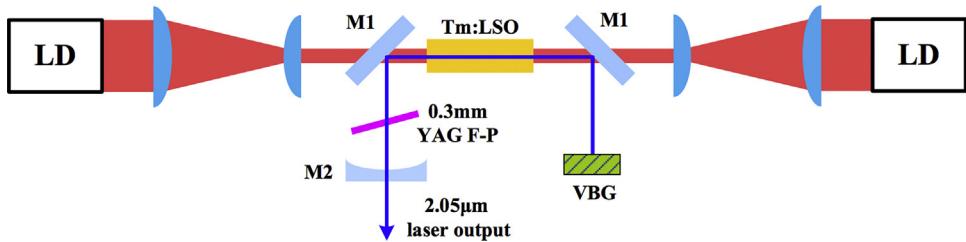
Solid-state lasers around 2 μm are useful due to its wavelength in the atmospheric transparency window and its eye-safe quality, so it can be applied in variety of fields, such as Doppler radar wind sensing, environment monitoring, spectroscopy and some basic researches [1–5]. In addition, continuous wave (CW) 2 μm laser has potential applications in laser welding of transparent plastic materials and in laser surgery and therapy.

Thulium-doped materials have several merits for generating light in this wavelength band, including a broad emission bandwidth, upper laser level has a long lifetime, absorption bands matched to high-power 800 nm commercially available diode laser, and the potential for high quantum efficiency due to a tow-for-one cross-relaxation process. Therefore, high power Tm lasers around 2 μm have been widely investigated [6–8]. However, as a typical quasi-three-level laser, the Tm-doped laser system suffers from a significant reabsorption loss and possesses a small stimulated-emission cross section, which can lead to low laser efficiency. To solve these problems, high-brightness diode pumping may be utilized to obtain high inversion, thereby minimizing reabsorption and increasing the laser gain. However, this can increase the thermal load, subsequently increasing the temperature-dependent reabsorption loss.

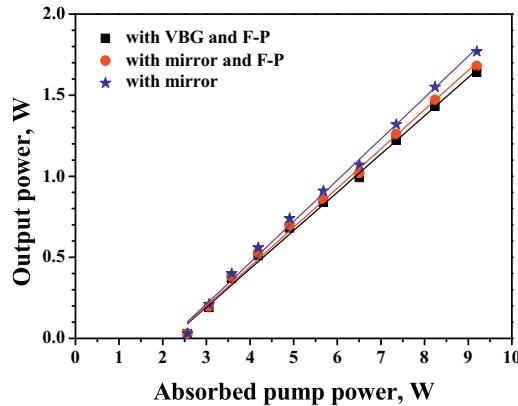
An alternative approach is to use a host that has a large Stark splitting of the Tm<sup>3+</sup> energy levels. Tm:Lu<sub>2</sub>SiO<sub>5</sub> (Tm:LSO) is such a kind of laser crystal with a large Stark splitting of 1094 cm<sup>-1</sup> existing in its ground-state level [9], which is much larger than 610 cm<sup>-1</sup> for Tm:YAG [10], 419 cm<sup>-1</sup> for Tm:YLF [11]. This advantage makes it quite suitable for suppressing the reabsorption loss and enhancing the laser efficiency. In the past few years, few works on the CW or Q-switched laser performances of Tm:LSO crystal were reported [12,13]. A single longitudinal mode Tm:LSO laser at 2003 nm was reported with maximum output power of 65 mW and slope efficiency of 6.73% [14]. For some applications, the narrow linewidth laser is very valuable. However, up to now there is less reported on the Tm:LSO laser with narrow linewidth.

\* Corresponding author.

E-mail address: [qyliu.cust@163.com](mailto:qyliu.cust@163.com) (Y. Liu).



**Fig. 1.** Schematic of the experimental setup.



**Fig. 2.** The output power of Tm:LSO laser with VBG and etalon.

In this paper, we demonstrated a narrow linewidth CW Tm:LSO laser with a central wavelength of 2054.24 nm and a linewidth of 0.12 nm by using a volume Bragg grating (VBG) and a Fabry-Perot (F-P) etalon. The maximum output power reaches 1.64 W when the absorbed pump power is 9.2 W, corresponding an optical-to-optical conversion efficiency and a slope efficiency of 17.8% and 23.6%, respectively.

## 2. Experimental setup

**Fig. 1** shows the schematic of the experimental setup. A 30 W laser diode with a 200  $\mu\text{m}$  core-diameter pigtail fiber was used as a pump source. The pump light was divided into two equal power beams to pump two ends of the Tm:LSO crystal. The pump laser beam was collected by a pair of coupling lenses with focus of 25 mm and 45 mm. The beam diameter located in the laser crystal was nearly 360  $\mu\text{m}$ . Considering the transmission losses, nearly 95% of the pump power was incident into the laser crystal. *B*-cut Tm:LSO crystals with a doped concentration of 3.0 at.% were used in the experiments, which had a cross section of 3  $\times$  3  $\text{mm}^2$  and length of 7 mm. Both end faces of the Tm:LSO crystals were antireflection coated at the laser wavelengths around 2.05  $\mu\text{m}$  and the pump wavelength. The actual pump absorption of Tm:LSO crystal is 87%. The Tm:LSO crystals were wrapped in indium foil and clamped in a copper crystal-holder, and the operating temperature was controlled at 18  $^\circ\text{C}$  by using a thermoelectric cooler.

A U-shape folded resonator geometry was used in this experiment. VBG as an element used in solid state lasers, has the stability and selection of wavelength, which can realize narrow linewidth output laser. The diffraction efficiency of the used VBG in this experiment was greater than 99% at 2054.2 nm. The actual transmittance of an AR-coated VBG is measured to be 90% at 790 nm. This pump absorption would lead to the elevation of the VBG temperature under the high pump level, which may result in a red shift of the central diffraction wavelength of the VBG. In order to avoid this effect, the pump light input to the laser crystal was instead through a 45° dichroic mirror in this work. The flat 45° dichroic mirror (M1) was high reflectivity (HR) ( $R > 99.7\%$ ) around the 2.06  $\mu\text{m}$  and high transmission at the pump wavelength ( $T \sim 95\%$ ). The output coupler was a plano-concave mirror (M2) with a 200 mm radius of curvature, and it was coated with 2.5% transmittance at 2.06  $\mu\text{m}$ . The physical resonator length was approximately 50 mm. In order to improve stability of output wavelength, we used a VBG and a YAG F-P etalon of 0.3 mm thick together to limit the laser wavelength.

## 3. Experimental results

**Fig. 2** depicts the output power of Tm:LSO laser with respect to the absorbed pump power, which were recorded by a power meter (PM30, the Coherent Inc.). Firstly, without F-P etalon, the VBG was instead a conventional mirror HR-coated at 2.06  $\mu\text{m}$ . The maximum output power was measured to be 1.77 W under an absorbed pump power of 9.2 W, corresponding

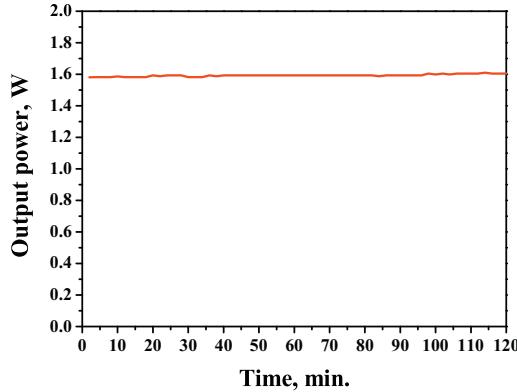


Fig. 3. The output power stability of Tm:LSO laser with VBG and F-P etalon.

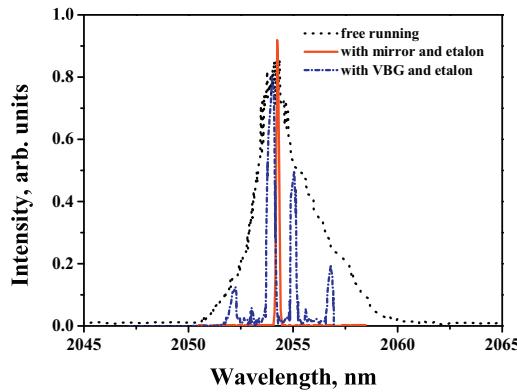


Fig. 4. Output spectrum of Tm:LSO laser.

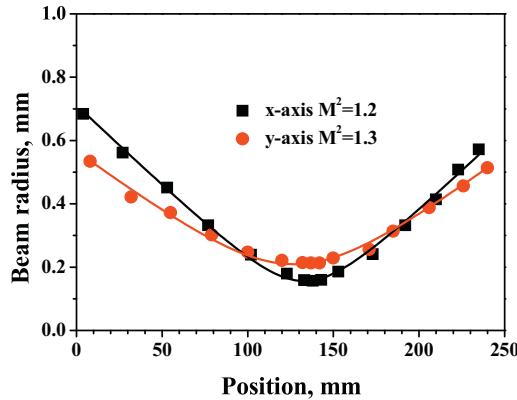
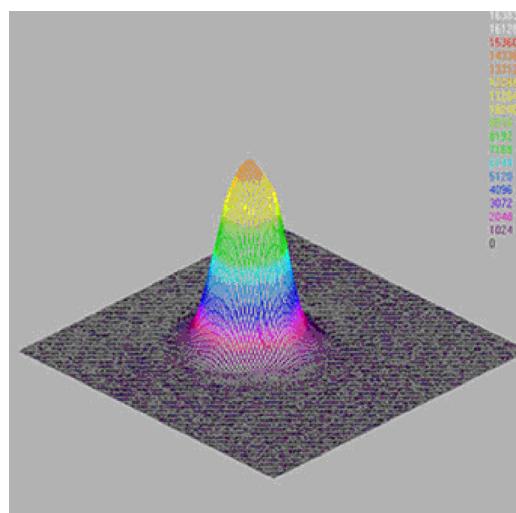


Fig. 5. The  $M^2$  measurement of Tm:LSO laser with VBG and etalon.

to a slope efficiency of 25.4% and an optical-to-optical conversion efficiency of 19.2%. Next, the F-P etalon was inserted in the cavity. At the same pump power, the output power was measured to be 1.68W, corresponding to a slope efficiency of 24.2% and an optical-to-optical conversion efficiency of 18.3%. Finally, the conventional mirror was instead the VBG, and the 1.64W of output power was achieved at absorbed pump power of 9.2W, corresponding to a slope efficiency of 23.6% and an optical-to-optical conversion efficiency of 17.8%. In addition, the F-P etalon was removed from the cavity, the change of output power was negligible for VBG-based setup.

The long term stability of the output power of Tm:LSO laser was also investigated over a period of two hours, and it is shown in Fig. 3. When the Tm:LSO laser ran at 9W of pump power, the laser output power fluctuated between 1.58W and 1.61W, which indicated that the fluctuation of the output power was only about 1.8%.



**Fig. 6.** The beam intensity distribution of Tm:LSO laser at the maximum output power.

In the experiment, laser wavelength was measured by a laser wavemeter (APE WaveScan). The output spectrum of Tm:LSO laser is shown in Fig. 4. With conventional mirror, the free running spectrum of Tm:LSO laser was measured. A central wavelength around 2054 nm with a linewidth of 10 nm was observed. With mirror and etalon, multiple peaks with a linewidth about 0.3 nm were observed, and the central wavelength was fluctuated with time. With VBG and etalon, the central wavelength at 2054.24 nm with a linewidth of 0.12 nm was achieved. Compared with the free running spectrum, it was very stable and narrow.

The  $M^2$  value of the Tm:LSO laser with VBG and etalon was measured by a 90/10 knife-edge method at the maximum output power, which were best-fitted to be 1.2 in the x-axis direction and 1.3 in the y-axis direction, respectively, as shown in Fig. 5. The Fig. 6 is the transverse output beam profile in the near field at the maximum output power, which was measured by a pyroelectric camera (Pyrocam III, the Spiricon Inc.).

#### 4. Conclusion

In summary, a linewidth-narrowed diode-pumped CW Tm:LSO laser with VBG and etalon has been demonstrated experimentally. As a result, 1.64W of laser output at 2054.24 nm was obtained with a slope efficiency of 23.6%. Then, the laser beam quality  $M^2$  was measured to be 1.2 in the x-axis direction and 1.3 in the y-axis direction, respectively.

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