High efficiency broadband (≈210 nm) in-band pumped Tm: LuGGG solid-state laser

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Abstract

Here, we demonstrate a broadband tunable (Lu$_{0.0541}$Tm$_{0.0548}$Gd$_{0.8911}$)$_3$Ga$_3$O$_{12}$ (Tm:LuGGG) laser in-band pumped by a home-made 1645-nm Er:YAG laser. A maximum average output power of 0.7 W at 1997 nm is obtained with a slope efficiency of 46.3%. We also demonstrate a continuously tuning output ranging from 1854 to 2066 nm with a tuning coverage of 212 nm. The results indicate that the Tm:LuGGG crystal is an excellent laser medium for high-efficient broadband light generation, which may help to explore potential applications in ultrafast lasers.

1. Introduction

Due to the absorption lines of CO$_2$, NO$_2$, and H$_2$O et al located around 2 µm, solid-state laser sources around 2 µm are currently investigated for a variety of applications, such as atmospheric remote sensing, high-resolution molecular spectroscopy and medical surgery [1–2]. Thulium-doped YAG (Tm:YAG) crystal represents an active material to realize laser oscillation in this spectral region attributing to their excellent thermo-mechanical properties and the availability of large grown size. In 2018, J.W. Zhang et al. reported a high efficiency Tm:YAG thin-disk laser oscillation with an output power of 24 W [3]. In 2021, J. Liu et al. realized a 9.1 W continuous-wave laser with a Tm:YAG single-crystal fiber [4]. Gd$_3$Ga$_5$O$_{12}$ (GGG) is another garnet host, known for many years but until 2009 studied with Tm-doping [5]. Except for good thermo-mechanical properties, GGG crystal possesses a weak concentration quenching, which allows higher doping levels [6]. In 2017, a continuous-wave Tm:GGG laser was realized with 2 at% dopant concentration of Tm$^{3+}$ ions delivering an output power of 0.58 W at 2002 nm [7]. By substituting a portion of Gd$^{3+}$ ions with Lu$^{3+}$, a disordered Tm:$(Lu_xGd_{1-x})_3$Ga$_5$O$_{12}$ (Tm:LuGGG) crystal was designed and grown with an increasingly more disordered degree than Tm:GGG crystal [8]. Accordingly, LGGG crystal could provide several various lattice positions for the doping ions, leading to significant inhomogeneous broadening both in absorption and emission spectra. The broadening emission spectrum is conductive to generate tunable and ultrafast lasers. The continuous-wave and Q-switched Tm:LuGGG crystal laser was realized by several groups, respectively [9–11]. Especially, J. Hou et al demonstrated a widely tunable Tm:LuGGG crystal laser with 148.4 nm tuning region ranging from 1907.5 to 2055.9 nm, indicating the broadening inhomogeneous emission spectrum of the crystal [11].

In this paper, we presented a tunable Tm:LuGGG crystal laser in-band pumped by a home-made Er:YAG crystal laser. The average output power, polarization, output stability and light quality of the pumping laser were investigated in details. A laser slope efficiency of 46.3% was obtained in a continuous-wave Tm:LuGGG crystal laser, with a maximum output power of 0.7 W at 1997 nm. Additionally, a continuously tuning coverage of 212 nm is achieved in Tm:LuGGG crystal laser ranging from 1854 to 2066 nm.

2. Experimental Setups

Figure 1 presents the schematic diagram of the (Lu$_{0.0541}$Tm$_{0.0548}$Gd$_{0.8911}$)$_3$Ga$_3$O$_{12}$ (Tm:LuGGG) tunable laser including two parts. Part 1 is a diode-pumped Er:YAG laser operating at 1645 nm regarding as the
pump source of Tm:LuGGG tunable laser. The laser medium is a 0.5 at. % Er:YAG crystal with a length of 24.5 mm and an area of 3*3 mm$^2$. A YAG polarizer was utilized to generate linear polarized light. Output coupler (OC) 1 is a plane mirror with a transmittance of 10% at 1645 nm. The pump light was focused into the Tm:LuGGG crystal with a diameter size of 60 µm by a couple optical lenses $f_3$ and $f_4$. The radius curvatures of the lenses were 400 and 75 mm, respectively. A $\lambda/2$ plate and a polarization beam splitter were conducted to control the intensity of the pump light. Mirrors $M_4$ and $M_5$ had a curvature radius of R=-100 mm with high transmittance coated around 1645 nm and high reflectivity coated around 2µm. The coating of plane mirror $M_6$ is the same as $M_4$ and $M_5$. OC2 is a plane mirror with different transmittance of 1%, 1.5%, 3% and 5% at 2 µm. In order to reduce the influence of the thermal lens effect, both crystals were wrapped with indium foil and mounted in a water-cooled copper block. The temperature of the flowing water was controlled at 14℃. A 2 mm thick quartz birefringent filter (BF) was applied as a wavelength selector. The average output power and laser spectra were measured by a power meter (Fieldmax-, Coherent) and a spectrograph (AQ6375, Yagogawa).

3. Results And Discussions

The Er:YAG laser output properties at 1645 nm were studied first. The corresponding relations between the CW laser output power and the absorbed pump power are plotted in Fig. 2a. A maximum output power was achieved to be 5.1 W with T = 10% output coupler, giving a slope efficiency of 41.3%. In order to investigate the polarization characteristic of the Er:YAG laser, a Glan-Taylor polarizer was applied to measure the laser power at different angles between the polarization direction of the laser output and the axis of the Glan-Taylor polarizer. Figure 2b presents the output laser powers versus variation of the angle. The extinction ratio of the Er:YAG laser was calculated to be 22.6 dB, which was conducted to enhance the absorption efficiency of the Tm:LuGGG crystal and reduce the thermal effect of the laser. Figure 2c displays the fitting line of the M-square factor measured by the knife-edge method at the output power of 4.8 W. The fitting results demonstrated that Er:YAG laser operated on TEM$_{00}$ mode with $M^2_x$ of 1.44 and $M^2_y$ of 1.33, respectively. The two dimensions output beam spatial distribution was inserted in Fig. 2c, presenting a TEM$_{00}$ mode Gaussian profile. Additionally, the output power versus time was recorded and shown in Fig. 2d. The RMS of the laser was calculated to be 0.88% during 1.5 h, exhibiting good stability. The laser spectrum centered at 1645.37 nm was inserted in Fig. 2d.

The performances of the Tm:LuGGG laser were first studied without the BF and using output couplers with transmittances of 1%, 1.5%, 3% and 5%, respectively. According to Tm-doped materials, in-band pumping scheme may bring many advantages of high absorption efficiency of the crystal, high laser slope efficiency, as well as reduced heat loading. Figure 3a describes the output power at 2 µm as a function of the in-band pump power. A maximum output power of 0.7 W was obtained with the T = 5% output coupler under a pump power of 1.75 W, corresponding to a slope efficiency of 46.3%. No thermal saturation phenomenon was observed during laser experiments at all four output couplers. Unfortunately, output couplers with higher transmittance were not available at the time of experiment. Hence, the output power may be further improved by using output coupler with higher transmittance and higher pump
intensity. Based on the slope efficiency and reflectivity of the output coupler [12], the round-trip loss could be fitted to be 0.61% as presented in Fig. 3b. The relatively low round-trip loss indicated that the Tm:LuGGG crystal possessed reasonable quality. The laser output spectra at different output couplers were recorded and shown in Fig. 3c. The peak value of the wavelength appeared blue shift with increasing the transmittance of the output couplers.

The Tm:LuGGG laser can be wavelength tuned by using BF as a wavelength selector. As displayed in Fig. 4, the laser was tunable over 210 nm both with T = 1.5% and T = 3% output couplers. The tuning coverage ranged from 1854 to 2066 nm at T = 1.5%, while it was from 1849 to 2060 nm at T = 3%. Table 1 summaries tunable laser properties with the Tm-doped garnet structure crystal. Due to inhomogeneous broadening of emission spectrum, the tuning coverages of the Tm-doped disordered garnet structure crystals were relatively broad, especially in Tm:CLTGG and Tm:CLNGG crystals. Compared with previous studies of the Tm:LuGGG crystal laser employing typical 790 nm LD as pump source [11], the high brightness pump source at 1645 nm used in our experiment allowed shorter wavelength laser operation due to high population inversion. Considering tuning range and output power, Tm:LuGGG crystal is a relatively decent crystal for applications in tunable and ultrafast laser at 2 µm.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Tuning coverage (nm)</th>
<th>Tuning Wavelength (nm)</th>
<th>Maximum power (mW)</th>
<th>Slope efficiency (%)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tm:CLTGG</td>
<td>286 (Toc = 0.5%)</td>
<td>1799–2085</td>
<td>~100</td>
<td>16.1%</td>
<td>[13]</td>
</tr>
<tr>
<td>Tm:CNNGG</td>
<td>168 (Toc = 0.5%)</td>
<td>1885–2053</td>
<td>111</td>
<td>-</td>
<td>[14]</td>
</tr>
<tr>
<td>Tm:CLNGG</td>
<td>224 (Toc = 0.5%)</td>
<td>1848–2072</td>
<td>120</td>
<td>-</td>
<td>[14]</td>
</tr>
<tr>
<td>Tm:GAGG</td>
<td>180 (Toc = 0.5%)</td>
<td>1856–2036</td>
<td>600</td>
<td>~ 20.1</td>
<td>[15]</td>
</tr>
<tr>
<td>Tm:LuGGG</td>
<td>149 (Toc = 1%)</td>
<td>1907–2056</td>
<td>~700</td>
<td>16.5</td>
<td>[11]</td>
</tr>
<tr>
<td>Tm:LuGGG</td>
<td>212 (Toc = 1.5%)</td>
<td>1854–2066</td>
<td>560</td>
<td>33.9</td>
<td>This work</td>
</tr>
</tbody>
</table>

### 4. Conclusions

In conclusion, the tunable laser properties of the Tm:LuGGG crystal laser were demonstrated in-band pumped by a home-made Er:YAG laser operating at 1645 nm. First, the pump source of 1645 nm laser was characterized with a maximum output power of 5.1 W, an extinction ratio of 22.6 dB, a power RMS value of 0.88% during 1.5 h, and M- square factors of 1.44 and 1.33 in x- and y-axis, respectively. The...
The maximum output power of Tm:LuGGG crystal laser at 2 µm was 0.7 W, corresponding to a slope efficiency of 46.2%. In tunable configuration, the laser tuning coverage was 212 nm ranging from 1854 to 2066 nm at T = 1.5% output coupler, which represents a significant increase of the tuning range to shorter wavelengths. The results indicate that in-band pumped Tm:LuGGG crystal was a promising configuration for generating widely tunable and ultrafast lasers at 2 µm.

**Declarations**

**Acknowledgements**

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**References**


**Figures**

**Figure 1**

Schematic diagram of the Tm:LuGGG tunable laser setup.
Figure 2

Output properties of the Er:YAG laser. (a) CW output power versus absorbed pump power; (b) Polarization characteristic; (c) Laser quality; (d) Output power stability and laser spectrum.
Figure 3

Output properties of the CW Tm:LuGGG laser. (a) Output power versus absorbed pump power; (b) Round-trip loss of the laser cavity; (c) Laser spectra at different transmittances.
Figure 4

Tunable properties of the Tm:LuGGG crystal at different transmittance of output couplers. (a) $T=1.5\%$; (b) $T=3\%$. 