2.7 μm dual-wavelength laser performance of LD end-pumped Er:YAP crystal

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Abstract: We demonstrate a laser diode (LD) end-pumped Er:YAP laser with dual-wavelength outputs of 2710 and 2728 nm. The maximum average powers of 739 and 738 mW are achieved in the continuous wave (CW) and pulse modes, which corresponds to optical-to-optical efficiencies of 10.1% and 12.3%, and the slope efficiencies of 12.1% and 13.8%, respectively. In addition, a comparison of laser performance on differently sized crystals indicates that the 1 × 1 × 5 mm3 Er:YAP crystal has a best cooling efficiency. This helps to decrease the thermal lensing effect, which contributes to improving laser efficiency and beam quality.

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1. Introduction

Er3+ serves as an active ion emitting 2.7-3 μm by 4I11/2 → 4I13/2 transition, which is commonly believed to be self-terminating because the lifetime of the laser upper level is far less than that of the lower level [1–3]. An effective method of reducing the lifetime of the lower laser level is to increase the Er3+ concentration properly, which is advantageous to population inversion [4]. Laser in the region of 2.7-3 μm belongs to the strong water absorption waveband, so it can be widely utilized in the biomedicine field, and laser in this region with Q-switched mode is prefer to utilize in the biomedicine field, because the extent of thermal damage to tissue can be reduced by shorter laser pulse duration [5,6]. Besides, laser in this region can also be used in many other fields, such as space military and scientific research [7], laser remote sensing and LIDAR [8], etc. In addition, laser operated at this waveband is also an ideal pumping source for Optical Parameter Oscillator (OPO) in realizing 3-5 and 8-12 μm mid-infrared laser [9,10].

The YAP crystal is an attractive candidate as a laser host due to its excellent thermodynamics and mechanical properties. Besides, the characteristic of natural birefringence [11] can also make it achieve a linearly polarized laser output directly [12]. Moreover, the Er:YAP has a lower phonon energy (570 cm−1) by comparing with the Er:YAG (846 cm−1), Er:GSGG (741 cm−1), and Er:GYSGG (732 cm−1) [13,14]. The low phonon energy can decrease non-radiation transition probability, which is benefited to decrease the lifetime of 4I13/2 level and improve laser efficiency.

Although the 2.7-3 μm laser output has been obtained in Er:YAP crystal pumped by a Xe lamp, the slope efficiency of the crystal is lower and the threshold is too high [15]. So far, the mid-infrared laser performance of the crystal pumped by laser diode (LD) has not been reported. Diode-pumped solid-state laser has been researched widely due to its compactness, high efficiency and better beam quality [16]. For Er3+ doped laser crystals, the ground-state particles can be excited into the energy level of 4I11/2 by around the 970 nm laser directly, which is beneficial to improve the energy conversion efficiency. So our study would focus on the laser performance of the Er:YAP crystal pumped by around the 970 nm LD. However, the...
generated heat of LD end-pumped system makes thermal lensing effect to become a serious problem [17], therefore, it is very significant and meaningful to investigate the influence of different crystal sizes on temperature distribution, thermal focal lengths and laser performance.

In this work, we report the laser performance of a LD end-pumped Er:YAP crystal with 10 at.% Er³⁺ ions and realize a 2710 and 2728 nm dual-wavelength laser output. Moreover, the temperature distribution, thermal focal lengths, laser efficiency and beam profile of the Er:YAP crystal with different sizes are demonstrated.

2. Experimental setup

Using a JDG-60 furnace (CETC26th, China) with an automatic diameter controlled (ADC) growth system, the Er:YAP crystal with dimension about Φ 29 mm × 70 mm was grown along the crystalline b-axis. The rotation and pulling rates are 7 rpm and 1 mm/h, respectively. The doping concentration of Er³⁺ ions in the initial raw materials is 10 at%. The starting raw materials were Er₂O₃ (5 N), Y₂O₃ (5 N), and Al₂O₃ (5 N) oxide powders, which were weighed accurately according to the structural formula Er₀.₁₀₅₉AlO₃. An iridium crucible with size of Φ 60 mm × 48 mm was used in high purity argon atmosphere to prevent oxidation. The as grown Er:YAP crystal was annealed in the flow H₂ atmosphere at 1250 °C for 24 h.

The Er:YAP crystal samples with parallel and polished end faces were cut into the sizes of 1 × 1 × 5, 2 × 2 × 5, 3 × 3 × 5 mm³, respectively. And the configuration based on a simple plane-parallel cavity for generating laser output is shown in Fig. 1. The LD emitting approximately 973 nm in continuous wave (CW) mode and another LD emitting approximately 962 nm in pulse mode were used as pumping sources, and they were collimated and focused onto an uncoated Er:YAP crystal with parallel and polished end faces. The input mirror was a K9 glass plate with an antireflection coating of high transmission (> 95%) at 970 nm and reflectivity of 100% around 2.7 μm. The output mirrors (CaF₂ substrate) with transmission of 0.5%, 2%, and 5% at 2.7 μm were applied to obtain the optimal laser output. The crystal was enclosed by a copper heat sink with cooling water passage, the cooling water was maintained at a temperature of 17 °C. An indium foil was covered on the crystal surface for closer contact with heat sink, which can improve the cooling efficiency of the crystal. The laser output power was measured by a power meter (Ophir 30A-BB-18). The laser beam profile and M² factor were determined by Pyroelectric Array camera (Ophir-Spiricon PY-III-HR).

![Fig. 1. Photograph of the Er:YAP crystals and schematic of laser pumped by the ~970 nm LD with CW or pulse modes.](image)
3. Results and discussion

3.1 Temperature distribution and thermal focal lengths

Fig. 2. Temperature distribution on the pumped end-faces for different size crystals. (a) 1 × 1 × 5 mm³; (b) 2 × 2 × 5 mm³; (c) 3 × 3 × 5 mm³.

The temperature distributions of Er:YAP crystal with different sizes pumped by LD are numerically simulated using mathematical software MATLAB, as shown in Fig. 2, and the relevant parameters are exhibited in Table 1. The temperatures at the center of end-face of the 1 × 1 × 5, 2 × 2 × 5 and 3 × 3 × 5 mm³ Er:YAP crystals are 330, 343, and 350 K, respectively. Therefore, the center temperatures of the crystal end-faces have an increasing trend as the Er:YAP crystal size increases. This result indicates that the crystal with small size has a higher heat dissipation efficiency, which should be beneficial to reduce the thermal lensing effect and improve the laser efficiency.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (κ)</td>
<td>8.64 W/(m·K)</td>
</tr>
<tr>
<td>Pump power (P_p)</td>
<td>5 W</td>
</tr>
<tr>
<td>Heat transfer coefficient (h)</td>
<td>1 W/cm²·K</td>
</tr>
<tr>
<td>Radius of pumping faculae (ω_p)</td>
<td>100 μm</td>
</tr>
<tr>
<td>Temperature of heat sink (T)</td>
<td>290 K</td>
</tr>
<tr>
<td>Size of crystal</td>
<td>1 × 1 × 5 mm³; 2 × 2 × 5 mm³; 3 × 3 × 5 mm³</td>
</tr>
</tbody>
</table>
Besides, the thermal focal lengths of the three crystals are also measured to illustrate the influence of the crystal size on the thermal lensing effect. The thermal focal lengths of three different size crystals as a function of pump power are shown in Fig. 3. The thermal focal length for $1 \times 1 \times 5 \text{ mm}^3$ Er:YAP crystal is about 55 mm when the pump power is 6.02 W, while the values of the $2 \times 2 \times 5$ and $3 \times 3 \times 5 \text{ mm}^3$ crystals are only 50 mm and 43 mm under the same conditions, respectively. These results fully demonstrate that the deformation of pump surface and refractive index change of $1 \times 1 \times 5 \text{ mm}^3$ crystal are smallest than those of the $2 \times 2 \times 5$ and $3 \times 3 \times 5 \text{ mm}^3$ crystals, and the thermal lensing effects can be effectively reduced, which is beneficial to improve the laser performance.

### 3.2 Laser performance

![Graph showing laser output power versus pump power for different size crystals.](image)

Table 2. Laser parameters of the LD end-pumped Er:YAP crystals with different sizes.

<table>
<thead>
<tr>
<th>Pump source</th>
<th>Crystal size (mm(^3))</th>
<th>Optical to optical efficiency</th>
<th>Slope efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>973 nm LD</td>
<td>$1 \times 1 \times 5$</td>
<td>10.1%</td>
<td>12.1%</td>
</tr>
<tr>
<td></td>
<td>$2 \times 2 \times 5$</td>
<td>9.1%</td>
<td>11.1%</td>
</tr>
<tr>
<td></td>
<td>$3 \times 3 \times 5$</td>
<td>8.5%</td>
<td>10.3%</td>
</tr>
<tr>
<td>962 nm LD</td>
<td>$1 \times 1 \times 5$</td>
<td>12.3%</td>
<td>13.8%</td>
</tr>
</tbody>
</table>
Table 2. Laser efficiencies of three crystals in two modes.

<table>
<thead>
<tr>
<th>Crystal Size</th>
<th>Pump Mode</th>
<th>CW Efficiency</th>
<th>Pulse Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 × 2 × 5</td>
<td>2 × 2 × 5</td>
<td>11.9%</td>
<td>13.5%</td>
</tr>
<tr>
<td>3 × 3 × 5</td>
<td>3 × 3 × 5</td>
<td>11.1%</td>
<td>12.6%</td>
</tr>
</tbody>
</table>

Figure 4 shows the laser output power as a function of pump power for different size Er:YAP crystals pumped by the 973 nm LD in CW mode and 962 nm LD in pulse mode, respectively. Meanwhile, an output coupler with 5% transmission and the cavity length with 12 mm are used throughout the entire experiment. The 962 nm LD is operated with pulse duration of 0.8 ms and repetition rate of 300 Hz. The laser efficiencies of three crystals in two modes are shown in Table 2. According to the experiment results, the optical to optical conversion efficiency and slope efficiency of the crystals have a slow decrease with the increase of crystals size, which are in accordance with the results of simulated temperature distribution and the thermal focal lengths. These results indicate that the crystal with a size of 1 × 1 × 5 mm³ has a best cooling efficiency, which is beneficial to decrease the thermal lensing effect and then improve the laser efficiency. The decrease tendency of the laser efficiency is weak, which might be caused by the high thermal conductivity of Er:YAP crystal.

Figure 5 shows the laser output power as a function of pump power for output coupling mirror with different transmissions. The 1 × 1 × 5 mm³ crystal is pumped by a 973 nm LD in CW mode and a 962 nm LD in pulse mode, and the cavity length is maintained at 12 mm. For 962 nm LD, a repetition rate of 300 Hz and a pulse duration of 0.8 ms are used throughout the experiment. The output couplers with transmissions of 2% and 5% generate the better results than that of the 0.5%. Using the output coupler with a transmission of 5%, the maximum laser power of 739 mW corresponding to the optical-to-optical efficiency of 10.1% and slope efficiency of 12.1% are obtained by the 973 nm LD with CW mode. Under the same condition, the maximum laser power of 738 mW corresponding to optical-to-optical efficiency of 12.3% and the slope efficiency of 13.8% are achieved by the 962 nm LD with pulse mode.

Fig. 5. Dependence of laser output power with different transmissions of the output coupler. (a) 973 nm LD in CW mode and (b) 962 nm LD in pulse mode.

The laser output power versus the pump power at different repetition rates of 100, 200, 300, 400 and 500 Hz are shown in Fig. 6. Meanwhile, an output coupler with 5% transmission, pulse duration with 0.8 ms, cavity length with 12 mm and crystal size with 1 × 1 × 5 mm³ are used throughout the experiment. The laser output exhibits approximate slope efficiency at different repetition rates of 100, 200, and 300 Hz, which are 13.6%, 13.1% and 13.8%, respectively. Moreover, the slope efficiency begins to decrease when the repetition rate increases to 400 Hz (12.1%), and it has obvious decrease (7.8%) when the repetition rate increases to 500 Hz, which is due to the thermal lensing effect is more obvious in high frequency. These results also indicate that the high thermal conductivity of Er:YAP crystal...
can permit it to be operated at high repetition rate up to 300 and even 400 Hz. The highest optical-to-optical efficiency of 12.3% and slope efficiency of 13.8% with a maximum laser power of 738 mW are obtained at a repetition rate of 300 Hz. The lowest threshold of 330 mW is achieved at a repetition rate of 100 Hz.

Figure 7 shows the laser output power as a function of pump power at different pulse widths of 0.6, 0.7, 0.8, 0.9 and 1.0 ms. Meanwhile, an output coupler with 5% transmission, repetition rate with 400 Hz, cavity length with 12 mm and crystal size with $1 \times 1 \times 5$ mm$^3$ are used throughout the experiment. For the Er:YAP crystal, the maximum laser power of 773 mW with a threshold of 649 mW is obtained at a repetition rate of 400 Hz, corresponding to the optical-to-optical efficiency of 11% and slope efficiency of 12.1%. The experiment result shows that the slope efficiency increases firstly and then decreases with increasing the pulse width, and the maximum laser power is obtained with a pulse width of 0.8 ms.

3.3 The $M^2$ factor

The laser beam profile and $M^2$ factor for different size Er:YAP crystals are determined to analysis the influence of crystal size on laser beam quality. An output coupler with 5%
transmission, repetition rate with 300 Hz, pulse duration with 0.8 ms and cavity length with 12 mm are used throughout the experiment. After focusing laser beam through the lens with focal length 400 mm at 200 mW output power, the camera is moved near the position of the lens focal point to record the horizontal and vertical diameter. The beam waist diameter and beam quality $M^2$ factor are obtained through the hyperbolic fitting, the results are shown in Fig. 8. The $M^2/H^2$ factors are 1.362/1.264 in the horizontal and vertical directions for $1 \times 1 \times 5 \text{ mm}^3$ crystal, 1.466/1.472 for $2 \times 2 \times 5 \text{ mm}^3$ crystal and 1.862/1.795 for $3 \times 3 \times 5 \text{ mm}^3$ crystal, respectively. The $M^2$ factor for $1 \times 1 \times 5 \text{ mm}^3$ Er:YAP crystal are little less than that of $2 \times 2 \times 5 \text{ mm}^3$ crystal and much less than that of $3 \times 3 \times 5 \text{ mm}^3$ crystal obviously. Therefore, the $1 \times 1 \times 5 \text{ mm}^3$ Er:YAP crystal presents a relatively higher laser beam quality, which should due to the best cooling efficiency.

![Fig. 8. Beam diameter versus propagation distance for three Er:YAP crystals. (a) $1 \times 1 \times 5 \text{ mm}^3$ crystal; (b) $2 \times 2 \times 5 \text{ mm}^3$ crystal; (c) $3 \times 3 \times 5 \text{ mm}^3$ crystal.](image)

### 3.4 Laser spectrum of the Er:YAP crystal

The specific spectral composition of Er:YAP laser is illustrated in Fig. 9. A dual-wavelength laser output is obtained and the central wavelengths are located at 2710 and 2728 nm, whose full width at half maximum are 3.2 and 2.3 nm, respectively. The result suggests that only the strongest two fluorescence peaks are strengthened and that laser oscillations are realized. Meanwhile, other fluorescence peaks are suppressed, as shown in the fluorescence spectra of the Er:YAP crystal [18].

![Fig. 9. Laser wavelength of the LD end-pumped Er:YAP crystal.](image)
4. Conclusions

We demonstrate the thermal analysis and LD end-pumped laser performance for different size Er:YAP crystals. The results show that the crystal with a size of $1 \times 1 \times 5$ mm$^3$ has a best cooling efficiency, which is beneficial to decrease the thermal lensing effect and then improve the laser efficiency. The maximum output powers of 739 mW pumped by 973 nm CW LD and 738 mW pumped by 962 nm pulse LD are obtained, corresponding to the slope efficiencies of 12.1% and 13.8%, respectively. The $M^2$ factor of the $1 \times 1 \times 5$ mm$^3$ Er:YAP crystal is less than those of the $2 \times 2 \times 5$ and $3 \times 3 \times 5$ mm$^3$ Er:YAP crystals, which indicates that the $1 \times 1 \times 5$ mm$^3$ Er:YAP crystal presents a highest laser beam quality. All the results suggest that the Er:YAP crystal with a proper size pumped by around 970 nm LD can realize 2.7 $\mu$m dual-wavelength laser output with high performance.

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References