2.92-µm high-efficiency continuous-wave laser operation of diode-pumped Er:YAP crystal at room temperature

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Abstract: Mid-infrared lasers have attracted attention for application to the fields of medicine and industry. In this study, we demonstrate continuous-wave laser operation of a diode-pumped 5 at % Er-doped YAlO₃ (YAP) single-crystal lasing at 2.92 µm with near-quantum-defect slope efficiency at room temperature. A high slope efficiency of 31% is achieved with a maximum output power of 0.674 W for a cavity length of 18 mm and an output coupler transmittance of 2.5%. This efficiency is 94% of the theoretical quantum-defect efficiency. Our results indicate that Er:YAP lasers can potentially be utilized to realize high-power mid-IR lasing.

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1. Introduction

Water (H₂O) exhibits a strong absorption peak at a wavelength of approximately 3 µm, which is attributed to the OH-radical stretching mode. Therefore, light with a wavelength of 3 µm is strongly absorbed by materials such as skin, teeth (containing H₂O), and glass (containing OH radicals). In this context, the further development of 3-µm laser light sources becomes imperative for application to the medical and industrial fields [1,2] to exploit the strong absorption characteristics of water/OH radicals. Such a laser source must exhibit stable operation at room temperature, ease of handling, and compact size when applied to the medical and industrial fields. Among certain kinds of laser sources, 3-µm mid-infrared (mid-IR) solid-state lasers satisfy the abovementioned criteria. Thus, researchers have actively focused on mid-IR solid-state lasers with lasing wavelengths of approximately 3 µm. Among the various mid-IR laser materials currently available, Er-doped materials such as Er:Y₂O₃ crystals [3], Er:Lu₂O₃ crystals [4], Er:Y₂O₃ ceramics [5], Er:Lu₂O₃ ceramics [6,7], and Er:YAG (yttrium aluminum garnet) [8] have long been studied. Recently, continuous-wave (CW) laser operation at 3 µm was demonstrated with the use of these materials via laser diode (LD) pumping. In addition, YAlO₃ (YAP) has also been studied as a possible lasing medium. YAP is a crystal with orthorhombic symmetry and a perovskite structure, and it is attractive for application as a high-power mid-IR solid-state laser material because of characteristics such as its high thermal conductivity, low phonon energy, and robust mechanical properties. Further, YAP crystals are optically biaxial and anisotropic, and exhibit thermal conductivities of 11.7, 10.0, and 13.3 W/m·K along the a-, b-, and c-axes, respectively, at room temperature [9]. Thus, a YAP single-crystal has a high thermal conductivity similar to that of YAG (ca. 11.2 W/m·K) [9], which is generally used as a laser material in industrial applications. Further, YAP exhibits a lower phonon energy of 550 cm⁻¹ [10] relative to Y₂O₃ (597 cm⁻¹) [3], Lu₂O₃ (618 cm⁻¹) [3], and YAG (857 cm⁻¹) [11]. The presence of low-energy phonons can reduce nonradiative transitions, which can improve the laser efficiency. Based on these observations, it has been posited that Er:YAP can be utilized to obtain high-power mid-IR laser output with high efficiency. In this regard, previous studies have demonstrated an
Er:YAP laser operating in the 3.0-μm spectral range via the application of a flash-lamp pumping scheme [12,13] and an Argon laser pumping scheme [14]. In addition, recent studies have reported on CW laser operation by diode-pumping Er:YAP at approximately 2.7 μm [15,16]. In 2018, Quan et al. [16] demonstrated a CW 10 at.% Er-doped YAP laser at a dual wavelength of 2710 and 2728 nm by diode-pumping at room temperature. The CW Er:YAP laser achieved a maximum output of 739 mW with the slope efficiency of 12.1%. However, high-output, high-efficiency, CW laser operation using Er:YAP at approximately 2.9 μm at room temperature has not been demonstrated previously. Therefore, in this study, we attempt to demonstrate high-output, high-efficiency CW laser operation using a diode-pumping Er-doped YAP at room temperature.

We report on a demonstration of 2.92-μm Er:YAP CW laser operation. When a 5 at.% Er:YAP crystal was pumped by an LD with a center wavelength of 976.2 nm at room temperature, CW lasing at a wavelength of 2920 nm was obtained for an absorbed pump power of 1.98 W. Further, a slope efficiency of 31% and an output power of 0.674 W was obtained with 3.49 W of absorbed pump power; these maximal values were obtained with a 2.5% output coupler (OC) transmittance. These experimental results indicate that the Er:YAP laser can find potential application as a mid-IR laser.

2. Optical properties of Er:YAP

In this study, a 5 at.% Er-doped YAP single-crystal (Crytur Co., Ltd.) was used for measuring the optical properties and for laser operation. The Er:YAP crystal was rectangular in shape with the aperture dimensions of 2 mm × 5 mm, and it was 8 mm in length. The aperture was uncoated, and the optical axis was aligned perpendicular to the “b” crystallographic axis. The absorption spectrum of Er:YAP in the range of 325–3200 nm was measured with a spectrophotometer (UV3600 Plus, SHIMADZU Co., Ltd.) at room temperature, as shown in Fig. 1. Note that Er:YAP exhibits no absorption around a wavelength of 3000 nm for laser emission with the \( ^4I_{11/2} \rightarrow ^4I_{13/2} \) transition. On the contrary, absorption bands due to Er\(^{3+}\) ions are observed in the range of 340–1660 nm. Each absorption band corresponds to the transitions between the Er\(^{3+}\) ion energy levels [17]. The inset in Fig. 1 shows the absorption bands at around 1000 nm originating from the \( ^4I_{15/2} \rightarrow ^4I_{11/2} \) transition of the Er\(^{3+}\) ions when subjected to laser pumping. These separated peaks are due to the Stark effect [17,18]. In this study, we used a fiber-coupled LD (K976A02RN-9.00WN0N-10255I10ESM0, BWT BEIJING) with a center wavelength (\( \lambda_{\text{center}} \)) of 976.2 nm, spectral width of 0.4 nm, core diameter of 105 μm, and numerical aperture (NA) of 0.22 as the excitation source. The center wavelength overlapped one of the absorption wavelengths at 976 nm with an absorption coefficient of 1.67 cm\(^{-1}\). Thus, laser oscillations with a wavelength of approximately 3 μm can be expected for this sample pumped by this LD. As shown in Fig. 2, luminescence at around 3 μm and 1.66 μm is observed for the \( ^4I_{11/2} \rightarrow ^4I_{13/2} \) and \( ^4I_{13/2} \rightarrow ^4I_{15/2} \) transitions, respectively. In our study, the fluorescence spectrum was measured by diode-pumping the Er:YAP with a LD, as mentioned earlier. We note from the figure that the spectrum exhibits peaks at around 1600 nm for the \( ^4I_{13/2} \rightarrow ^4I_{15/2} \) transition and at 2800 nm for the \( ^4I_{11/2} \rightarrow ^4I_{13/2} \) transition. The single exponential decays of fluorescence, which indicate the fluorescence lifetime, were measured with an infrared detector (C12492-210, HAMAMATSU) and analyzed using an oscilloscope with a frequency band of 500 MHz (TDS5054B, Tektronix). The lifetimes of the \( ^4I_{13/2} \rightarrow ^4I_{15/2} \) and \( ^4I_{11/2} \rightarrow ^4I_{13/2} \) transitions are 7.3 and 0.85 ms, respectively. A peculiarity of the Er\(^{3+}\)-doped laser is that the lower-level lifetime is greater than that of the upper level [4,19]. Here, attention is required to compare spectroscopic parameters in YAP crystal because there are different absorption coefficients by the axes in the YAP crystal [20]. Thus, it is difficult to draw comparisons spectroscopic parameters such as absorption coefficient and lifetime at this paper owing to the lack information on the crystal axis in Ref [15] of 1 at.% Er:YAP and Ref [21] of 10 at.% Er:YAP. We aim to measure the dopant dependence of the absorption coefficient and lifetime in future work.
To investigate the stimulated emission cross-section ($\sigma_{em}$), which corresponds to the laser oscillation characteristics of Er:YAP, we calculated $\sigma_{em}$ for the $^4I_{11/2} \rightarrow ^4I_{13/2}$ and $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition of Er:YAP from the following the Füchtbauer–Ladenburg (F-L) relationship [22]

$$\sigma_{em}(\lambda) = \frac{\lambda^5 \cdot I(\lambda)}{8\pi n^2 c \tau_{rad} \lambda I(\lambda) d\lambda},$$  

where $\lambda$, $I(\lambda)$, $c$, $n$, and $\tau_{rad}$ denote the wavelength of the fluorescence spectrum of the Er:YAP, intensity of the Er:YAP fluorescence at $\lambda$, speed of light, refractive index for $\lambda$, and radiative lifetime obtained from the Judd–Ofelt (JO) theory [23,24], respectively. The $\tau_{rad}$ of $^4I_{11/2} \rightarrow ^4I_{13/2}$ and $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition were 2.70 and 9.59 ms, respectively. Figures 2(a) and 2(b) show the spectrum of $\sigma_{em}$ for the $^4I_{11/2} \rightarrow ^4I_{13/2}$ and $^4I_{13/2} \rightarrow ^4I_{15/2}$ transitions in Er:YAP, respectively. From Fig. 2(a), $\sigma_{em}$ for the $^4I_{11/2} \rightarrow ^4I_{13/2}$ transition at four specific wavelengths, which were measured lasing wavelengths in a previous research [14], are listed in Table 1. In addition, the room-temperature $\sigma_{em}$ value of the $^4I_{11/2} \rightarrow ^4I_{13/2}$ emission band of Er:YAP and those of other Er$^{3+}$-doped mediums such as Er:YAG, Er:Lu$_2$O$_3$, and Er:Y$_2$O$_3$ were compared. These results are listed in Table 2. From Table 2, we note that the $\sigma_{em}$ values of the $^4I_{11/2} \rightarrow ^4I_{13/2}$ transition lie in the range of $0.3-2.4 \times 10^{-19}$ for Er:YAP, $1.0-7.0 \times 10^{-20}$ for Er:YAG [25], $0.4-3.0 \times 10^{-20}$ for Er:Lu$_2$O$_3$ [7], and $0.1-1.0 \times 10^{-19}$ for Er:Y$_2$O$_3$ [26]. The $\sigma_{em}$ range of Er:YAP is higher than those of Er:YAG, Er:Lu$_2$O$_3$, and Er:Y$_2$O$_3$. Thus, $^4I_{11/2} \rightarrow ^4I_{13/2}$ laser emission using Er:YAP is expected to attain more efficient oscillation at room temperature than these other materials.

![Fig. 1. Room temperature absorption spectrum of Er:YAP, ranging from 0.325 to 1.70 nm.](image-url)
Fig. 2. Room temperature fluorescence spectra of Er:YAP with peaks at around (a) 3 µm ($^{4}I_{11/2}$ → $^{4}I_{15/2}$ transition) and (b) 1.6 µm ($^{4}I_{13/2}$ → $^{4}I_{5/2}$ transition), respectively.

<table>
<thead>
<tr>
<th>Table 1. Comparison of room-temperature-stimulated emission cross-section of 5 at.% Er:YAP at various wavelengths.</th>
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<tbody>
<tr>
<td>Wavelength [nm]</td>
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<tr>
<td>$\sigma_{em}$ of $^{4}I_{11/2}$ → $^{4}I_{15/2}$ in Er:YAP [cm$^2$]</td>
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<tr>
<th>Table 2. Comparison of room-temperature-stimulated emission cross-section of various Er$^{3+}$-doped laser medium.</th>
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<tbody>
<tr>
<td>$\sigma_{em}$ of $^{4}I_{11/2}$ → $^{4}I_{15/2}$ [cm$^2$]</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
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<tr>
<td>$^{4}I_{11/2}$</td>
</tr>
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3. CW laser operation at room temperature

To investigate the Er:YAP laser properties, we investigated diode-pumped Er:YAP CW laser operation at room temperature. Figure 3 shows a schematic of the experimental setup utilized for Er:YAP CW laser operation. The pump laser was focused into the Er:YAP medium by using two plano-convex lenses with focal distances of 20 and 30 mm, and then a spot diameter of 165 µm was obtained at the focusing point. The plane–plane resonator (shown in the figure) with a cavity length of 18 mm consisted of a dichroic mirror (DM) and an OC. The DM exhibited excellent transmission at 976.2 nm and good reflection at 2.92 µm. The OC transmittance ($T_{oc}$) was set to 1%, 2%, 2.5%, and 5% at 2.92 µm in this experiment to determine the optimum OC transmittance. The Er:YAP crystal was cooled with water to maintain the temperature at 16 °C during CW operation. The mid-IR laser output was measured using a power meter (3A-SH, OPHIR) with a 2.88–2.96-µm bandpass filter (FB2750-500, Thorlabs). The lasing spectrum of the Er:YAP was measured using an optical
spectrum analyzer (OSA205C, Thorlabs) with a spectral resolution of 0.1 nm. Figure 4(a) shows the CW output power as a function of the absorbed power at various levels of OC transmittance. We note, from the figure, that the output power increases linearly as the absorbed power increases from the laser output threshold for each value of $T_{oc}$. The maximum output power ($P_{out}$) at an absorbed pump power of 3.49 W is 0.674 W with a slope efficiency $\eta = 31\%$. Then, the optical–optical efficiency, which is defined as the ratio of $P_{out}$ to the absorbed pump power, was 19%. In addition, a $P_{out}$ of 0.516 W and a value of $\eta$ of 23% are obtained for a $T_{oc}$ of 5%. Figure 4(b) shows the measured lasing wavelength ($\lambda_{output}$) of 5 at.% Er:YAP CW laser at various absorbed pump powers for $T_{oc} = 2.5\%$. At the absorbed pump power of 1.19 W, which was the laser-threshold, $\lambda_{output}$ of 2769 nm was measured. At the absorbed pump power of 1.91 W, $\lambda_{output}$ increased from 2769 to 2920 nm. At the absorbed pump power of 1.98 W, $\lambda_{output}$ of 2920 nm, with a spectrum width of 0.8 nm (FWHM), was obtained. Finally, $\lambda_{output}$ of 2920 nm was dominant for absorbed pump powers greater than 3.49 W.

The quantum-defect slope efficiency ($\eta_S$), which denotes the efficiency of the conversion from pumping light to laser emission light of an Er:YAP laser, can be obtained as the ratio of $\lambda_{center}$ to $\lambda_{output}$ [27] which corresponded to an $\eta_S$ value of 33% in our study. A comparison of the experimental results and theoretical efficiency revealed that this experimental value was 94% of $\eta_S$.

The slope efficiency of our result is significantly improved from previous works Refs [15,16]. This is because of the efficient resonant interaction between neighboring ions. This depopulates the $^4I_{13/2}$ by the $^4I_{13/2} \rightarrow ^4I_{15/2}$ and $^4I_{11/2} \rightarrow ^4I_{9/2}$ energy exchange, which is known as energy transfer upconversion (ETU). Then, the higher laser level of $^4I_{9/2}$ is populated by the $^4I_{9/2} \rightarrow ^4I_{11/2}$ phonon transitions. The pumping density of our work was critical to obtain this phenomenon. At the 2920-nm laser oscillation, ETU was observed, as mentioned in [28].

![Fig. 3. Schematic of setup of Er:YAP laser utilized in this study.](image-url)
4. Optimization of transmittance of output coupler

In our setup, the laser resonator suffers from internal resonator losses ($\delta$) due to $T_{oc}$ and a loss of light due to diffraction. Here, $\delta$ is one of the factors that causes the reduction in the laser output. Therefore, the suppression of $\delta$ is necessary to attain a high laser output. The value of $\delta$ can be varied by changing the value of $T_{oc}$. By using a higher $T_{oc}$ to enhance the laser output, $\delta$ increases and the internal light in the resonator is reduced before being amplified. Meanwhile, $T_{oc}$ cannot be set to zero to suppress the internal cavity loss because no laser output can be extracted. Thus, the optimum $T_{oc}$ value must be identified to obtain the maximum output power. The laser output power ($P_{out}$) emitted from the OC [27] can be expressed as

$$P_{out} = A \left( \frac{T_{oc}}{2-T_{oc}} \right) I_s \left( \frac{2g_0I}{\delta - \ln(1-T_{oc})} - 1 \right),$$

where $A$ denotes the LD beam cross-section ($= 0.000214 \, \text{cm}^2$), $I_s$ the pump saturation intensity, $g_0$ the unsaturated gain coefficient, $l$ is the length of the medium, and $\delta$ is the resonator loss. Thus, Eq. (2) relates the transmittance of the OC and the laser output power. Therefore, the optimized OC transmittance ($T_{opt}$) for the maximum output power can be obtained via the partial differential $\partial P_{out}/\partial T_{oc} = 0$. Consequently, we have

$$-\ln(1-T_{oc}) = \left( \frac{2g_0I}{\delta - 1} \right) \delta.$$  \hspace{1cm} (3)

From Eq. (2), we can see that parameters $g_0$ and $\delta$ must be identified to calculate $T_{opt}$. Consequently, in Fig. 5, we plot the measured $P_{out}$ values at 3.49 W of pumping power for each $T_{oc}$ value to investigate the relationship between $P_{out}$, $g_0$, and $\delta$. Upon fitting Eq. (2) to the experimental data, the $g_0$, $\delta$, and $I_s$ were determined to be 0.05887 cm$^{-1}$, 0.02707, and 310 kW/cm$^2$, respectively. Here, the fitted error of $g_0$ and $\delta$ were ± 0.000313 cm$^{-1}$ and ± 0.000646, respectively. The accuracy of $g_0$ and $\delta$ were 0.532% and 2.34%. Thus, value of $g_0$ and $\delta$, which were obtained from fitting Eq. (2), had high accuracy. The $T_{opt}$ value, which was obtained by substituting $g_0$ and $\delta$ into Eq. (3), was determined to be 2.3%. Further, the optimum output power $P_{opt}$ with $T_{opt} = 2.3\%$ was 0.676 W. Thus, the $T_{oc}$ value of 2.5% used in the experiment was reasonable for the OC.

Furthermore, the relationship between $g_0$ and $\sigma_{em}$ is given by [27]:

![Fig. 4. (a) Laser output power of Er:YAP crystal as a function of absorbed pump power; (b) lasering spectrum of Er:YAP crystal at various absorbed pump power for $T_{oc} = 2.5\%$.](image)
\[ g_0 = \sigma_{\text{em}} \tau_\text{f} \eta_Q \eta_B \eta_s P_{\text{abs}} / h \nu_L V, \] (4)

where \( \tau_\text{f} \), \( \eta_Q \), \( \eta_B \), \( P_{\text{abs}} \), \( h \nu_L \), and \( V \) are the fluorescence lifetime, quantum efficiency for the transition \( ^4I_{11/2} \rightarrow ^4I_{13/2} \), mode fill efficiency, absorbed pump power, photon energy for laser emission, and region of the pump beam that passes through the medium. In addition, these parameters are summarized in Table 3. The \( \sigma_{\text{em}-\text{g0}} \), that of Er:YAP at 2.92 \( \mu \)m as calculated from Eq. (4), was \( 5.4 \times 10^{-20} \text{ cm}^2 \), which is the same order of magnitude as that of \( 3.0 \times 10^{-20} \text{ cm}^2 \), obtained from F-L relationship.

### Table 3. Parameters of \( \sigma_{\text{em}} \) calculated from \( g_0 \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsaturated gain coefficient ( (g_0) )</td>
<td>0.059 [cm(^{-1})]</td>
</tr>
<tr>
<td>Fluorescence lifetime ( \tau_f )</td>
<td>0.85 [ms]</td>
</tr>
<tr>
<td>Quantum efficiency ( \eta_Q )</td>
<td>31 [%]</td>
</tr>
<tr>
<td>Quantum-defect slope efficiency ( \eta_d )</td>
<td>33 [%]</td>
</tr>
<tr>
<td>Mode fill efficiency ( \eta_B )</td>
<td>33 [%]</td>
</tr>
<tr>
<td>Absorbed pump power ( P_{\text{abs}} )</td>
<td>3.49 [W]</td>
</tr>
<tr>
<td>Photon energy for laser emission ( h\nu_L )</td>
<td>( 6.8 \times 10^{-19} ) [J]</td>
</tr>
<tr>
<td>Region of the pump beam that passes through the medium ( (V) )</td>
<td>0.0051 [cm(^3)]</td>
</tr>
</tbody>
</table>

5. Conclusion

We demonstrated the room-temperature 2.92 \( \mu \)m CW laser operation with slope efficiency of 31% using 5 at.% Er:YAP crystal. Our results indicate, to the best of our knowledge, the first successful demonstration of an Er:YAP CW laser with the highest reported slope efficiency at 2.92 \( \mu \)m. In addition, emission cross sections of the Er:YAP crystal were evaluated by fluorescence lifetime measurements and emission spectroscopy at 2.9 \( \mu \)m wavelength. In future, we plan to realize higher-efficiency, higher-power Er:YAP CW lasers by optimizing cavity length, changing the Er\(^{3+} \) concentration, and adjusting the cooling system. In conclusion, the Er:YAP laser has the potential for a new high-power and efficient mid-IR light source, making such lasers promising for use in mid-IR laser applications.

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