Highly efficient Er:YAP laser with 6.9 W of output power at 2920 nm

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Abstract: We report on the efficient high-power operation of a laser-diode-pumped Er3+-doped yttrium aluminum perovskite (Er:YAP) laser in the 3 μm spectral region at room temperature. 6.9 W of continuous-wave (CW) output power was obtained at 2920 nm. The slope efficiency was as high as 30.6% with respect to the absorbed pump power, which is close to the quantum defect limit (33.4%). To the best of our knowledge, this is the highest CW output power generated from 3 μm Er3+-doped solid state lasers at room temperature. Furthermore, our analysis has shown that more than 10 W of output power based on Er:YAP is possible by further mitigating the thermal lens effect.

1. Introduction

Large quantities of molecules in the atmosphere that will lead to the greenhouse effect, such as H2O, N2O and CO2, show abundant absorption lines in the mid-infrared spectral region around 3 μm [1]. Mid-infrared lasers at this wavelength are attractive for applications in differential absorption systems for highly efficient concentration detection of these molecules. The feature of strong water absorption at this wavelength also makes them suitable for laser surgery [2]. High power 3 μm lasers, which are quite necessary for pumping the Fe2+ lasers [3], Dy3+ lasers [4], and frequency-converted lasers [5] to generate longer wavelengths. Driven by these requirements, several types of high-power 3 μm solid state lasers have been developed, mainly including frequency converted lasers optical parametric oscillator (OPO) [6,7], optical parametric amplifier (OPA) [8], and solid state lasers based on Ho3+, Er3+, and Cr2+ ions [9–11]. In these kinds of lasers, Er3+-doped solid state lasers can be excited by direct laser diode (LD) at ~976 nm, which avoids multiple laser stages from LD to the final target wavelength. That will increase the total optical-to-optical conversion efficiency and reduce the cost and the complexity.

Er3+-doped solid state lasers have been widely demonstrated and have proved to be efficient methods to generate the 3 μm lasers [10,12]. In Er3+ laser systems, continuous population inversion depends on the effective energy transfer up-conversion (ETU) process, which benefits from a high doping concentration. However, a high doping concentration will inevitably result in serious thermal effects, e.g., change in gain cross-section, thermal stress and fracture damage, owing to the quantum-defect-induced thermal loading in a short gain medium. Further, multi-phonon relaxation process between the 4I11/2 and 4I13/2 energy levels will also lead to extra heat accumulation [13]. Thus in a high power laser system, in addition to efficient heat dissipation via heat sinks, the thermal effects can also be mitigated by using a host material with low phonon energy and excellent thermal properties. These features can increase the laser conversion efficiency and effectively reduce the heat accumulation in the crystal.

Er3+-doped sesquioxides (Er:Lu2O3, Er:Sc2O3, Er:Y2O3) are attractive in generating high power 3 μm lasers in terms of low phonon energy (Lu2O3: 618 cm−1, Sc2O3: 672 cm−1, Y2O3: 597 cm−1) and comparable conductively with YAG [14]. Up to now, 14 W of CW output power has been reported from a cryogenic cooled Er:Y2O3 laser [15]. Also, 5.9 W of CW output power
from an Er:Lu$_2$O$_3$ laser has been reported [12], which is the highest output power generated from 3 \( \mu \)m Er$^{3+}$-doped solid state lasers at room temperature. Nevertheless, the high melting point of these crystals (~2400 °C) [14] has made them difficult to grow. Fortunately, Er:YAP also has low phonon energy and excellent thermal properties. It can be grown by Czochralski method (melting point 1875 °C) and its thermal conductivity as well as thermal expansion coefficient are similar with those of YAG [16]. Thermal shock parameter \( R \) of end-pumped Er:YAP (\textit{Pbnm} of space group), which defines the maximum thermal loading giving a smallest value along the crystalline axis of ~920 Wm$^{-1}$ according to [17]:

\[
R = \frac{K\sigma_{\text{fracture}}}{\alpha T E}
\]  

where \( K \) is the thermal conductivity [11.6 Wm$^{-1}$K$^{-1}$ (\( ||a|| \)), 9.9 Wm$^{-1}$K$^{-1}$ (\( ||b|| \)), 12.3 Wm$^{-1}$K$^{-1}$ (\( ||c|| \))] [18], \( \sigma_{\text{fracture}} \) is the maximum thermal stress when the fracture occurs (160 MPa) [19], \( \alpha \) is the expansion coefficient [9.18×10$^{-6}$ K$^{-1}$ (\( ||a|| \)), 1.94×10$^{-6}$ K$^{-1}$ (\( ||b|| \)), 7.61×10$^{-6}$ K$^{-1}$ (\( ||c|| \))] [18], and \( E \) is the Young’s modulus (220 GPa) [19]. This value is higher than that of YAG (790 Wm$^{-1}$) [20], permitting it to tolerate higher thermal loading. Moreover, the maximum phonon energy of YAP (550 cm$^{-1}$) [21]) is even lower, thus less phonon-induced non-radiative relaxation (NR) can be expected in Er:YAP laser [22]. The anisotropic property of Er:YAP also allows direct linearly polarized laser emission, which will reduce the depolarization loss under high power operation. Therefore, Er:YAP is a promising laser material for yielding high power 3 \( \mu \)m laser efficiently.

Laser operations based on Er:YAP at ~3 \( \mu \)m have also been reported in these years [21,23–25]. In 2018, C. Quan et al. reported an output power of 739 mW with two laser wavelengths at 2710 nm and 2728 nm from an Er:YAP laser, and the slope efficiency was 12.1% [23]. In 2019, our group presented a 670 mW Er:YAP laser emitting at 2.9 \( \mu \)m, with a higher slope efficiency of 31% [21]. We also demonstrated a passively Q-switched Er:YAP laser, in which the primary demonstration of CW output power was 1.17 W, with a slope efficiency of 29% [25], which is the highest output power generated from an Er:YAP laser at ~3 \( \mu \)m so far.

In this work, we present a higher output power, i.e., 6.9 W from an Er:YAP laser emitting at 2920 nm. The slope efficiency is as high as 30.6% with respect to the absorbed pump power. This value is close to the theoretical quantum defect limit, i.e., 33.4%. Higher output power is limited by the destabilization of the cavity mode. Crystal damage has not been observed, benefitting from the excellent physical properties of Er:YAP and a high laser conversion efficiency. To the best of our knowledge, this result represents the highest CW output power generated from 3 \( \mu \)m Er-doped solid state lasers at room-temperature.

2. Experimental setup

In this paper, the Er:YAP crystal is labeled according to the \textit{Pbnm} notation of space group. Because of the anisotropic structure of Er:YAP, the thermal conductivities and expansion coefficients along the \( a \)-axis and the \( c \)-axis are similar and are higher than those along the \( b \)-axis [18]. To achieve a better heat dissipation and relatively uniform thermal expansion along the radial direction, we chose a \( b \)-cut sample (provided by Crytur Ltd.) to avoid the crystal fracture as much as possible for a potential high thermal gradient. Moreover, the laser will also acquire a higher gain when it propagates along the \( b \)-axis [26], which is beneficial to improve the laser conversion efficiency. The crystalline axes and placement of the Er:YAP crystal, and the experimental setup are shown in Fig. 1. The crystal was doped with an Er$^{3+}$ concentration of 5 at.\%, with dimensions of 2 mm × 8 mm × 5 mm along \( a \)-, \( b \)- and \( c \)-axes, respectively. The \( a \)-axis and \( c \)-axis were placed parallel to horizontal (\( x \)) and vertical (\( y \)) directions, and the \( b \)-axis was parallel to the laser axis (\( z \)). Both two end surfaces of the crystal were not anti-reflection-coated but optically polished parallel. The crystal was wrapped with a 0.05 mm thick indium foil and...
mounted in a specially-designed water-cooled copper holder to achieve a good heat dissipation. The water temperature was kept constant at 16 °C.

In the Er:YAP laser system, it can be predicted that the thermal lens effect will be very obvious during high power operation. Therefore, a plano-plano cavity was designed to achieve a larger stable region [27]. The laser cavity consists of a plane input mirror (IM, T=97% at 960–980 nm, R >99% at 2.6–3 μm) and a plane output coupler (OC1: T=1% at 2.8–3 μm, R=91% at 960–980 nm; OC2: T=2.5% at 2.8–3 μm, R=85% at 960–980 nm; OC3: T=5% at 2.8–3 μm, R=90% at 960–980 nm). Meanwhile, the distances between the two mirrors and the crystal were also adjusted as short as possible to ensure the stability of the resonator and reduce the water vapor absorption, giving a total cavity length of ~13 mm. A dichroic mirror (DM) was placed behind the output coupler to separate the laser and residual pump light. The pump source was a fiber-coupled 976 nm LD (provided by BWT Beijing LTD.) with a non-polarization-maintained fiber core diameter of 105 μm (0.22 NA) without wavelength stabilization. Due to the power limit of the fiber connector, the maximum pump power was restricted to be 50 W. Then by using a telescopic lens system consisting of two lenses (f=30 mm and f=100 mm), a minimum pump radius of ~175 μm was obtained in the crystal. Since the pump beam quality factor of $M^2$ was measured to be ~25, the confocal parameter was estimated to be ~15 mm, covering the entire Er:YAP crystal effectively.

3. Results and discussions
3.1. High-power CW laser generation

We first checked the pump absorption of the Er:YAP crystal at different pump powers. A wavelength-locked 976 nm LD was used to confirm the variation of pump absorption of the Er:YAP crystal. By increasing the incident pump power from ~1 W to ~47 W, the single-pass absorption of the Er:YAP in non-lasing state was measured to be ~71%, and the fluctuation was less than 5%. Thus, the ground state bleaching effect can be neglected for the current pump intensity. We can also ignore the difference in pump absorption while using different OCs. On the other hand, using the current pump source whose wavelength was not stabilized, the single-pass absorption of the same crystal was measured to increase from 30% (3 W of incident pump power) to 59% (45 W of incident pump power), resulting from the red-shift of the pump wavelength. To further determine the total pump absorption with lasing, the reflected pump powers from the crystal surface and the OC that will contribute to the lasing were estimated and taken into account the total absorbed pump power.

Laser performance of Er:YAP was characterized using three OCs (Toc=1%, 2.5% and 5%). The output power dependences on the absorbed pump power is shown in Fig. 2. With increasing the pump power, the Er:YAP laser produced maximum output powers of 4.3 W (absorbed pump
power of 21 W), 6.9 W (absorbed pump power of 24.7 W), and 4.7 W (absorbed pump power of 22.2 W) with 1%, 2.5%, and 5% Toc, respectively. The corresponding slope efficiencies were found to be 22.1%, 30.6%, and 25.2%. The maximum output power, i.e. 6.9 W represents the highest value ever reported from 3 µm Er-doped solid state lasers at room temperature, and obviously the maximum overall optical-to-optical efficiency (28%) is higher than that of the typical OPO system [6]. Then laser spectra were recorded by a spectrum analyzer (771B-MIR, Bristol Inst.) at different output powers, as is shown in Fig. 3(a). At around 100 mW of output power, the laser wavelengths were determined to be 2824 nm and 2844 nm for Toc=1%, 2797 nm and 2824 nm for Toc=2.5%, and 2797 nm for Toc=5%. The difference in laser wavelength could be explained by the changes in population ratio of upper (4I_{11/2}) and lower (4I_{13/2}) energy levels. Figure 3(b) shows a brief energy level diagram of Er^{3+} ion [28]. With the increasing of Toc, the population ratio will increase in order to make the system achieve a higher laser gain to overcome the increased cavity loss. As a result, the shorter wavelength will acquire a higher gain [29], leading to the shift of laser wavelength with different Toc at low power level. However, at high pump intensity (W-level output power), owing to a longer lifetime of 4I_{13/2} level than that of 4I_{11/2} level [28], the population will accumulate gradually on the 4I_{13/2} level, resulting in a reduction in the population ratio. In this case, the impact on the population ratio from the population accumulation will be more significant than changing the Toc. Finally, the laser wavelength will shift to a longer wavelength and be stabilized at 2920 nm.

Fig. 2. Output power dependence on absorbed pump power for different OC.

From Fig. 2 we can see that after the output power reaches the highest level, obvious output power saturation can be observed with each OC if we further increase the pump power. We can thus estimate the total thermal loading in the Er:YAP crystal from the difference between the absorbed pump power and laser output power at these saturation points. Because of the similar thermal loading, we think that the power saturation can be attributed to the thermal lensing. To confirm the assumption, effective thermal focal length (f_{th}) was measured at different absorbed pump power [30] with Toc of 2.5% which gave the highest slope efficiency. During the measurement, the thermal lens was assumed to locate in front of the crystal. Figure 4 shows the optical power of thermal lens (D=1/f_{th}) at different absorbed pump power. In x and y directions, the optical power of thermal lens were determined to be D_{x}=3.14P_{ab} and D_{y}=1.93P_{ab}, respectively, where P_{ab} represents the absorbed pump power. In the current experiment, the cooling of the crystal was more effective in the y directions, thus the thermal gradient in the y direction is smaller [31], resulting in the optical power difference in two directions. At the maximum absorbed pump power, the effective thermal focal length in x direction can be calculated.
to be less than $\sim 12$ mm based on ABCD matrix, which is close to the unstable region of the resonator, resulting in the destabilization of the cavity mode and the subsequent power reduction.

Figure 5 shows a typical result of the $M^2$ measurement at output power of 3.7 W. The laser beam was focused by using a lens, and the beam radii at different positions were measured using the 10/90 knife-edge method. After the fitting by hyperbolic equations, the $M^2$ were determined to be 2.2 and 1.8 in $x$ and $y$ directions, respectively. The difference in beam quality between two directions can be attributed to the difference in thermal focal length. Also, the laser beam was collimated by a lens with 200 mm focal length and then recorded by a camera working in the mid-infrared region, as shown in Fig. 5. Under the combination of different heat distribution and refractive index of the crystal regarding the two directions, the pattern shows an obvious elliptical shape.

### 3.2. Power scaling ability analysis

We specially focused on the power scaling ability of the LD-pumped Er:YAP laser. In the current experiment, in spite of the limitation of output power by the thermal lens effect, we did not observe the thermal-stress-induced crystal damage even at the maximum absorbed pump power.
Actually, the thermal lens effect can be mitigated by means of enlarging the pump radius or other compensation approaches [32]. Therefore, the maximum possible output power is mainly limited by the crystal damage. For a more general situation, we consider a symmetrical laser crystal for simplicity, e.g., a rod type with 1 mm radius to evaluate the power scaling ability of Er:YAP laser. Because of the anisotropic character of Er:YAP, it is difficult to obtain the analytic solution of thermal distribution. However, we can neglect the anisotropy of Er:YAP because of the similar thermal properties along the \(a\)- and the \(c\)-axes. In this case, the maximum temperature difference \(\Delta T_{\text{max}}\) and its induced maximum tensile stress \(\sigma_{\text{max}}\) on the incident surface can be given by [17]:

\[
\Delta T_{\text{max}} = \frac{\eta \alpha P_{ab}}{4 \pi K (1 - e^{-\alpha l})} \left( 1 + 2 \ln \frac{r_b}{\omega_p} \right)
\]  

(2)

\[
\sigma_{\text{max}} = \frac{\sigma_T \eta E P_{ab}}{4 \pi K (1 - e^{-\alpha l})} \left[ 1 - \frac{1}{2} \left( \frac{\omega_p}{r_b} \right)^2 \right]
\]  

(3)

where \(\eta\) is the heat generation parameter (0.7), \(\alpha\) is the absorption coefficient (1.15 cm\(^{-1}\)), \(l\) is the crystal length (8 mm), \(r_b\) is the crystal radius (1 mm), and \(\omega_p\) represents the average pump radius (186 \(\mu\)m, the same with the current experiment). Thermal conductivity and expansion coefficient of Er:YAP were chosen along \(a\)-axis [18]. According to the fracture limit stress of YAP (160 MPa) [19], the maximum tolerable absorbed pump power and the corresponding \(\Delta T_{\text{max}}\) of the crystal were calculated to be \(-88\) W and \(-350\) K, respectively. Since the maximum absorbed pump power was \(-25\) W in our experiment, the same absorbed power level only results in \(-100\) K of temperature difference and \(-45\) MPa of tensile stress in this model, which are 28% of the damage limit. Thus it can be expected that the output power can be further improved before the crystal damage.

It should be noted from the Eqs. (2) and (3) that the temperature difference and the thermal stress can be reduced by increasing the pump radius or reducing the crystal diameter. Here enlarging the pump radius was considered for the power scaling ability estimation for it can alleviate the thermal lens effect at the same time according to \(D \propto P_{ab} \omega_p^2\) [20]. The laser rate-equations [33] as well as the thermal lens effect were combined to estimate the possible output power. To ensure the slope efficiency, the minimum effective thermal focal length was set to be 13 mm, according to our experiment. Table 1 shows the predicted laser performances with different average pump radii. It can be seen that the maximum possible output power is enhanced...
by enlarging the pump radius. Over 10 W of output power can be achieved when the average pump radius is over 230 μm.

| Table 1. Predicted laser performances with different pump radii. |
|-------------------|----------------|----------------|----------------|----------------|----------------|
| ω_{p0} (μm)       | 190            | 200            | 220            | 230            | 250            |
| Max. P_{ab} (W)   | 25             | 27.7           | 33.5           | 36.6           | 43.3           |
| Output power (W)  | 7.3            | 8.1            | 9.9            | 10.5           | 12.4           |
| ΔT_{max} (MPa)    | 45.6           | 50.4           | 60.7           | 66.1           | 77.8           |

During the power scaling operation, in addition to enlarging the pump radius, the uniformity of the pump power distribution in the crystal will also affect the laser performance. Double-end pump structure can not only reduce the temperature difference and thermal stress on the crystal surface, but also improve the pump uniformity, which is beneficial to increase the output power [34]. Moreover, effective heat removal such as using the micro-channel heat sink [35] or the direct liquid cooling [36] method is also necessary for the improvement of output power. With these methods, a higher output power can be expected in the future.

4. Summary

In conclusion, we have experimentally demonstrated a high power LD pumped Er:YAP laser at 2920 nm. Using a b-cut Er:YAP crystal with 5 at.% doping level and a two-mirror laser cavity, laser performances were characterized with different OCs. An output power up to 6.9 W was obtained with Toc of 2.5%. The results confirm that the Er:YAP is suitable for generating high-efficient and high-power 3 μm laser. In applications, this laser is very attractive for rapid material processing, e.g., polymer [37]. In our next work, we will focus on enlarging the pump radius, optimizing the pump configuration and heat sinks, etc., to further scale the output power.

Funding

Japan Society for the Promotion of Science (15KK0245, 18H01204); Amada Foundation (AF-2018228-C2, AF-2019221-B3); Murata Science Foundation (H31助助009); National Institute for Fusion Science (UFEX5003, ULHH040).

Disclosures

The authors declare no conflicts of interest.

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