14.1 W continuous-wave dual-end diode-pumped Er:Lu$_2$O$_3$ laser at 2.85 μm

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We present our efforts towards power scaling of Er:Lu$_2$O$_3$ lasers at 2.85 μm. By applying a dual-end diode-pumped resonator scheme, we achieve an output power of 14.1 W at an absorbed pump power of 59.7 W with a slope efficiency of 26%. In a single-end pumped resonator scheme, an output power of 10.1 W is reached under 41.9 W of absorbed pump power. To the best of our knowledge, this is the first single crystal Er:Lu$_2$O$_3$ (ceramic) [13], Er:Lu$_2$O$_3$ (ceramic) [14] Er:YAlO$_2$ (crystal) [12], Er:Y$_2$O$_3$ (ceramic slab) [15] have delivered output powers of 5.9 W, 6.7 W, 6.9 W and 13.4 W, at room temperature. Cooling with liquid nitrogen (77 K), output power of 24 W [16] was realized with

Fig 1. Simplified energy levels of Er$^{3+}$ ions and energy transfer mechanism.
Er:Y$_2$O$_3$. While, the highest output power among the fluoride lasers is ~4 W by Er:YLF [17].

Among the reported gain media, Er:Lu$_2$O$_3$ is one of the most promising candidates to achieve high power mid-infrared laser output. It shows a high thermal conductivity, even at high doping concentrations [18]. Here, diode single- and dual-end-pumped CW Er:Lu$_2$O$_3$ laser oscillator concepts are investigated with the aim of further power scaling. In a single-end-pumped Er:Lu$_2$O$_3$ resonator, a slope efficiency of 25.5% was realized with an output power of 10.1 W at an absorbed pump power of 41.9 W. By applying a dual-end-pumping scheme, we homogenized the thermal load in the Er:Lu$_2$O$_3$ gain material and achieved the highest output power of any room-temperature crystalline Er$^{3+}$-doped gain crystal in the mid-infrared, so far. A laser output power of 14.1 W was achieved at a total absorbed pump power of 59.7 W. The corresponding slope efficiency amounted to 26% and the power stability is better than ±1.3% over one hour. To the best of our knowledge, this is the first Er$^{3+}$-based room-temperature 3-μm CW crystalline laser with more than 10 W of output power.

2. Experimental setup

The experimental setup is depicted in Fig. 2. Fig. 2 (a) shows the single-end-pumped resonator configuration. In both cases, the gain medium is a $3 \times 3 \times 10$ mm$^3$ Er(7 at.%)/Lu$_2$O$_3$ crystal grown by the heat exchanger method [19] cooled to 10 °C (prepared by Christian Kränkel). The input coupling mirror (IC) is concave with a radius of curvature of 10 m. It is anti-reflection (AR) coated for the range of the pump wavelength between 960 and 990 nm and highly reflective (HR) coated for the range of possible laser wavelengths between 2700 and 2900 nm. We used two different plane mirrors as output couplers (OCs) for the laser radiation. These are AR coated in the pump wavelength range and exhibit transmissions (T) of 3% and 5% for the laser wavelength. To avoid resonator losses by water vapor absorption, the laser cavity was set up as short as possible, leading to ~14 mm long resonators. The coupling fiber of the 100-W pump diode has a core diameter of 105 μm and an NA of 0.22. The pump laser wavelength is stabilized at 976 nm with a full spectral width at half maximum of 0.4 nm. In the single-end-pumped scheme (Fig. 2 (a)), the pump beam is collimated by lens L1 and then focused into the laser crystal by lens L2. In the dual-end-pumped scheme (Fig. 2 (b)), the collimated pump beam is separated by a polarizing beam splitter (PBS). The p-polarized (p-pol.) pump beam is focused into the Er:Lu$_2$O$_3$ gain medium from forward direction by lens L2 and the s-polarized (s-pol.) light is applied from backward direction by lens L3. Such a polarization beam separation design is also useful to protect the laser diode from damage of residual pump light in backward direction, but should not affect the performance of the cubic Er:Lu$_2$O$_3$ crystal. In both schemes, the laser signal is separated from the residual pump by a 45° dichroic mirror (DM) which is AR coated for the pump and HR coated for the laser wavelength incident under this angle.

3. Laser experiments and results

3.1 Laser performance of water-cooled Er:Lu$_2$O$_3$ lasers

By placing the crystal tightly wrapped in indium-foil in a water-cooled copper heat sink, power scaling of the single-end- and dual-end-pumped resonators was investigated. Firstly, the CW laser performance of the single-end-pumped laser was investigated with a coupling lens group, in which the focal lengths of the lenses L1 and L2 are 30 mm and 150 mm, respectively, yielding a coupling group of 30:150. For T = 3%, the resonator allowed for a maximum of 6.0 W of laser output under 27.5 W of absorbed pump power. For the 5% OC mirror, 6.2 W were realized under 32.8 W of pump power (Table 1). The corresponding slope efficiencies amount to 24% and 21% using the OC mirrors of 3% and 5% transmission, respectively. Limited by the serious thermal load, a higher output power was not feasible by further enhancing the pumping power.

To improve the output power, the thermal intensity was reduced by enlarging the pump beam diameter to ~600 μm with a coupling lens group of 35:200. As shown in Fig. 3 (a), slope efficiencies of 28% and 25% were achieved with OCs of 3% and 5% transmission, respectively. Under a maximum absorbed pump power of 33.3 W, output powers of 8.1 W and 7.2 W, respectively, were achieved in the configuration shown in Fig. 2 (a). Thus, in the 35:200 configuration, the slope efficiencies were improved by a factor of 1.2. Theoretical calculations show that a perfect mode matching requires an even larger pump diameter of ~1000 μm, but we did not find improved results using a 30:200 coupling group for further enlarging the pump beam diameter.

The dual-end-pumping scheme can create a more homogenous distribution of the pump light and thus of the inversion in the crystal. Due to the long lifetime and significant population of the lower laser level, the Er$^{3+}$-based 3-μm laser can be treated as a three-level laser system. For such lasers, a more homogeneous distribution of the population inversion can reduce the reabsorption of the laser photons [20]. Moreover, a homogenous distribution of the pump light also homogenizes the thermal load in the gain area, enabling higher pump and thus output powers [21].

![Fig. 2. Laser schemes of (a) the single-end-pumped and (b) the dual-end-pumped Er:Lu$_2$O$_3$ laser.](image)

![Fig. 3. Laser characteristics of the (a) single-end-pumped and (b) dual-end setup pumped for different T by using 35:200 and 35:200:200 lens group, respectively.](image)
Using a 30:150:150 lens group (the focal lengths of the lenses L1, L2, and L3 are 35 mm, 200 mm, and 200 mm, respectively), the performance of the dual-end-pumped Er:Lu2O3 laser was characterized. Output powers of 8.1 W and 7.2 W were realized with 3% and 5% OC transmission, respectively. The slope efficiency amounted to 21% in both cases (Table 1). In comparison to the single-end-pumped experiments with the same lens group, this amounts to an increase of the output power of ~30%.

By employing the more efficient coupling lens group 35:200:200, output power and slope efficiency were further improved. As shown in Fig. 3 (b), this configuration enabled for the first time to reach more than 10 W of output power. A laser output power of 10.1 W was realized under an absorbed pump power of 43.6 W using 3% OC transmission, amounting to 23% optical-to-optical efficiency.

While the dual-end-pumped configuration is advantageous to reduce the lasing threshold and to increase the output power, it exhibits a lower slope efficiency. To identify the reasons, we separately characterized the forward and backward single-end-pumped resonators. To this end, we investigated the laser using only the p-pol. forward or only the s-pol. backward pump beam. The corresponding laser characteristics are listed in Table 1. The slope efficiencies of the forward pumped lasers are close to those of the single-end-pumped lasers, and mostly higher than that of the related dual-end-pumped lasers. In contrast, the slope efficiencies of the backward pumped lasers are lower than the single-end-pumped and dual-end-pumped lasers. We believe that the reduced slope efficiencies of the dual-end-pumped lasers are caused by an imperfect spatial matching between the backward pump beam and the laser mode area. Consequently, a higher efficiency and correspondingly higher optical output power should be feasible by further improving the coupling conditions of the backward pump beam.

While we obtained an output power of 10.1 W in the water-cooled dual-end-pumped Er:Lu2O3 resonator, further scaling by increasing the pump power was not successful, which we attribute to thermal effects.

### 3.2 Laser performance of TEC cooled Er:Lu2O3 lasers

To further explore the power scaling potential of our laser and improve the temperature control, we exchanged the water-cooling of the gain crystal by a thermoelectric cooler (TEC). In this setup, the gain crystal was tightly embedded in a passive copper heat sink glued to the cold side of a TEC, while the hot side of the TEC is glued to a water-cooled copper heat sink. This configuration enables to control the cooling temperature with a precision of 0.1 °C, which ensures a more stable temperature of the laser crystal compared with the directly water-cooled experiments.

With this cooling setup, we repeated the single- and dual-end-pumped laser experiments with the 35:200 and 35:200:200 lens groups, respectively. As shown in Fig. 4, the optimized cooling led to a remarkable improvement of the laser output power compared to the directly water-cooled experiments shown in Fig. 3. In the single-end-pumped scheme, an output power of 10.1 W was achieved under an absorbed pump power of 41.9 W at a slope efficiency of 27% and an optical-to-optical efficiency of 24%. This amounts to a power improvement of more than 25%.

In the dual-end-pumped scheme, the resonator delivered even 14.1 W of mid-infrared laser output (Fig. 4 (b)). This is the highest output power of any Er3+-based room-temperature 3-μm CW crystalline laser. The laser exhibits a slope efficiency of 26% at an optical-to-optical efficiency of 24% with respect to the absorbed pump power.

### 3.3 Further characteristics of the CW Er:Lu2O3 lasers

In particular for Er3+-based 3-μm lasers, being prone to self-termination, the power stability is a fundamental parameter. Thus, we measured the long-term output power fluctuations at

| Table 1. Summary of the results obtained with different Er:Lu2O3 resonator configurations |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| cooling         | laser scheme    | coupling lens group | pump direction | polarization | output coupler transmission | maximum absorbed pump power | highest output power | slope efficiency (%) |
| single-end-pumped scheme | 30:150 | forward | non-pol. | 3% | 27.5 | 6.0 | 24 |
|                 | 35:200 | forward | non-pol. | 5% | 32.8 | 6.2 | 21 |
| water           | dual-end-pumped scheme | 30:150:150 | forward & backward only | / | 5% | 32.0 | 7.2 | 25 |
|                 | 35:200:200 | forward only | p-pol. | 3% | 26.0 | 5.2 | 22 |
|                 |                 | s-pol. | 5% | 26.0 | 4.4 | 20 |
| TEC             | single-end-pumped scheme | 35:200 | forward | non-pol. | 5% | 35.5 | 7.3 | 25 |
|                 | dual-end-pumped scheme | 35:200:200 | forward only | p-pol. | 3% | 24.7 | 6.6 | 28 |
|                 |                 |    | s-pol. | 5% | 25.6 | 5.9 | 26 |
|                 |                 |    | only | s-pol. | 3% | 26.8 | 5.3 | 22 |
|                 |                 |    | only | only | 5% | 27.9 | 5.0 | 21 |
|                 |                 |    |          | 3% | 41.9 | 10.1 | 27 |
|                 |                 |    |          | 5% | 41.9 | 9 | 25 |
|                 |                 |    |          | 3% | 59.7 | 14.1 | 26 |
|                 |                 |    |          | 5% | 59.7 | 12 | 22 |
different output power levels. First, we measured the stability of the water-cooled dual-end-pumped resonator at output power levels between 2 and 8 W using 3% of OC transmission. The stability at the highest power level is shown by the blue curve in Fig. 5 (a). As indicated in Fig. 5 (b), we found the instability (PV) to decrease from ±7.2% at 2 W to ±3.5% at 8.2 W of output power. As seen in Fig. 6, for lower output powers, dual-wavelength lasing around ~2845 nm is typically observed, which may lead to mode competition contributing to the output power instabilities. However, we attributed the main, somewhat regular, pattern in the power characteristics to the heating/cooling cycle of the chiller used for the water cooling of the laser crystal, which motivated further investigations under TEC cooling.

The long-term output power fluctuations under TEC cooling at 12 W of output power and T = 3% are shown by the red curve in Fig. 5 (a), the progress of the instability vs. output power is shown in Fig. 5 (b). The significantly higher temperature stability of the TEC cooled laser crystals avoids the abrupt and large-amplitude power variations seen for the water-cooled experiments, and thus enables more stable laser output. Which means the periodic fluctuations of the output power in the water-cooled laser can be attributed to thermal effect. At the highest measured power level of 12 W the instability (PV) of the TEC cooled laser amounted to only ±1.3%. At power levels around 9 W, comparable to the highest power investigated in the water-cooled experiments, the instability is as low as ±1%, which corresponds to an improvement by a factor of 3.5. These results clearly show that the temperature stability of Er3+-doped gain media for 3 µm lasers is a crucial factor to achieve stable laser output power.

The laser spectra of the dual-end-pumped Er:Lu2O3 lasers using 3% OC transmission at different output powers were measured by an OSA207C Fourier transform spectrum analyzer (Thorlabs Inc.). As shown in Fig. 6, the laser emission wavelength of the TEC-cooled dual-end-pumped lasers changes in the range of 0.25 W of output power. For output powers below 0.2 W, single, dual, and multi-wavelength operation in the 2720 nm region is observed. At 0.3 W of output power, the onset of lasing at 2845 nm is observed and lasing around 2720 nm slowly fades out. At power levels above 0.3 W, 2845 nm is the only laser wavelength. Such a behavior was previously observed [12], and results from reabsorption of the laser at ~2720 nm with increasing power levels by increasing population of the lower laser level. Moreover, we found a slight red-shift of the center wavelength with increasing output power, yielding a center wavelength of 2846,1 nm for 13.8 W of output. These observations lead us to believe that spectral tuning of the laser output wavelength is feasible.

Finally, we determined the beam quality of the dual-end-pumped resonator at 3% OC transmission by the knife-edge method at different power levels. An uncoated CaF2 lens with focus length is 100 mm is employed. A razor blade is fixed on a two-axis manual translation stage (resolution: 10 µm) to measure the beam waist in both X and Y directions. As indicated in Fig. 7, the M2 factors in the sagittal (M2x) and meridional plane (M2y) of the TEC-cooled dual-end-pumped lasers gradually reduce from 1.7 × 1.5 (@ 2 W) to 2.7 × 2.5 (@12 W).
Fig. 7. M² values versus output power level for 3% OC transmission in the dual-end-pumped water-cooled resonator configuration, inset: spatial beam characteristics and M² values at 2 W.

4. Conclusion

In conclusion, we presented our efforts to scale the output power of diode-pumped Er:Lu₂O₃ lasers emitting around 2.85 μm by applying a high power, narrow-emission pump diode and a dual-end-pumped resonator scheme as well as an improved temperature stability of the gain medium by applying direct TEC-cooling. In a single-end-pumped water-cooled configuration, we obtained an output power of up to 10.1 W under 41.9 W of absorbed pump power, an improvement of more than 70% compared to previous results obtained with Er:Lu₂O₃ [12], and also higher than any other crystalline Er³⁺-based 3-μm laser at room temperature [11]. However, this result was limited by the onset of thermal effects. To homogenize the thermal load and allow for higher pump power levels, we thus applied a dual-end-pumping scheme, and realized a record high output power of 14.1 W under 59.7 W of pump power at a slope efficiency of 26%. Improving the temperature stability by using a high precision TEC improved the long-term stability of this laser emitting at 2.85 μm to better than ±1.3% at 12 W of output power. Considering slope efficiencies of up to 36% reported in previous work with Er:Lu₂O₃ [12], we anticipate output power levels in excess of 20 W to be possible with our dual-end-pumped laser scheme by optimizing the pump wavelength, the coupling conditions of the pump source as well as the output coupler transmission and the spatial overlap of the pump and the laser beam.

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References.