High-Power, High-Efficiency Tm:YAG and Ho:YAG Thin-Disk Lasers

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Continuous-wave Tm:YAG and Ho:YAG thin-disk lasers with maximum optical-to-optical efficiencies of 41% and 58% respectively are presented. Pumped by a 780 nm laser diode, the Tm:YAG laser generated a maximum output power of 24 W. In comparison, the Ho:YAG laser, pumped by a fiber laser at 1908 nm, delivered a maximum output power of 50 W. The reported output powers are, to the best of our knowledge, the highest among all thin-disk lasers emitting at ≈2 μm, and provide a solid foundation for the further development of next-generation 2 μm thin-disk technologies.

1. Introduction

High-power laser sources operating in the 2 μm spectral region have numerous applications including the generation of attosecond pulses, XUV frequency combs, and high-harmonics towards the X-ray range.[1–3] Aside from research, diverse real-world applications such as material processing and medical treatment also benefit considerably from such sources.[4–6] In addition, 2 μm sources can serve as an effective driver for generating broadband mid-infrared radiation, bringing the attractive properties of powerful coherent light deep into the mid-infrared.[7–10] Among all the gain media emitting around 2 μm, Tm:YAG and Ho:YAG are two of the most promising candidates for building high power lasers, since they share the same excellent thermal and mechanical properties with Yb:YAG—arguably the most widely used gain medium in the 1 μm range for high power lasers. Furthermore, the lasing wavelengths of both Tm:YAG and Ho:YAG, around 2-2.1 μm, are located away from regions of strong water-vapor absorption; this simplifies the laser setup and facilitates beam delivery in ambient air, aiding their adoption by applications outside of the lab environment.

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Compared to Ho:YAG, Tm:YAG can be directly pumped by commercially available laser diodes at 785 nm. Although the quantum defect is over 60%, Tm:YAG lasers can in theory achieve, in the presence of cross-relaxation process, a maximum slope efficiency of 78%. The corresponding pump quantum efficiency, when pumped at 785 nm, can therefore approach a value of 2,[11] efficiently converting ≈800 nm light into the 2 μm region. Such lasers have been studied in different geometries including crystal rod, waveguide, and slab.[12–14] On the other hand, Ho:YAG possesses a gain cross-section 7 times larger than Tm:YAG.[4,15] For efficient lasing at 2.1 μm, Ho:YAG can be in-band pumped at 1.908 μm by either a Tm-fiber source or by a diode laser.[15] The only drawback for both Tm:YAG and Ho:YAG crystals is their susceptibility to excited-state absorption and up-conversion processes,[4,16] limiting the maximum usable rare-earth doping concentration.

When high power output is required, three competitive gain material geometries, namely slab, fiber and thin-disk are commonly used for laser construction. Slab and fiber amplifiers have demonstrated high performance at 2 μm wavelength, delivering an output power of approximately 200 W and 1 kW respectively.[17–19] Thin-disk technology has also been demonstrated successfully at 1 μm, with 10 kW power extracted from a Yb:YAG thin-disk continuous-wave (CW) laser based on a single disk.[20,21] Further scaling to 30 kW has also been demonstrated using 10 disks within a single resonator.[22] In the 2 μm range, several thin-disk lasers based on different combinations of Tm or Ho doped host crystals such as YAG, YLF, KYW, and LLF_4 have been reported, demonstrating the viability of this approach.[16,23–32] Transition-metal doped II-VI semiconductor laser materials such as Cr:ZnSe have also been experimentally realized in thin-disk geometry.[33,34] An overview of the published results on CW thin-disk lasers emitting around 2 μm is shown in **Figure 1**.

Compared to the power output of 1 μm thin-disk lasers, the development of 2 μm thin-disk lasers is, nevertheless, still at an early stage; the highest published output power is only 21 W.[27] Here we report a Ho:YAG thin-disk laser and a Tm:YAG thin-disk laser capable of delivering 50 W and 24 W respectively. To our knowledge these are the highest output powers from any thin-disk laser in the 2 μm region, and limited only by the available pump power in both cases. The diode pumped Tm:YAG thin-disk laser has a maximum optical-to-optical efficiency of 41%, which is the most efficient Tm:YAG thin-disk laser to

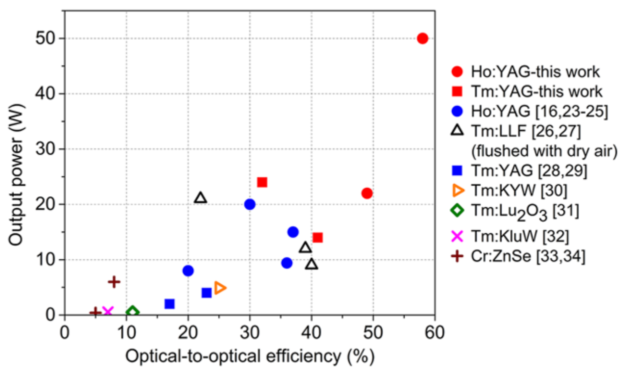

Figure 1. Overview of optical-to-optical efficiencies and output power reported for various thin-disk lasers in the 2 μm region.

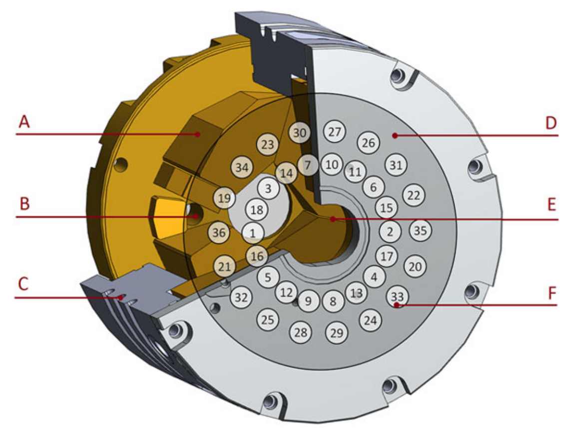

Figure 3. Layout of the 72-pass thin-disk pump cavity. A: Retroreflective prisms; B: Input for the pump radiation; C: Grooves for the water tubes, used for cooling the pump cavity and the optics inside; D: Parabolic mirror; E: Window for the laser beam; F: Locations and orders of pump beam coming to the parabolic mirror. The pump cavity was used for imaging of the pump light with the parabolic mirror and prisms, resulting in 72 passes through the gain medium. More detailed information is introduced in Ref. [36]

date. The output power level also surpasses previous results for Tm:YAG thin-disks by a factor of 6.[28,29] The Ho:YAG thin-disk laser, pumped by a Tm-fiber laser, has an optical-to-optical efficiency of 58%, which is the highest optical-to-optical efficiency reported of all 2 μm thin-disk lasers.

2. Experimental Section

2.1. Tm:YAG Thin-Disk Laser

The layout of the Tm:YAG thin-disk laser is depicted in **Figure 2**a. The laser contained a Tm:YAG thin-disk crystal with a Tm^{3+} doping concentration of 4% (Scientific Materials Corporation). The disk thickness was 300 μm and the ratio between the pump-spot diameter to the disk thickness was between 6 and 13—around the ratio of 10, above which the advantages of one dimensional heat flow become significant.[35] A fiber-coupled laser diode (DILAS) that can deliver a maximum power of 80 W at 780 nm was used to pump the Tm:YAG thin-disk (see Figure 2b). The disk's front-side was anti-reflection coated (R<0.2%) for the pump and laser emission wavelengths, while the back-side was coated for high reflection (R>99.9%) at both wavelengths. It was mounted on a water-cooled diamond heat sink and housed within a multi-pass pump head (TRUMPF Laser GmbH) that sent the pump beam through the disk 72 times (see **Figure 3**), resulting in an estimated pump absorption of over 95% at the peak absorption wavelength of ≈780 nm. Together with an output coupler (OC) and a concave end-mirror (EM), a V-shaped, 200 mm long cavity was formed with the thin-disk acting as a folding mirror.

The laser was first operated with a pump-spot diameter of 2.2 mm. Since the absorbed pump power could not be directly determined and the estimated pump absorption was over 95%, we analyzed all our results based on the incident pump power entering the thin-disk pump head. **Figure 4**a shows the dependence of the output power on the incident pump power at different output coupling ratios of 0.5%, 1%, 1.5%, and 2%. The most efficient operation was achieved with the 1% output coupler, resulting in a slope efficiency of 44%. The corresponding pump quantum efficiency was 116%, indicating the occurrence of cross-relaxation in the gain crystal.[11] The slope efficiencies measured with the other three output couplers were 39% (OC = 1.5%), 38% (OC = 0.5%), and 27% (OC = 2%). The maximum output powers for

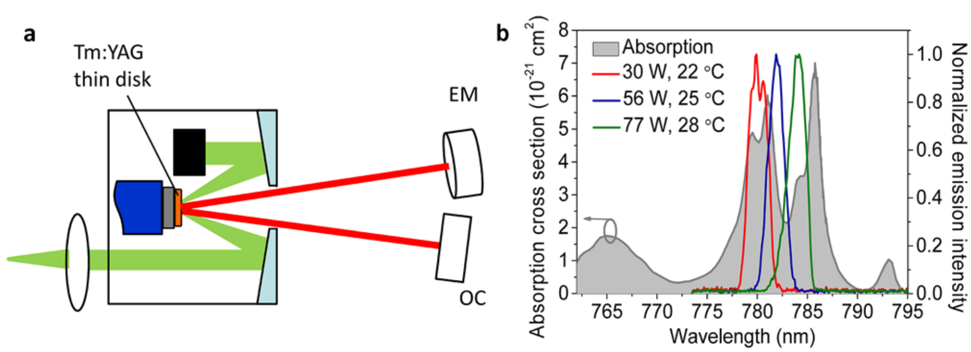

Figure 2. a) Layout of the Tm:YAG thin-disk laser. OC: output coupler; EM: concave end-mirror. The EM had a radius of curvature (ROC) of −400 mm. The Tm:YAG thin-disk was slightly concave, with an ROC of −20 m. A lens was used to couple the pump light into the multi-pass pump head. b) Absorption cross-section spectrum of Tm:YAG and the emission spectra of the pump diode at different pump powers and diode temperatures. The emission peak shifted towards the longer wavelengths as the diode temperature increased.

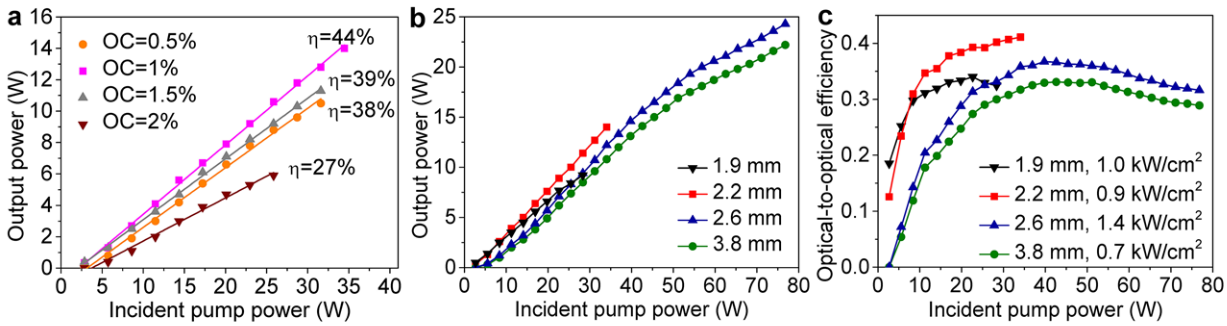

Figure 4. a) Dependence of output power on pump power and the corresponding slope efficiencies (η) at different output coupling ratios. The pump-spot diameter was fixed at 2.2 mm. b) Dependence of output power on incident pump power at different pump-spot diameters, at a constant OC of 1%. c) Optical-to-optical efficiencies at different pump-spot diameters, at a constant OC of 1%. The pump-power densities at which the maximum disk temperature of 150 °C was reached are also shown. In the case of the 3.8 mm pump-spot (green curve) the disk reached only 120 °C at the full available pump power of 77 W.

the four output couplers were 14 W (OC = 1%), 11.3 W (OC = 1.5%), 10.5 W (OC = 0.5%) and 6 W (OC = 2%), corresponding to optical-to-optical efficiencies of 41%, 36%, 34%, and 23%. To prevent disk damage, the pump power was limited such that the disk temperature never exceeded 150 °C.

To investigate the power scalability of the thin-disk geometry, in which higher power extraction can be expected by simply increasing the gain area, the pump-spot sizes were varied using different pump beam collimation lenses (see Figure 2a). Figure 4b shows the dependence of the output power on the pump-spot size at a fixed output coupling ratio of 1%. While the highest slope efficiency was obtained with a pump-spot diameter of 2.2 mm, the limit on thin-disk temperature restricted the pump power to 34 W, yielding an output power of 14 W. When the pump-spot diameter was increased to 2.6 mm or 3.8 mm, higher pump powers could be supported at the same pump intensity and the corresponding acceptable pump powers were larger than 77 W—the maximum pump power available. As a result, the maximum output powers were increased to 24 W and 22 W respectively.

Furthermore, the smaller pump-spot diameters of 1.9 mm and 2.2 mm corresponded to ratios between the beam diameter and the disk thickness of 6.3 and 8.6. Thus, the heat flow towards the diamond heat sink was not truly one-dimensional in these cases and the laser might have benefited from the non-negligible heat removal through the pump cylinder's lateral surface. At pump powers above 35 W, the warming of the pump diode shifted the pump wavelength to a region with lower pump absorption (Figure 2b). As the reduction in absorbed pump power was not directly measurable during the experiment, the optical-to-optical and slope efficiencies—both of which were derived from the incident pump power only—appeared to be lower for the 2.6 mm and 3.8 mm spot diameters pumped at higher powers. In addition, for the 3.8 mm diameter spot the maximum pump intensity was limited by the available pump power. Inhomogeneity in thin-disk quality could also play a role in the differences in efficiencies observed, as the pump-spot location varied slightly when the pump beam collimation lenses were exchanged. Even though the temperature of the diode's cooling water could in principle be lowered to stabilize the wavelength under high power operation, in practice it was not lowered below 16 °C due to the risk of water condensation.

The maximum optical-to-optical efficiencies at different pump-spot sizes lie between 30% and 41% (Figure 4c). A roll-over in optical-to-optical efficiency can be observed for the 2.6 mm and the 3.8 mm diameter pump-spots at higher powers, which can also be attributed to the shift in pump wavelength and reduced absorption at higher diode temperatures. For the 1.9 mm and 2.2 mm diameter pump-spots the pump absorption was optimal.

The measured output spectrum of the Tm:YAG laser, with a central wavelength of 2014 nm, is shown in **Figure 5**a. Figure 5b shows the corresponding beam quality, which has an M^2 value of 11.7 at a maximum output power of 24 W, pump-spot diameter of 2.6 mm and OC ratio of 1%. The M^2 was reduced to 10.5 and 10 at lower output powers of 20 W and 15 W respectively.

2.2. Ho:YAG Thin-Disk Laser

The setup for the Ho:YAG thin-disk laser is shown in **Figure 6**a. The 10 mm diameter, 200 μm thick Ho:YAG thin-disk crystal has a Ho^{3+} doping concentration of 2.5% (FEE GmbH). It was pumped by a Tm-fiber laser with a maximum output power of 120 W, and a constant output wavelength of 1908 nm throughout the entire power range. Rather than directly coupled onto the thin-disk, the single-mode pump light was first transmitted through a 550 μm diameter multimode fiber to create a homogenous pump-spot—required to prevent the formation of small foci inside the pump head that could damage optical components. The transmission efficiency of the pump light from the pump source to the entrance of the thin-disk pump cavity was 80%. Similar to the Tm:YAG setup, the pump light passed through the thin-disk 72 times, resulting in an estimated pump light absorption of over 95%.

The ratio between the pump-spot diameter and the Ho:YAG thin-disk's thickness was also in the range of 6–13, depending on the size of the pump-spot. The laser was initially operated with a pump-spot diameter of 1.2 mm, and the corresponding dependence of the output power on the incident pump power is plotted

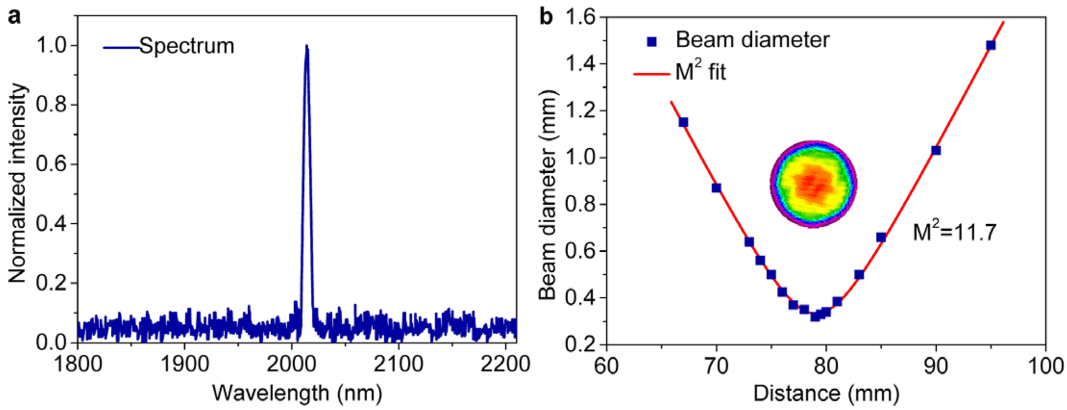

Figure 5. a) Output spectrum of the Tm:YAG laser centered at 2014 nm, measured with an FTIR spectrometer (Bristol A771). b) The measured beam profile (Ophir Pyrocam IIIHR) and beam diameters, together with the M^2 fit.

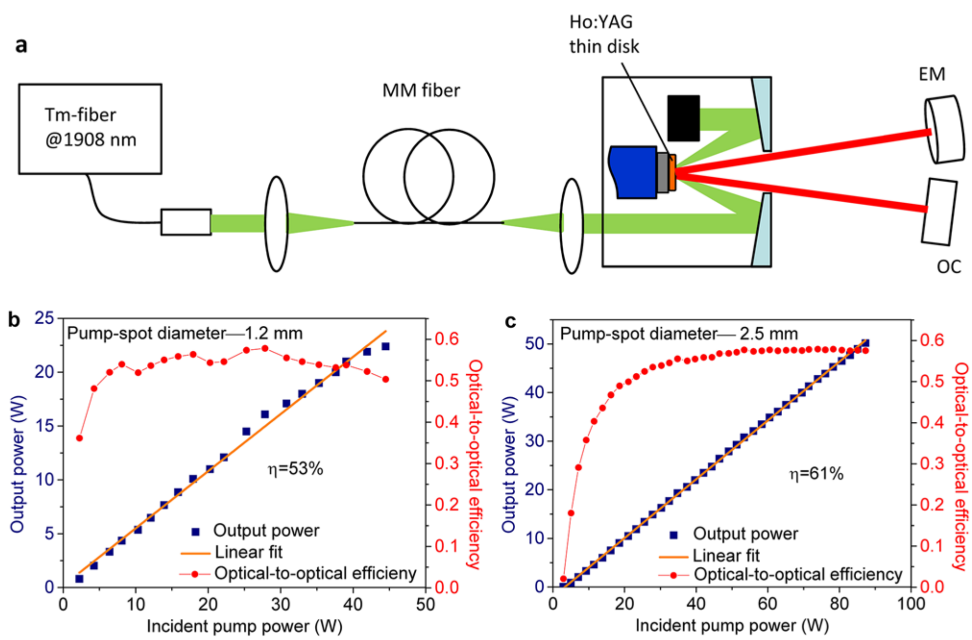

Figure 6. a) Layout of the Ho:YAG thin-disk laser. The concave end-mirror had a ROC of -2 m. The output coupling ratio was 1.8%. b,c) Output power, slope efficiency (η) and optical-to-optical efficiency versus incident pump power at pump-spot diameters of b) 1.2 mm and c) 2.5 mm, respectively.

in Figure 6b, which shows a slope efficiency of 53%. The maximum optical-to-optical efficiency was 58% at an incident pump power of 28.5 W and pump intensity of 2.5 kW cm^{-2}, yielding an output power of 16 W. The highest output power, at 22 W, was achieved when the pump power was further increased to 45 W. The corresponding optical-to-optical efficiency was, however, reduced to 49%—likely due to the stronger thermal effects at the higher pump intensity of 4 kW cm^{-2}. To prevent thin-disk damage, the pump power was not increased further.

By increasing the pump-spot diameter to 2.5 mm using different collimation lenses, the full power of the fiber pump could be utilized. When pumped at 87 W, the thin-disk laser delivered a maximum output power of 50 W, at an optical-to-optical efficiency of 58% and a slope efficiency of 61% (see Figure 6c). The maximum pump power density was only 1.8 kW cm^{-2}—significantly lower than for the 1.2 mm diameter pump-spot case. Consequently, no roll-over in output power was observed (Figure 6c), and it would be possible to raise the pump and output powers further given a more powerful pump source.

Figure 7a shows the output spectrum of the Ho:YAG thin-disk laser with two peaks at 2091 nm and 2097 nm. Figure 7b shows the beam quality measurement, indicating an M^2 value of 5.3 at the maximum output power of 50 W and a pump-spot diameter of 2.5 mm. The M^2 values were smaller at lower output powers, and were measured to be 4.9 and 4.4 at 40 W and 30 W respectively.

3. Discussion

The first demonstration of Tm:YAG thin-disk laser[28,29] validated the viability of the thin-disk approach at 2 μm. Here we have

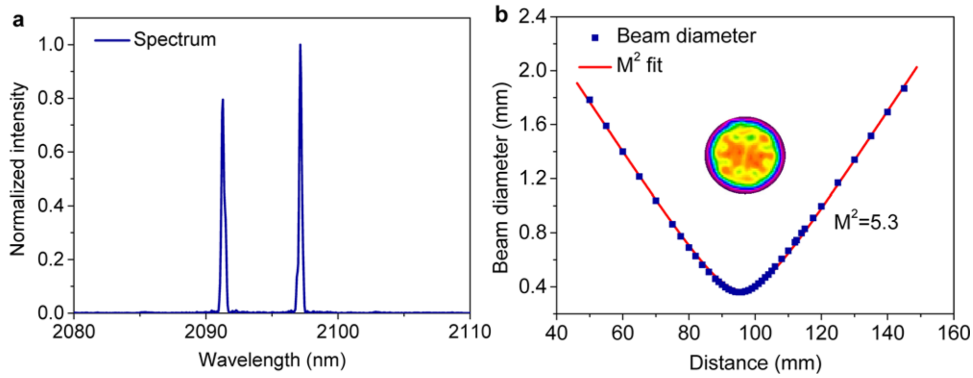

Figure 7. a) Output optical spectrum of the Ho:YAG thin-disk laser, showing two peaks at 2091 nm and 2097 nm. b) Measured beam profile and beam diameters, together with the M^2 fit.

expanded upon the concept by incorporating thinner disks, increased Tm^{3+} doping concentration, state-of-the-art coating designs, and increased number of passes of pump light using the newly developed 72-pass thin-disk pump head (Figure 3). The result is an increase in the output power by a factor of six, and an improvement in the slope efficiency by a factor of two. Moreover, a slope efficiency of 44% clearly indicates, for the first time in Tm:YAG thin-disk lasers, the onset of the cross-relaxation process.

The Ho:YAG thin-disk laser's output power and optical-to-optical efficiency are also significantly higher than any previously reported 2 μm thin-disk lasers. In particular, the slope efficiency, at 61%, approached that of Yb:YAG thin-disk lasers operating at 1 μm wavelength,[21] pointing to the feasibility for future Ho:YAG lasers to deliver output at levels comparable to established Yb:YAG systems.

The maximum output powers demonstrated for both the Tm:YAG and Ho:YAG thin-disk lasers are currently limited by the available pump power. Based on the pump power densities of 1.4 kW cm^{-2} for the Tm:YAG laser and 4 kW cm^{-2} for the Ho:YAG laser already achieved in this work, output powers approaching 1 kW are feasible if larger pump-spots ($\approx$15 mm diameter for Tm:YAG and $\approx$8 mm diameter for Ho:YAG) are used, together with $\approx$2 kW of pump power. In the Ho:YAG case, this power could be provided by powerful 1908 nm diode lasers which are gradually lowering in price, thus mirroring the success and flexibility of diode pumped Yb:YAG thin-disk lasers. Although the current pump head can only handle 3 kW of pump power, the 72-pass pump-cavity design can in principle be applied to larger pump heads that can sustain 16 kW of pump power,[21] enabling a potential output power beyond 1 kW.

The scaling of output powers for 2 μm thin-disk lasers is particularly challenging due to two conflicting considerations: the necessity to obtain high inversion-levels to compensate for the disk's limited thickness, and the strong up-conversion and excited-state absorption effects in Tm- and Ho-doped lasers at increased inversion-levels.[37] Although the trade-off could be investigated theoretically by modeling the rate equations, parameters such as the up-conversion and cross-relaxation coefficients need to be known precisely, which can only be confirmed experimentally.[24,29] The described results provide additional empirical data for verifying the magnitude of these variables and aid future simulation efforts.

The presented work on Ho:YAG and Tm:YAG multimode thin-disk lasers laid a solid foundation for exploring other operating regimes. For example, a CW Ho:YAG thin-disk laser generating output at the fundamental TEM_{00} mode at an average power of 20 W has recently been realized, which was subsequently used for demonstrating the first Kerr-lens mode-locked operation of Ho:YAG, producing a train of 220 fs pulses.[38] Next-generation amplifier technologies based on Ho:YAG thin-disk lasers will also significantly benefit from the reported results.

Apart from Ho:YAG and Tm:YAG crystals, other materials could also be investigated, incorporating the improved techniques reported here. For example, both $Tm:Lu_2O_3$ in single crystal form—which has shown even more efficient performance than reported here in rod geometry[37]—as well as ceramic $Tm:Lu_2O_3$[39,40] are great candidates for use in future 2 μm thin-disk lasers, due to their larger emission cross-sections compared to Tm:YAG, and broader emission bandwidths compared to Ho:YAG.

4. Conclusion

We have demonstrated two high power and highly efficient thin-disk lasers based on Tm:YAG and Ho:YAG crystals operating in the multimode regime, contributing to the rather limited experimental efforts in the development of 2 μm thin-disk lasers. For the Tm:YAG thin-disk laser, a maximum optical-to-optical efficiency of 41% and slope efficiency of 44% have been obtained, representing the highest efficiency reported from Tm:YAG thin-disk lasers. Using a larger pump-spot diameter of 2.6 mm, the laser delivered an output power up to 24 W, which is the highest output power of any Tm:YAG thin-disk laser. The Ho:YAG thin-disk laser produced an output power of 50 W, at an optical-to-optical efficiency of 58% and slope efficiency of 61%, which are the highest power and highest efficiency of any thin-disk laser in the 2 μm region. These results lay the ground work for scaling the thin-disk lasers' output power towards kW-level in the near future.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

high power and high efficiency, Ho:YAG thin-disks, infrared lasers, Tm:YAG thin-disks

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