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# 656 W Er-doped, Yb-free large-core fiber laser

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**A continuous-wave erbium-doped ytterbium-free fiber laser generates a record-breaking pump-power-limited output power of 656 W at ∼1601 nm when cladding pumped by 0.98 μm diode lasers. The slope efficiency was 35.6% with respect to launched pump power, and the beam quality factor ($M^2$) was ∼10.5. This $M^2$ value excludes a fraction ∼25% of the power that emerged from the cladding, which we attribute in part to mode coupling between the 146 μm core and 700 μm inner cladding. Whereas these parameters are adequate for in-band tandem pumping of Tm-doped fiber lasers, we predict that an output power of over 1 kW is possible through pumping with state-of-the-art 0.98 μm diode lasers, even with a smaller core that allows for improved beam quality.**



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Recent years have seen significant progress in the power of cladding-pumped ytterbium-doped fiber lasers (YDFLs) operating at 1.0–1.1 μm [1]. There is also great interest in high-power erbium-doped fiber lasers (EDFLs) emitting at 1.5–1.6 μm, due to their relative eye safety and the atmospheric transparency [2]. The pumping of mid-infrared laser sources is another application. However, owing to spectroscopic differences between Er and Yb ions, the power of EDFLs has lagged far behind that of Yb-doped ones. Specifically, it is difficult to cladding-pump EDFLs, since the small absorption cross section and concentration quenching [3] make it difficult to reach adequate pump absorption. One approach to overcoming this is to co-dope ("sensitize") with Yb, which absorbs the pump energy before it is transferred to the Er ions. Such Er:Yb co-doped fiber lasers (EYDFLs) can be cladding-pumped by efficient 0.9–1 μm diode lasers and have been scaled to 297 W of output power [4], which is the highest power reported to date. However, the onset of parasitic Yb lasing at 1–1.1 μm, as well as a high thermal load impede further power scaling. Furthermore, to promote efficiency, the host glass is doped with high concentrations of rare earth and phosphorus [5]. This leads to a high numerical aperture (NA), which degrades the beam quality. High efficiency in-band cladding-pumping of Er-doped fibers with 1535 nm EYDFLs is an alternative approach. In this way, an output power of 264 W was obtained [6]. Although the 264 W laser was also co-doped with Yb, this played no part in the laser cycle. Indeed, the approach has also been used with Yb-free EDFLs, pumped by 1535 nm EYDFLs as well as by 1480 nm fiber Raman lasers. The high pump brightness of this so-called tandem-pumping approach [7], in which a fiber laser pumps another fiber laser, allows for a small inner cladding, which increases the pump absorption. Even core-pumping is possible, through which over 100 W of output power has been generated [8]. However, tandem pumping significantly increases system cost and complexity.

Therefore, despite the low pump absorption, cladding-pumping directly with diode lasers remains an attractive alternative for Er-doped Yb-free fiber lasers. This approach has been pursued with 1.5 μm pump diodes, which offers a low thermal load in the EDFL as one of its attractions. Unfortunately, however, multimode 1.5 μm pump diodes lag their 0.9–1 μm counterparts in power as well as efficiency. Thus, the highest output power of 88 W from an EDFL in-band-pumped by diodes was limited by the available diode laser power at 1.53 μm [9]. In addition, despite the high optical-to-optical efficiency that can be achieved with in-band pumping, the overall efficiency suffers from the low efficiency of 1.5 μm pump sources. As a result, the overall electrical-to-optical efficiency may well be below 15% [10].

Alternatively, it is also possible to cladding-pump Yb-free EDFLs with diode lasers at 0.98 μm. This was investigated in the 1990s by Minelly *et al.* [11] and has since then reached 103 W of output power [12]. Furthermore, 0.98 μm pump diodes can reach several kilowatts of power, which opens up for kilowatt-level EDFLs. However, to accommodate such pump sources requires a relatively large inner cladding. An option for maintaining adequate pump absorption is then to also scale the core size. Indeed, an Er-doped fiber with core diameters as large as 73 μm has been reported [13], although this was for scaling of pulse energy rather than of (average) power. Such large cores degrade the beam quality, but this may still be acceptable for some applications, e.g., pumping of Tm-doped fiber lasers emitting at ∼2 μm.

Here we present an Er-doped Yb-free fiber laser cladding-pumped by 0.98 μm diode lasers, with record-breaking output power from any Er-doped fiber source. For this, we designed and fabricated a tailored Er-doped fiber with 0.7 mm inner cladding to suit our pump source, a modest Er concentration to avoid quenching, a large 146 μm diameter core to improve the pump absorption, and a 36 m length to absorb the pump and distribute the thermal load. We used a simple end-pumped configuration with up to 1910 W of launched pump power and reached 656 W of output power centered at 1601 nm with 35.6% slope efficiency versus launched pump power. There was no roll-off, and the output power was only limited by the available pump power.

An Er:Al-doped silica preform was designed and fabricated in-house by the standard modified chemical-vapor deposition (MCVD) and solution doping technique [5]. Figure 1 shows the refractive index profile of its 1.6 mm diameter core. The preform was milled to 5.7% of the diameter into a "D-shape" in order to improve the pump absorption and then drawn to a fiber with a core diameter of 146 μm and a NA of 0.08 ($V = 23$ at 1.6 μm). The inner cladding had a diameter of 660 (round-to-flat) and 700 μm (round-to-round). The fiber was coated with a low-refractive-index polymer which provided a nominal inner-cladding NA of 0.48. The inner-cladding small-signal absorption was measured to ~0.45 dB/m at the 979 nm peak. Based on these data, we estimated the $Er^{3+}$-concentration to $1.2 \times 10^{25}$ ions/m$^3$.

The experimental laser configuration is depicted in Fig. 2. Although the fiber was 36 m long, the operating pump absorption was initially only ~5 dB, which we attribute to the relatively modest "D-shaping" of the inner cladding. Therefore, we coiled the fiber into a figure-eight shape with a diameter ~23 cm to scramble the pump modes, which improved the pump absorption to ~11 dB (92%). We used three 1.1 kW diode-laser-stack-based sources centered at 977 nm and with 3 dB linewidth of 4 nm to pump the fiber through both of its ends, via a combination of lenses and dichroic mirrors. In one end of the fiber, two of the pump sources were spatially beam-combined into one beam. The launch efficiency was ~73% in the beam-combined end and ~87% in the other end for a total pump launch of up to 1.91 kW. Both ends were polished perpendicularly to the fiber axis. At the end of the laser cavity with a single pump source, high-reflectivity feedback was provided by a pair of dichroic mirrors having high transmission for the pump and high reflection for the signal. The laser output coupler was formed by the 3.5%-reflecting facet in the other end of the fiber. The out-coupled signal was separated from the pump beam by another dichroic mirror having the same characteristics as the feedback mirrors. Both fiber ends were held in temperature-controlled metallic V-grooves, matched to the fiber size and designed to prevent thermal damage to the fiber coating by any non-guided pump or signal power, or by the heat generated in the laser cycle. Furthermore, the bulk of the fiber was coiled on metal cylinders and air-cooled by fans, albeit with a total of ~1 m of the fiber between the v-grooves and metal cylinders suspended in air.

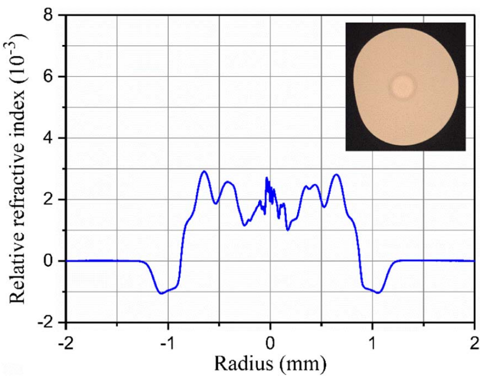


**Fig. 1.** Refractive index of the Er:Al-doped preform. Inset: fiber image.

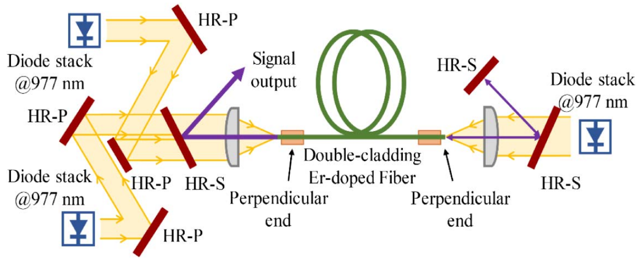


**Fig. 2.** Schematic of the Er-doped fiber laser. HR-P, high reflectivity for the pump; HR-S, high reflectivity for the signal.

The laser output power as a function of the launched pump power is shown in Fig. 3(a). The maximum output power was 656 W with a slope efficiency of 38.7% with respect to absorbed pump power and 35.6% with respect to launched pump power. The output power increased linearly with pump power and showed no roll-off. The average thermal load at full power was 30 W/m, calculated from the difference between absorbed pump power and generated output power. The output spectrum measured by an optical spectrum analyzer at full power is plotted in Fig. 3(b). It was centered at 1601 nm and had a 3 dB linewidth of 4.2 nm. The fraction of amplified spontaneous emission was 0.2%.

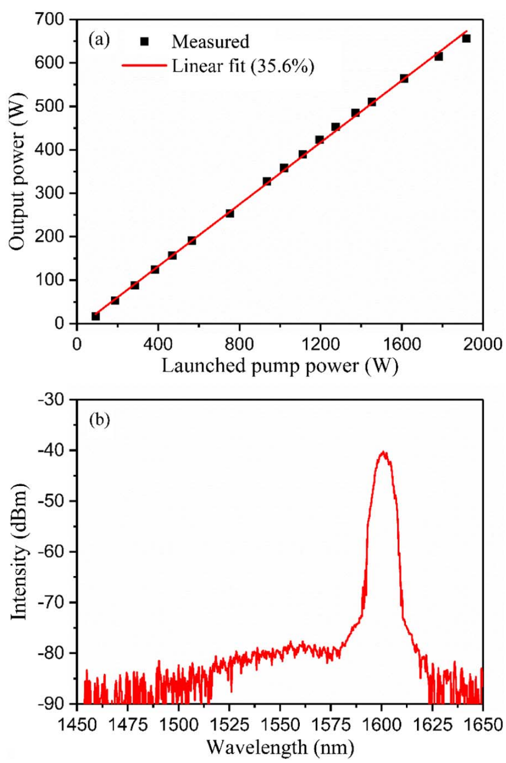


**Fig. 3.** (a) Laser output power versus launched pump power. (b) Optical spectrum at 656 W output power; resolution, 1 nm.

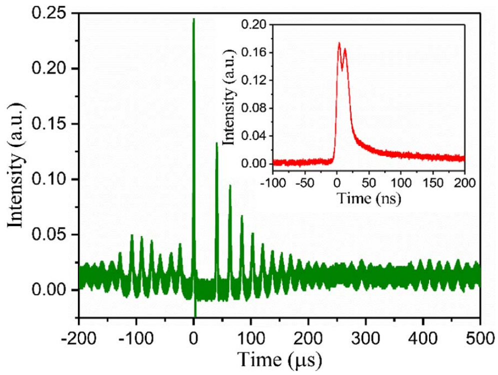


**Fig. 4.** Time-trace of potentially damaging self-pulsing. Inset: sub-pulse.

In our initial experiments [14], pulsing caused the fiber ends to fail. The temporal-power characteristics were monitored using a 460 kHz photodetector (Thorlabs PDA100A-EC) and an oscilloscope, and showed a series of high-intensity pulses at irregular intervals. In erbium-doped fiber lasers, such behavior can be caused by clustered erbium ions [15,16]. Figure 4 shows one transient with an oscillation frequency of ~50 kHz and a damping time of ~200 μs. The inset shows an individual pulse with a duration of 20 ns measured by a 12 GHz photodetector and a 20 GHz oscilloscope (Tektronix DSA 72004B). We believe that these pulses reached energies and peak powers high enough to damage the fiber facet. Investigations of failed ends supported this view. However, with more careful polishing of the fiber end, we managed to largely suppress self-pulsation. Although occasional pulses were still observed, these did not damage the fiber ends even at maximum output power.

The beam quality factor ($M^2$) of the output signal was measured using a scanning-slit beam profiler (Thorlabs BP104-IR), and the result can be seen in Fig. 5. At full output power, the $M^2$-factor became 10.45 and 10.53 in orthogonal directions, according to a hyperbolic fit to the measured beam width at the $1/e^2$ intensity level. This agrees well with the beam quality (~12.5) calculated from the refractive-index profile with an incoherent ray approximation under the assumption of all core-guided modes being equally excited. There was no significant power dependence of the beam quality. However, about 25% of the output power emerged from the inner cladding.

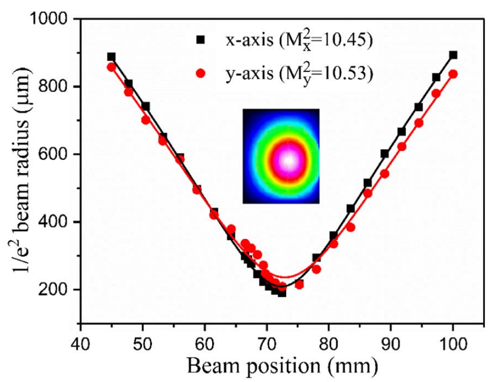


**Fig. 5.** Beam radius of the output signal in orthogonal directions at maximum power measured with a scanning slit. Inset: output signal beam profile as reconstructed from two scans in orthogonal directions.

Note that this did not affect the $M^2$-calculation, since it was based on the $1/e^2$-intensity level.

We next consider possible improvements in power and brightness. State-of-the-art pump diodes can produce more than 140 W of power from 105 μm cores at 0.15 NA, which is bright enough for launching over 10 kW of pump power through each end of our EDF. However, our slope efficiency implies that ~60% of the pump power is converted into heat. Thermal loads averaging over 100 W/m are seldom used and may not be realistic, but 100 W/m still allows for 2 kW of output power.

Higher conversion efficiency is also possible and would mitigate thermal effects. We achieved 53% slope efficiency with respect to absorbed pump power when a 2 m long piece of the fiber emitting at 1558 nm was core-pumped at 976 nm. The shortening of the fiber reduces the background loss, which increases the efficiency. In turn, at fixed output power, the higher efficiency reduces the thermal load by nearly half, relative to that with the 38.7% slope efficiency achieved in the 36-m cladding-pumped fiber.

The Er spectroscopy is marred with potential problems. When pumped at 0.98 μm, bottle-necking from the 0.98 μm pump level ${}^4I_{11/2}$, due to its lifetime of ~10 μs [17] in aluminosilicate, reduces the pump absorption at high pump rates. This is also a potential limitation. However, in our fiber, this is still negligible relative to our pumping rate of $\sim 1250\ s^{-1} = (800\ \mu s)^{-1}$ on average at 656 W, and remains negligible also at 2 kW of output power.

A significant fraction of the power was in the cladding, which not only is undesirable, but also unusual. There are several possible reasons for cladding-power. Our fiber has a small cladding/core area ratio, and this may lead to cladding modes with significant overlap with the core and, thus, with high gain. We calculated ~200 of arbitrary modes to investigate this, but did not find any mode with high overlap. Furthermore, significant coupling amongst cladding modes is expected and indeed evidenced by the increase in absorption when the fiber was shaped to a figure-eight. Therefore, we discard the possibility of high gain for some cladding modes.

Another possible reason is that the HR-cavity mirror reflects a part of the light back into the cladding. To avoid this, the mirror should be placed one focal length from the lens in the equivalent of a so-called $4f$ configuration. At the same time, constraints imposed by our layout called for a mirror with a lens distance of at least 150 mm. However, a lens that combines the large NA required for the pump launch with a focal length of at least 150 mm was not available. A multi-lens arrangement can then be used to improve the coupling back into the core, but was difficult because of layout constraints. Mirror butt-coupling is another possibility, but this was not attempted due to the high-power levels. A ray-based analysis under the assumption that all core modes were equally excited suggested that a ratio as large as ~33% would be coupled back into the cladding rather than the core due to the excessive mirror—lens distance in our configuration, even if perfectly aligned, although the higher gain for the core-guided light means that the ratio would improve in the output end of the fiber. To further investigate the effect of reflecting light into the cladding, we removed the external feedback mirror and instead had the fiber facets form the cavity. Although the facets are not perfectly perpendicular to the fiber axis, this is expected to improve the core feedback ratio to over

90%. The cladding-power did decrease, but only from 25% to 15%, and part of this improvement can be attributed to the higher gain in this cavity, which increases the gain discrimination between core and cladding modes.

Leakage of light propagating in the core into the cladding is another possibility. The large core supports many modes with similar propagation constants, which readily couple to each other. The coupling may well be enhanced by the fabrication process with the small perform-to-fiber diameter draw-down ratio, which is expected to result in relatively large inhomogeneities at high spatial frequencies. The similarity between measured and calculated beam quality is an indication of significant mode coupling. Power may then leak from the low-NA core into the cladding via bend loss of high-order core modes. In addition to bending, coupling to the cladding can also be induced by micro-bending and other inhomogeneities, even if the fiber is straight [18]. The large core, the low NA, and the small area ratio are likely to lead to a comparatively large fraction of core and cladding modes with similar propagation constants and significant overlap, which enhance such coupling.

We therefore investigated to what extent light from a quasi-single-mode source at 1.05 μm launched into the core would couple into the cladding. We found that only ~40% of the power remained in the core after 36 m of the coiled fiber, compared to over 95% after a 30 cm straight length. Thus, we believe that there was significant leakage of power from the core to the cladding.

Looser coiling with less bending may improve the beam quality. Furthermore, the performance of passive large-core fibers suggests that leakage can be overcome even at a 23 cm bend diameter, e.g., through more homogeneous fiber fabrication. On the other hand, a smaller core should also reduce coupling to cladding modes as well as coupling between core modes, and should then also allow for improved $M^2$ value or even single-mode operation as reported in Ref. [19]. There the Er-doped fiber had a core diameter of 60 μm and an inner-cladding diameter of 240 μm, which allows for ~3.5 kW of pump power launched through each end. The peak pump rate becomes close to 100,000 $s^{-1} = (10\,\mu s)^{-1}$, so bottlenecking would be significant. It is possible to decrease the lifetime of the pump level by phosphorus co-doping [20] but, on the other hand, the bottlenecking helps to distribute the absorbed pump power and, thus, the thermal load along the fiber. According to simulations of an EDFL with a 60 μm diameter core, $50 \times 10^{25}$ ions/m$^2$ concentration-length product (similar to our fiber) and 20 dB inner-cladding small-signal pump absorption, the output power became 206 W and the pump absorption 17.5 dB for a pump power of 350 W, in the absence of excess loss mechanisms such as propagation loss. For 3.5 kW of pump power, the output power became 2.01 kW and the pump absorption decreased to 13.3 dB, due to an average pump-level population of 12%. Thus, even though the bottlenecking is significant with a 60 μm core, it was still possible to reach 2 kW of output power. At 2 kW, the thermal load would remain around 100 W/m, which may be manageable, although thermal mode instability [21] may well preclude single-mode operation.

In conclusion, we have demonstrated a high-power fiber laser emitting in the eye-safe wavelength range. The laser is based on an Er-doped Yb-free large-core fiber fabricated with conventional MCVD and solution doping. The fiber laser was cladding-pumped by 0.98 μm diode lasers, and we note that cladding-pumping with 9xx nm diodes is the simplest and most popular pumping scheme for high-power fiber lasers. The fiber laser produced a record power level from any Er-doped fiber laser, i.e., 656 W at 1601 nm. The slope efficiency was 35.6% with respect to launched pump power. The $M^2$ value of 10.5 is adequate for pumping Tm-doped fiber lasers. Our further analysis suggests that Yb-free EDFLs with over 1 kW of power and high beam quality are possible with judicious fiber design and state-of-the-art pump diodes.

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