110 W High-Efficiency Er-Nanoparticle-Doped Fiber Laser

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Abstract: An Er-nanoparticle-doped fiber laser cladding-pumped at 975 nm generates 110 W at 1605 nm with 40.6% slope efficiency and M^2~7. High Er-concentration (4×10^{25} ions/m^3) and pump brightness allows for adequate pump absorption even without Yb-codoping.
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There is continued strong interest and progress in the power scaling of fiber lasers operating at nominally eye-safe wavelengths around 1.6 and 2 µm [1]. For Er-doped fiber lasers (EDFLs), Yb co-doping is often used to improve the pump absorption, whereby 300 W of output power has been reached through cladding-pumped with 1 kW of power at 0.98 µm [2]. However Er:Yb co-doped material has a high refractive index, which frustrates core area scaling with high beam quality. It also has a complex spectroscopy, where parasitic 1060-nm emission hampers high-efficiency, high-power operation [2]. Yb-free EDFLs avoid those problems, and have now been power-scaled to 656 W of output power through cladding-pumping with 1.9 kW of power at 0.98 µm. However, erbium's small pump absorption cross-section combined with a relatively low concentration (1.2×10^{25} ions/m^3) and poor pump beam quality required a large-diameter inner cladding (~700 µm) and core (146 µm), and a 36-m long fiber [3,4]. This still precluded high beam quality (M^2=14). Here, we take advantage of recent progress in high-brightness 0.98-µm pump diodes and high-concentration nanoparticle (NP) doping [5] to realize an efficient 0.98-µm cladding-pumped Er-doped fiber laser with Er-concentration as high as 4×10^{25} ions/m^3. The combination of reduced core diameter (to 45 µm) and fiber length (to 23 m), and a relatively large inner-cladding diameter (264 µm) opens up for high-power, low-nonlinearity, high-brightness operation. Here, we reached 110 W of output power at 1605 nm with M^2=7. The slope efficiency was 32.3% and 40.6% with respect to launched and absorbed pump power.

A fiber was designed in which erbium ions were encaged in an aluminum NP host. The NP dispersion was synthesized by co-precipitation of salts of erbium and aluminum in the presence of a surfactant, followed by ripening [5]. The NP dispersion was then doped into the preform core in a manner similar to that for solution doping. The fiber had an octagonal inner cladding with 264-µm corner-to-corner diameter. A low-refractive-index polymer coating provided a nominal inner-cladding NA of 0.48. The Er^{3+}-NP doped aluminosilicate core had a diameter of 45 µm and an NA of 0.18 (V=15.7 at the signal wavelength of 1605 nm). The small-signal absorption in the inner cladding was ~1.1 dB/m at the 979-nm peak, from which we estimate the Er^{3+} concentration to 4×10^{25} ions/m^3.

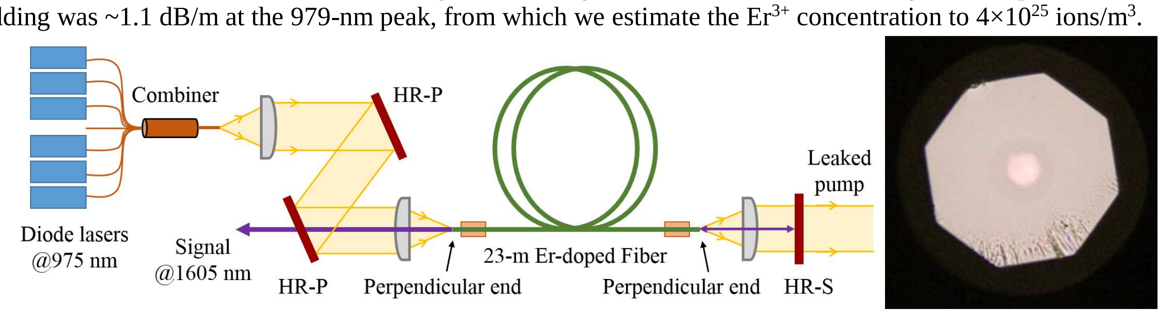

Fig. 1. EDFL schematic and image of the fiber. HR-P: high-reflectivity for pump, HR-S: high-reflectivity for signal.

The experimental laser configuration is shown in Fig. 1. Six multimode diode lasers with wavelength centered at 975 nm were combined by a 7×1 fiber combiner, which provides 420 W of maximum pump power from a 125-µm diameter, 0.46-NA pigtail. The pump beam was free-space coupled into the Er-doped fiber with lenses, with a launch efficiency of ~85%. The 23-m long fiber yielded an operating pump absorption of 7 dB. The reduction from the small-signal absorption is at least in part caused by partial excitation of the Er-ions. A higher absorption would be preferable and we estimate it would improve to 8.2 dB by pumping at the 979-nm peak. Both ends were cleaved perpendicularly to the fiber axis, with the cleave in the pump launch end acting as output coupler with 4% Fresnel reflection. At the other end of the fiber laser cavity, a lens-coupled dichroic mirror provided high-reflectivity

(>97%) feedback for the signal, while unabsorbed pump was transmitted. The laser output beam was separated from the pump beam by another dichroic mirror with characteristics opposite to those of the feedback mirror. Both fiber ends were held in temperature-controlled metallic V-grooves to prevent thermal damage to the fiber coating. For further heat-sinking, the fiber was coiled on a 12.5-cm diameter metal cylinder and air-cooled by fans.

The laser output power as a function of the absorbed pump power is shown in Fig. 2(a). The laser threshold was 4.3 W and the maximum output power was 110 W, limited by available pump power. The laser output power increased linearly with the pump power and showed no evidence of roll-off even at the highest power. The slope efficiency was 40.6% with respect to absorbed pump power. Given the ~20% (68 W of leaked pump power) pump leakage, this dropped to 32.3% with respect to launched pump power, but we expect that double-passing the pump would significantly improve this, as well as the output power. The output spectrum measured at the maximum output power of the laser is plotted in the inset. The spectrum was centered at 1605 nm and had a 3-dB linewidth of 6 nm. The fraction of amplified spontaneous emission was less than 0.1%. The average heat dissipation at full power was only ~7 W/m, and no thermal degradation of the coating was observed. Pulsing is also a potential failure mechanism. The temporal power characteristic was monitored with 12 GHz bandwidth using a photodetector and an oscilloscope, as shown in Fig. 2(b) at full power. Moderate self-pulsing was observed with pulse duration around 50 ns. The peak amplitude in Fig. 2(b) is ~8 times the average amplitude, from which we estimate the maximum pulse energy to 40 μJ. This is unlikely to damage the laser, and no damage was observed.

The beam quality of the output signal was measured using a Photon Inc. Nanoscan scanning slit beam profiler. See Fig. 2(c). At full power, the M^2-factor was 6.8 and 7.1 in orthogonal directions, according to a hyperbolic fit to the measured beam width. This value is compatible with equal excitation of all modes of the core. We did not attempt to improve the beam quality, e.g., by using a mode-selective aperture or bendloss filtering. However mode-coupling can be relatively weak at 1605 nm in a 45-μm core, so significant improvements may well be possible.

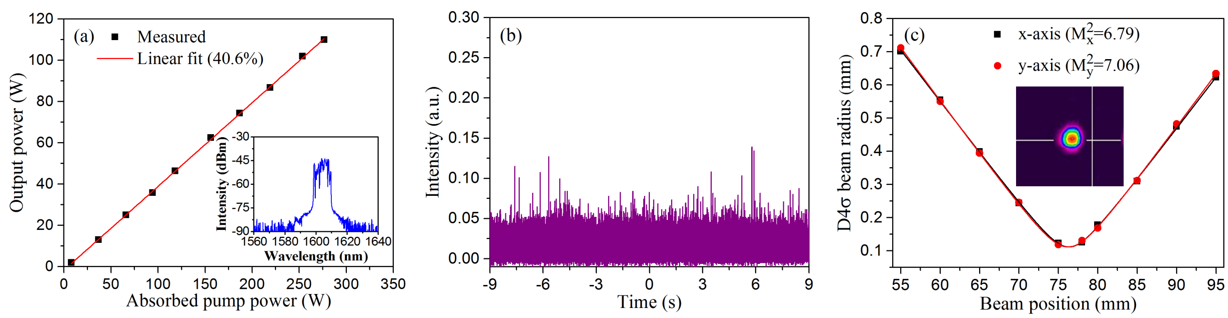

Fig. 2. (a) Laser output power *versus* absorbed pump power. Inset: Laser output spectrum at 110 W output. Resolution: 0.5 nm. (b) Temporal power characteristic (c). Measured beam radius of the output signal in the horizontal and vertical beam axes at maximum output power.

In conclusion, we reported an Yb-free Er-nanoparticle high-concentration fiber laser directly pumped by diode lasers at 975 nm. The fiber laser is capable of producing an output power of 110 W at 1605 nm with a beam quality (M^2) of ~7. The slope efficiency was as high as 40.6% with respect to absorbed power, which is comparable to the highest reported Yb-free Er-doped fiber laser cladding-pumped at 0.98 μm while with much lower Er concentration (0.7×10^{25} ions/m^{-3}) [6]. Finally we note that this fiber can at least in principle be scaled to well over 1 kW of output power, given its relatively large inner cladding and the brightness of state-of-the-art 0.98-μm pump diodes.

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