Ytterbium-doped large-core fiber laser with 1 kW continuous-wave output power

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Abstract: We demonstrate a highly efficient cladding-pumped ytterbium-doped fiber laser. It generated up to 1 kW of continuous-wave output power at 1.1 μm with 80% slope efficiency and a good beam quality, when end-pumped through both fiber ends.

OCIS codes: (140.3510) Lasers, fiber; (140.3480) Lasers, diode-pumped

1. Introduction

In recent years, the dramatically increased output power from high-power rare-earth doped silica fiber lasers has made them interesting for high-power applications in science and industry in areas such as material processing, marking, medicine, and range finding. The rise in power is due mainly to improvements in fiber design and fabrication and in the performance of pump diode sources including multi-emitter lasers diodes, diode bars, and diode stacks. In silica, neodymium (Nd^{3+}), ytterbium (Yb^{3+}), erbium (Er^{3+}), Thulium (Tm^{3+}), are common dopants, with which one can access different wavelengths from the near infrared range to the so-called eye-safe range (0.9 – 2 μm). In the high power regime, Yb-doped fibers make exceptional sources in the 1 – 1.1 μm wavelength range because of an excellent power conversion efficiency of over 80% and a broad tunability over several tens of nanometers [1,2]. Consequently, Yb-doped fiber lasers (YDFLs) are leading the race to higher-power fiber lasers. For example, 10 kW of output power has been reached from highly multi-moded devices that combined the outputs from several YDFLs [3]. The power achieved in high-brightness output beams from single-fiber configurations is lower, but has nevertheless reached over 500 W in 30 – 40-m long Yb-doped fiber devices [3,4]. Notwithstanding these excellent achievements, many applications would benefit from even higher output powers with the high beam quality and simplicity that single-fiber devices can offer.

In this paper, we describe further power-scaling of a single-fiber laser configuration to an output power of 1 kW. For this to be realized, we used a higher pump power, a larger inner cladding, and a larger core than in previous work.

2. Experiments and Results

End-coupling of the pump beam into the inner cladding of double-clad fiber through its ends in a so-called end-pumping scheme is the simplest and most efficient way to pump a double-clad fiber with a diode-stack pump source. Alternative side-pumping techniques seem likely to fail at high pump powers, or use too thin fibers for an efficient pump launch [5,6]. In an end-pumped configuration, a large inner cladding is required in order to accommodate the large pump beams of high-power diode stacks. With a sufficiently thick inner cladding, a conventional core diameter of, e.g., 10 μm or less would lead to excessively long fibers due the low pump absorption rate resulting from the small overlap of the pump with the core. The background loss would become excessive, which would degrade the output power. Undesirable nonlinear scatterings such as stimulated Raman scattering [7] and stimulated Brillouin scattering can also degrade the laser performance. Therefore, a large core is preferable [1,4]. A large core can also mitigate the facet damage of fibers. For reliable cw operation we target a signal power density of no more than 1 W/μm^2, though considerably higher power densities may well be allowable [8]. Considering these constraints, we fabricated a Yb-doped large-core fiber and arranged the experimental setup with the fiber and appropriate diode-stack-based pump lasers to realize a high-power fiber laser which emits 1 kW of cw output power.

A double-clad Yb-doped large-core fiber was designed to meet the requirements for power-scaling to kW-level. It was pulled from a preform that was fabricated in-house by the modified chemical-vapor deposition and solution doping technique. The fiber had a 43-μm diameter Yb-doped core with a numerical aperture (NA) of 0.09, centered in the preform. With this design, the mode-field area for the fundamental mode becomes ~1100 μm^2. The D-shaped inner cladding had a 650/600-μm diameter for the longer/shorter axis after being milled. This diameter was chosen to enable efficient coupling of the high power pump sources. The fiber was coated with a low-refractive-index polymer outer cladding which provided a nominal inner-cladding NA of 0.48. The small-signal absorption rates in the inner cladding were ~1.5 dB/m and ~3 dB/m, respectively, at the two pump wavelengths of 972 nm and 975 nm. This corresponds to an Yb^{3+}-concentration of ~4500 ppm by weight. The fiber length used in the laser experiments was 8 m.

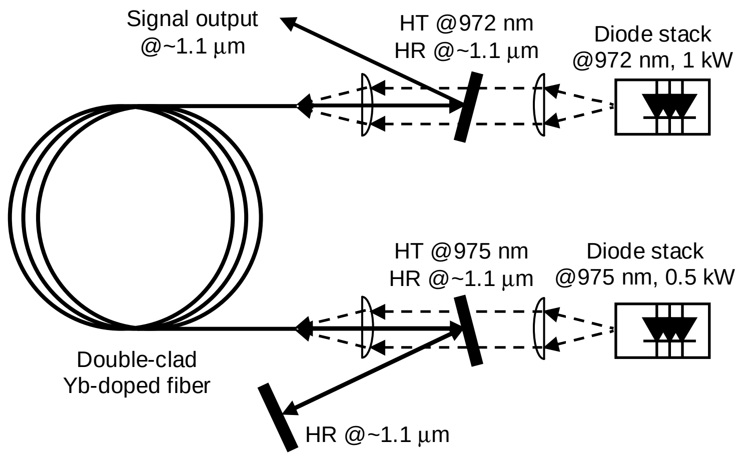
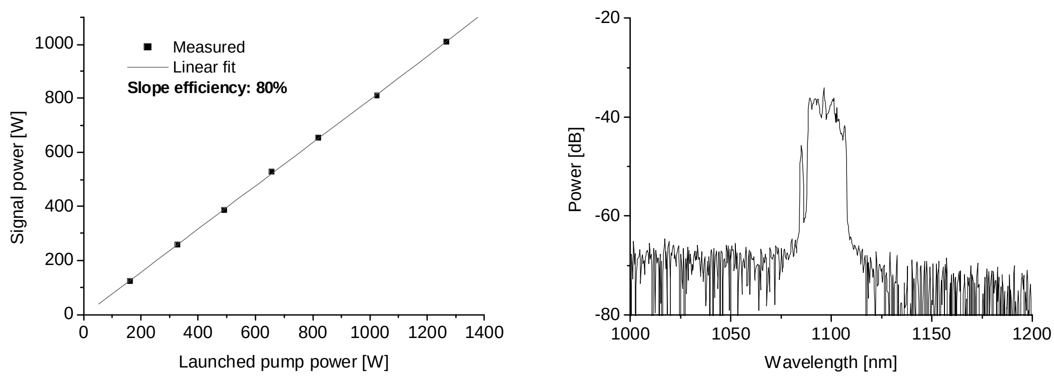


Fig. 1. Yb-doped fiber laser arrangement used with two diode-stack pump sources. HR: high reflectivity, HT: high transmission.

The experimental setup is shown in Fig. 1. We used a double-sided end-pumping scheme, with two pump sources launched into opposite ends of the fiber. Two diode-laser-stack-based pump sources were used, emitting 1 kW at 972 nm and 0.5 kW at 975 nm, respectively. The pump beams were coupled into the active fiber via collimating and focusing lenses [1]. We could launch a combined maximum pump power of 1.3 kW, corresponding to ~85% of the power incident on the fiber. In one end of the laser cavity, high-reflectivity feedback was provided by a pair of dichroic mirrors, with high transmission at the pump wavelength and high reflection at the signal wavelength. The mirrors were external to the fiber and coupled to it via a lens. The laser output coupler was formed by a 4% reflecting flat perpendicular cleave in the other end of the fiber. The signal was separated from the pump beam with another dichroic mirror. Both ends of the fiber were held in temperature-controlled metallic V-grooves 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 itself.



(a) (b)

Fig. 2. (a) Fiber laser output power vs. launched pump power, and (b) laser output spectrum at full power.

The laser output power characteristics are shown in Fig. 2, together with the output spectrum at full output power. The maximum laser output power of 1.01 kW was obtained from a single end of the fiber. The slope efficiency with respect to the launched pump power was 80%. The pump leakage was estimated to be below 1.7%. The standard deviation of the temporal power was <1.2%, measured with a photo-detector of 3.5-ns rise/fall time and a 400 MHz bandwidth oscilloscope. The output power increased linearly with launched pump power. There was no evidence of any power limitation due to nonlinear scattering, nor was any stimulated Raman scattering observed. Compared to previous results generating up to 500 W from 30 – 40-m long fibers with 12- and 24.5-μm core diameters [3,4], our fiber was significantly shorter (8 m) and had a bigger core (43-μm diameter). This suggests a very high threshold for undesirable nonlinear scattering for our YDFL. Experimentally, nonlinear scattering was completely suppressed. We measured a beam quality factor (M^2) of 3.4. This must be considered to be a good result, bearing in mind the relatively high V-parameter of 11.2 of the core at 1.1 μm, and given that no special measures were taken to suppress operation on higher-order modes. Given that we may be relatively far from the damage threshold, one could consider making the core smaller (provided acceptable pump absorption can be maintained), which would allow for an improved beam quality. The core NA could also be reduced to improve the beam quality. There are also mode-selecting techniques such as a fiber taper and bend-loss filtering that can be used to improve the beam quality further in the multi-mode core [9,10].

3. Conclusion

We have demonstrated a highly efficient, high Yb concentration, double-clad Yb-doped large-core fiber laser with a cw output power of 1.01 kW at 1.1 μm based on an 8-m single fiber. No evidence of roll-over in laser output power at the highest launched pump powers (~1.3 kW) was observed, suggesting that our laser could be scaled to even higher powers using a more powerful pump source or, for example, with additional multiplexed-pump sources. Though the laser was not diffraction-limited (M^2 = 3.4), there are several options to improve the beam quality.

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4. References

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