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Erbium-ytterbium co-doped cladding pumped fiber laser tunable from 1533 to 1600 nm with up to 6.7 W of output power

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We describe a high-power erbium-ytterbium co-doped fiber laser, cladding-pumped by a beam-shaped 915 nm diode bar. The laser was tunable from 1533 to 1600 nm with 6.7 W of out-put power at 1550 nm in a single-polarization, narrow linewidth, temporally stable beam.

Introduction

Cladding-pumped fiber lasers offer a unique combination of high power, high efficiency, compactness, simple service-free operation, and high reliability. The long thin shape of fiber lasers reduces the thermal loading density and is attractive for heat removal. Optical waveguiding further safeguards against thermal distortion of the lasing field even at high powers. For these reasons, fiber lasers can be power-scaled without the reduction of efficiency and brightness that are common problems for conventional "bulk" lasers. To date, 110 W of nearly diffraction-limited output has been reported from an ytterbium-doped fiber laser at a wavelength of 1.1 µm [1]. While ytterbium-doped fiber lasers are attractive because of their efficiency, emission in other wavelength regions requires other dopants. For the important wavelength range around 1.55 µm, there are erbium-ytterbium co-doped fiber lasers (EYDFLs) and amplifiers (EYDFAs) [2, 3]. EYDFLs and EYDFAs have attracted considerable attention, though mostly at modest power levels in line with the requirements for optical communications (typically below 1 W). However, EYDFLs and EYDFAs can deliver more power than that, making them attractive for other applications, e.g., in LIDAR, which benefit from the eye-safe nature of 1.55 µm light. In some cases, a wavelength-tunable output is required. So far, however, a high-power cladding-pumped tunable EYDFL has not been described in the literature. Here, we present such a laser with an external grating for wavelength tuning. The laser had a maximum output power of 6.7 W at 1550 nm and was tunable from 1535 to 1600 nm with a linewidth of 0.25 nm.

Experimental set-up

The set-up for the tunable EYDFL is shown in Fig. 1. The erbium-ytterbium co-doped fiber (EYDF) was pumped by a 915 nm diode bar from Optopower. A two-mirror beam-shaper equalized the beam propagation parameters of the pump beam in orthogonal directions to enable efficient launch into the fiber [4]. The pump beam was launched via two dichroic mirrors and a gradient-index lens with a 25 mm focal length into the EYDF. The pump launch end of the fiber was perpendicularly cleaved, providing a 4% reflecting output coupler. The pump power in the beam-shaped beam was ~40 W, of which ~25 W could be launched into the EYDF. The far end of the EYDF was spliced to a standard single-mode fiber with a numerical aperture of 0.12 and a core diameter of 8 µm. The splice loss from the EYDF to the single-mode fiber was less than 1 dB. The other end of the single-mode fiber was angle-polished to suppress reflections. An external diffraction grating blazed for 1.55 µm with 600 lines/mm mounted on a rotation stage provided a wavelength selective tunable feedback via an aspheric lens with a 14 mm focal length. We estimate that the fiber-to-grating-to-fiber reflectivity was ~30%. The standard single-mode fiber in the cavity prevented signal light from being fed back into cladding-modes. Furthermore, with a good splice to the EYDF, the single-mode beam from the single-mode fiber can be preserved through the multi-moded EYDF, thus significantly improving output beam quality [5, 6]. The laser output was taken from the pump launch end through the dichroic mirror, as shown in Fig. 1.

The EYDF was a 3.3 m long conventional double-clad fiber, with a core for guiding the lasing light centered in a circular inner cladding that also served as a waveguide for the pump light. The fiber was made in-house with the standard MCVD and solution doping technique. The core consisted of a phosphosilicate glass activated with Er^{3+} and Yb^{3+}. It had a diameter of 12 µm and a numerical aperture of ~0.18, resulting in a calculated cut-off wavelength of 2.7 μm with five modes supported at 1550 nm. However, with a modified fiber design it would be possible to reduce the core NA to ~0.1, which would make the core single-moded at 1550 nm without any other change in performance. The inner cladding was made of pure silica and had a diameter of 125 μm. It was coated by a low-index UV-curable polymer outer cladding that provided a nominal numerical aperture of 0.48 for light in the inner cladding. Our fabrication process for erbium-ytterbium co-doped fibers (EYDFs) is described in [7].

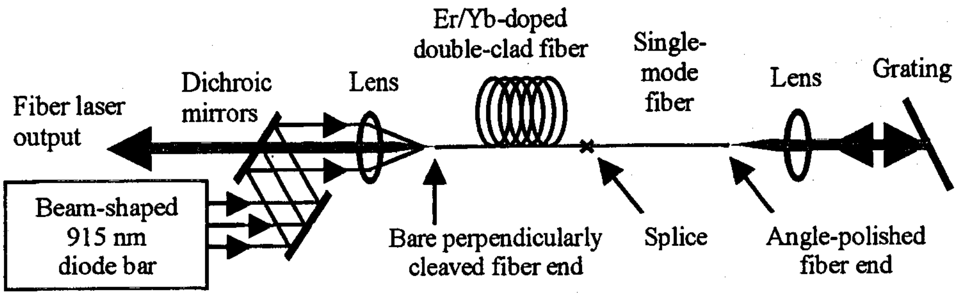

Fig. 1. Configuration of tunable fiber laser

From a large number of EYDFs fabricated in house, we selected a fiber with large pump absorption for this EYDFL. This allowed us to use a short fiber, which can be useful for reducing nonlinear effects and which tends to make high-power fiber lasers more stable. We measured the absorption in a 1 m long piece of fiber and found it to be ~2.7 dB at the absorption peak at around 975 nm and ~2.0 dB at the pump wavelength (915 nm). It was measured with a white light source that filled the NA and the aperture of the inner cladding. We also measured the erbium core absorption at the 1535 nm peak to be 60 dB/m. The pump beam in an actual EYDFL is typically launched under different conditions, which modifies the absorption somewhat. Much more important, though, is that different pump modes (of the inner cladding) are absorbed at different rates. In a double-clad fiber with a rare-earth doped core centered in a circular inner cladding, a large number of pump modes have a poor overlap with the core. The absorption of such pump modes will be poor. For efficient absorption of all pump light, it is necessary to scramble the pump modes. See [8]. In our laser experiments, we scrambled the modes by bending the fiber into a figure-eight. Figure 2 illustrates the absorption spectra, measured with and without bending the fiber to a figure-eight. By bending the fiber, we increased the small-signal absorption of the 1 m long fiber to 4.9 dB at 915 nm and to 13.4 dB/m at the 975 nm peak. Thus, the 3.3 m long EYDF used in the laser set-up should absorb at least 90% of the pump power.

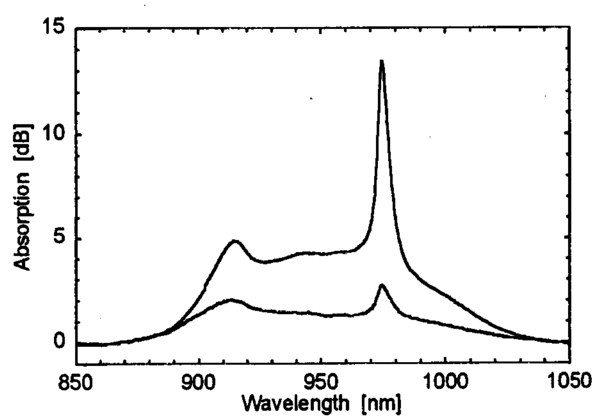

Fig. 2. Absorption spectra of a 1 m long piece of our EYDF. The curve with the low absorption was measured without any sharp bends on the fiber. The curve with the high absorption was measured with the fiber bent into a figure-eight.

Results

The EYDFL was initially operated in a free-running configuration, with a perpendicular cleaved fiber end providing feedback for laser oscillation, without the single-mode fiber and the diffraction grating used for the tunable laser. We measured a slope efficiency of 37% and a threshold of ~0.5 W with respect to launched pump power with a 3.5 m long EYDF. The pump transmission was around 8% (corresponding to 11 dB absorption). This is somewhat lower than achieved in the white light absorption measurement, because of insufficient mode scrambling in the longer fiber used for the laser experiments and because the fiber had been rearranged. The bleaching of the Yb-absorption at high pump power was small, ~1 dB. The low bleaching is a characteristic of efficient EYDFs, as it implies that excited Yb-ions were rapidly de-excited via energy transfer to Er-ions.

Tunable fiber lasers benefit from the high gain and broadband emission of rare-earth doped fibers. With the single-mode fiber and diffraction grating providing feedback (Fig. 1), the EYDFL could be tuned over a large part of the erbium emission band. Figure 3 shows the output power of the laser as a function of wavelength. The variation in output power was less than 3 dB from 1533 nm to 1600 nm. Thus, the tuning range was 67 nm (full width at half-maximum). A maximum output power of 6.7 W was obtained at 1550 nm with a pump-to-signal conversion efficiency of 27%. The shift in the emission peak towards 1550 nm from the intrinsic peak at ~1535 nm is caused by reabsorption in the EYDF. Losses at the diffraction grating, including fiber back-coupling losses and splice losses, may have caused the reduction in conversion efficiency of the tunable laser compared to the free-running laser.

The linewidth of the output beam was much narrower than that of the free running laser. It remained approximately constant over the whole tuning range at less than 0.25 nm. The inset in Fig. 3 shows one example. The temporal behavior of the laser output was monitored using a fast InGaAs photodiode. Good temporal stability was observed throughout the whole tuning range of the laser with power fluctuations of less than 10%. We believe the short fiber length contributed to the relatively good stability of the fiber laser. In contrast, long high-power cladding-pumped fiber lasers often suffer from instabilities. The single-mode fiber spliced in one end of the EYDF improved the beam quality. We did not measure the beam quality directly. However, we found that more than 95% of the total output power was preferentially linearly polarized in a single direction. This is a result of the polarization dependence of the diffraction grating and the fact that a mode that is linearly polarized in one end of the cavity is also linearly polarized in the other end. Different modes would be polarized at different orientations. The high degree of polarization purity indicates that the output was nearly single-moded.

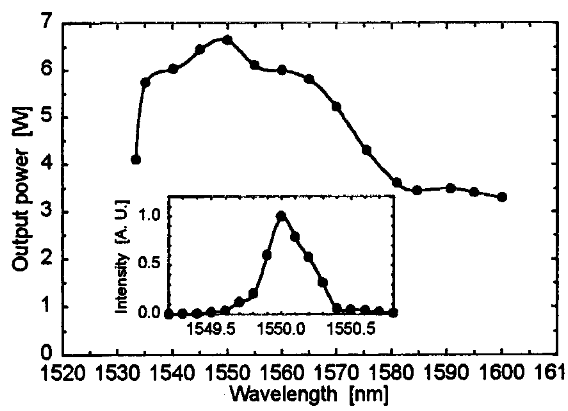

Fig. 3. Output power vs. wavelength. Inset: Line-shape of laser.

In conclusion, we have described a tunable erbium-ytterbium co-doped fiber laser, cladding-pumped at 915 nm. In a free-running laser configuration, we obtained a slope efficiency of 38% with respect to launched pump power. The tunable fiber laser emitted up to 6.7 W of output power with a tuning range from 1533 to 1600 nm, in a high-brightness, single-polarization, narrow linewidth, temporally stable beam. These properties make the laser attractive as a pump source for various nonlinear frequency conversion schemes.

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