264 W output power at 1585 nm in Er–Yb codoped fiber laser using in-band pumping

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We demonstrate a high-power cladding-pumped Er–Yb codoped fiber laser with 74% efficiency. A pump-limited output power of 264 W is obtained using in-band pumping at 1535 nm. We compare the efficiency of 1480 and 1535 nm pumping through numerical simulations and experimental measurements.

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In recent years, high-power fiber lasers operating near 1 μm have been successfully developed using diode pumping at 970 nm of double-clad ytterbium (Yb)-doped fibers [1–3]. However, translating the advances in terms of optical efficiency and output power to the 1.5 μm spectral window that provides atmospheric transparency at eye safe wavelengths has proven difficult due to the high quantum defect when using diode pumping of codoped erbium (Er)–Yb fibers. In 2007, the first demonstration of a fiber laser near 1.5 μm with multi-hundred watts output power was achieved using a cladding-pumped, large mode area (LMA), Er–Yb codoped fiber [4]. Even though 300 W of output power was reached, the slope efficiency was low and dropped from 40% to 19% at high pump power (>600 W) due to the saturation of the cross-relaxation process between Yb and Er ions. Such high-power Er–Yb codoped fiber lasers can also emit a significant amount of 1 μm radiation, and thus, be the subject of catastrophic failure due to the onset of self-pulsation [5]. In-band pumping was therefore proposed as an alternative pumping solution that offers high efficiency and low thermal load [6–8]. Using an Yb-free Er-doped LMA fiber, an output power of 88 W was obtained and the output power was limited by the available diode laser power at 1.53 μm [6]. Another option for in-band pumping is to use 1480 nm Raman fiber lasers pumped by a Yb-doped fiber laser. With core pumping an output power of 100 W was demonstrated with a slope efficiency of 71% using such pumps [9]. Cladding pumping, compatible with multimode pump lasers, is, however, the preferred choice for power scalability. The lower inversion level associated with cladding pumping also contributes to lower the impact of pair-induced quenching [7]. Recently, a 75 W cladding-pumped laser at 1585 nm was demonstrated with 976 nm pumps leading to a slope efficiency of 40% [10].

In this Letter, we design a fiber laser suitable for commercial, defense, and aerospace applications that require efficient, high output power, lightweight and robust laser sources. We use in-band cladding pumping, an approach that meets these requirements, compatible with the current state-of-the-art of semiconductor laser diode technology and can lead to high slope efficiency. We first focus on the Er-doped fiber design, optimizing the dopant concentration and solubility. We then describe the 1535 nm fiber lasers that were used in this demonstration as in-band pumps. With the proposed laser configuration, we demonstrate a record output power of over 260 W at 1585 nm with 74% slope efficiency for 370 W launched pump power. Finally, we contrast the efficiency of 1480 and 1535 nm cladding pumping of Er-doped fiber lasers. In conclusion, we discuss how this work provides a solution for power scaling of 1.5 μm fiber lasers.

The proposed configuration consists of a double-clad Er–Yb codoped fiber pumped by 36 fiber lasers emitting at 1535 nm, as shown in Fig. 1. The active fiber was designed to have 1.1 dB/m cladding absorption at 1535 nm. Launching light from a broadband source in a free space configuration with a spot size and NA larger than those of the fiber (overfilled condition), we measured a total absorption of ~20 dB at 1535 nm for an 18 m of Er–Yb codoped fiber. The measured value was validated using the theoretical formula (1) relating the core absorption, α_{core}, core diameter, φ_{core}, and cladding diameter, φ_{clad}, to the cladding absorption, α_{clad}:

$$\alpha_{\mathrm{clad}} = \alpha_{\mathrm{core}} \times \left[\frac{\varphi_{\mathrm{core}}}{\varphi_{\mathrm{clad}}}\right]^2. \tag{1}$$

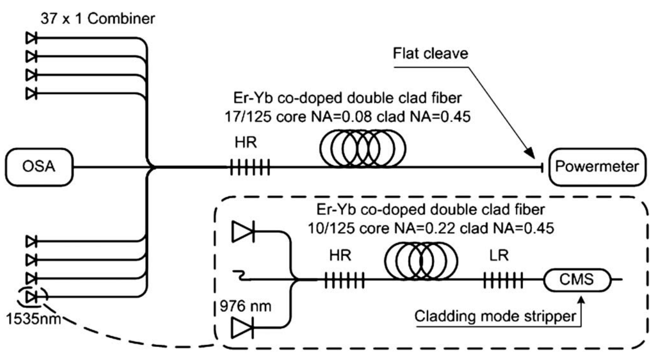

Fig. 1. High-power 1585 nm fiber laser configuration. Thirty-six fiber lasers emitting 11 W each at 1535 nm are used to pump an 18 m long Er–Yb codoped laser cavity. HR, high-reflectivity fiber Bragg grating; LR, low-reflectivity fiber Bragg grating; CMS, cladding mode stripper; OSA, optical spectrum analyzer.

The second cladding was made of a low-index polymer, so that the first cladding had a NA of 0.45 and a diameter φ_{clad} of 125 μm. An alumino-phospho-silicate glass matrix was used for the doped core (17 μm core diameter, core NA = 0.08). Yb was added to increase Er ion solubility and reduce quenching, without participating in the lasing transitions [8]. During the fiber design phase, four preforms were fabricated with different Er–Yb concentration ratios. All fibers were initially drawn with a single cladding and their performances were compared in terms of absorption at 1535 nm and slope efficiency for 1535 nm in-core pumping, as shown in Table 1. The clustering level was also characterized using the measurement technique described in [11]. The core of preform no. 1 devitrified during manufacturing and the resulting fiber showed large background losses due the low erbium solubility of the Yb-free, phosphorus-rich glass matrix. Codoping with ytterbium helped to lower the losses to an acceptable level. A clear link between increasing clustering level and decreasing efficiency was observed. An Er:Yb concentration ratio of 1:3.3 gave the best results and the fiber used in this demonstration is drawn from this preform.

The cavity consisted of a fiber Bragg grating (FBG) acting as the high reflector and 18 m of Er–Yb codoped double-clad with the cleaved fiber end acting as the output coupler (OC). The 1585 nm FBG, with a 3 dB bandwidth of 2 nm and a reflectivity of 30 dB, was UV written in a single-mode double-clad fiber having an 11 μm core diameter and a NA of 0.08.

The cavity was pumped by 36 fiber lasers emitting at 1535 nm. The dashed box in Fig. 1 depicts the 1535 nm pumps. Each one of these lasers is pumped by two diodes delivering a total pump power of 31 W in the fiber core at 970 nm. Each fiber laser thus pumped had a maximum output power of 11 W at 1535 nm. The active Er–Yb fiber used to build the pump lasers is a commercially available fiber (CoractiveDCF-EY-10/128) designed for high-power telecom/CATV amplifiers. This fiber has a core diameter of 10 μm, a NA of 0.22, and a cladding absorption of ~2 dB/m at 915 nm. In this fiber, the high ytterbium concentration, necessary for optimizing cross-relaxation between Yb and Er ions, is at the origin of the high absorption at 970 nm, causing a high thermal load. The output power of the pump laser was thermal limited and at maximum power operation, the fiber reached a temperature above 85 deg. Because the acrylate coating is specified up to 100°C, the pump fiber lasers were water cooled for long-term operation. The central branch of the $2+1 \to 1$ pump combiner was terminated using the "Endlight" feature of a Fujikura fusion splicer to achieve a low backreflection level [12]. The 1535 nm laser cavity consisted of two FBGs acting as high reflector (HR) and low reflector (LR). Both HR and LR were written in a double-clad passive fiber with a core diameter of 8 μm and a NA of 0.12. Both active and passive fibers were designed so that the match between the mode field diameters of the fundamental modes is higher than 95%. Fusion splicing of the active fiber to the FBGs was done by active alignment and the splice loss was estimated to be about 0.15 dB. The HR had over 30 dB reflectivity while the LR reflectivity was set to 0.5 dB. The HR and LR were designed so that the LR reflection bandwidth of 0.3 nm falls within the HR reflectivity of 3 nm after grating annealing. This overlap between the reflection bandwidths is introduced to guarantee a stable laser operation when the fiber reaches high temperatures causing shifts in reflected wavelengths. A cladding mode stripper was used to eliminate residual 970 nm pump before the main cavity. The average efficiency of the pump lasers is 35.6% calculated as the ratio between the output and the launched power at 970 nm. The outputs of these pump lasers were combined using a custom-made pump combiner that merges 37 standard single-mode fibers inputs (SMF28) into one coreless 125 μm fiber with a NA of 0.45. The manufacturing technique of the $37 \to 1$ fused fiber bundle combiner is described in [13] and [14]. The pump combiner losses are evaluated to be ~0.3 dB. The central branch of the power combiner is connected to an optical spectrum analyzer (OSA) with a resolution of 0.1 nm that is used to monitor the spectrum of the counterpropagating signal.

Figure 2 shows the laser output power at 1585 nm measured as a function of launched pump power at 1535 nm. A 74% efficiency with respect to launched pump power is obtained without any sign of saturation indicating that the maximum output power was pump-limited. The laser output power was stable, within ~1% of fluctuation, tested for 1 h of operation at 264 W. The heat was dissipated through an uncooled heat sink spool. Unforced air cooling was enough to dissipate the heat load due to the high laser efficiency and low background losses. The optical spectra, measured with an OSA with a resolution bandwidth of 0.1 nm, at an output power of 60 and 260 W, are displayed in Fig. 3. The figure displays an amplified spontaneous emission (ASE) level 50 dB below the signal level. The same figure shows a power-dependent

Table 1. Parameters of the Four Fabricated Preforms

No.	Er:Yb Ratio (%)	Losses at 1.2 μm (dB/km)	α_{core} at 1.5 μm (dB/m)	Slope Efficiency (%)	Clustering (%)
1	no Yb	>900	70.6	n/a	n/a
2	1:2.5	120	98.5	63	4.36
3	1:3.3	10	59.7	78	1.16
4	1:10	83.1	59.4	39	10.64

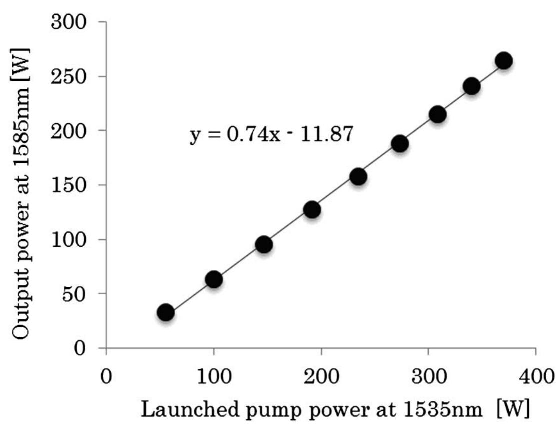

Fig. 2. Output power at 1585 nm as a function of the total 1535 nm pump power launched in the cladding.

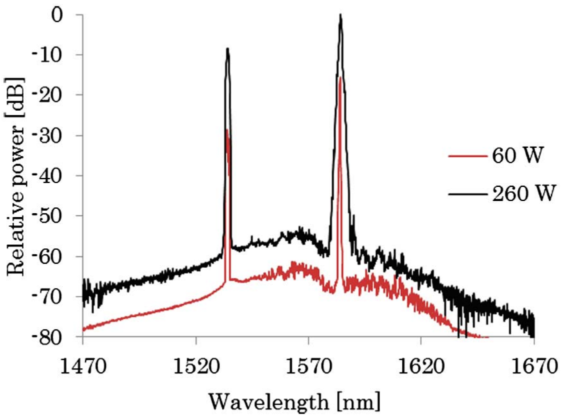

Fig. 3. Optical spectrum measured at output powers of 60 and 260 W. The optical spectrum analyzer is connected to the central branch of the 37 to 1 combiner.

spectrum broadening of the laser at 1585 nm. The measured spectral width at full width at half-maximum broadened from 0.3 nm at 60 W to 1 nm at 260 W. This spectral broadening is associated with four-wave mixing between the laser longitudinal modes. These measurements are in agreement with the theoretical model describing high-power fiber lasers linewidth broadening as function of power at 1064 nm [15].

In-band pumping with fiber lasers was adopted for this proof-of-principle demonstration because the price of commercially available 1535 nm pump diodes is still prohibitive. Indeed, the fiber laser cavity was designed to be compatible with high brightness, high power, and commercially available semiconductor diodes. Therefore, it is worth investigating the performance gained by using 1535 nm in-band pumping rather than 1480 nm, a wavelength readily accessible with standard pump diodes. We performed a comparative study of these two pumping wavelengths using the experimental setup shown in Fig. 4.

The linear fiber laser cavity was pumped by three commercially available semiconductor diodes emitting either at 1480 or 1535 nm. The diode output fiber is a multimode fiber with a core diameter of 105 μm and a NA of 0.22. A $3 \rightarrow 1$ pump combiner was used to couple up to 15 W of power (three diodes combined) into the cladding of a double-clad alumino-phospho-silicate Er–Yb codoped fiber (core diameter of 13 μm, core NA $= 0.08$). The fiber we used for this experiment has a fluorine-doped silica cladding with a NA of 0.28 and low absorption at 1480 and 1535 nm. This fiber was drawn from the same preform as the one we previously described, and thus has the same small signal core absorption. An all-glass fiber is required for this experiment because the initial fiber

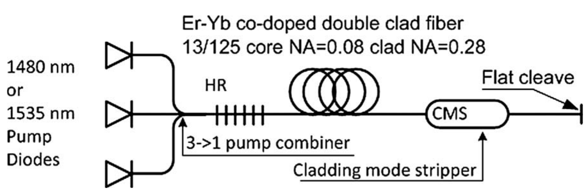

Fig. 4. Experimental setup used to compare pump wavelength efficiency. A silica cladding (NA $= 0.28$) Er–Yb codoped fiber laser cavity is pumped at either 1480 or 1535 nm.

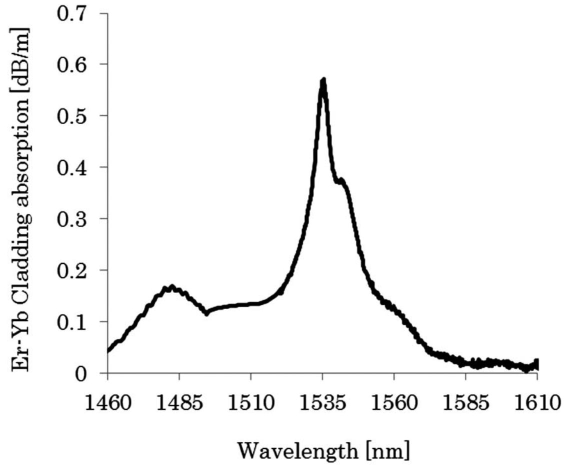

Fig. 5. Cladding absorption of the double-clad Er–Yb codoped fiber used for comparing the efficiency of 1480 and 1535 nm pumping.

length was set to 40 m, making the cladding absorption significantly affect the laser efficiency. The experiment consisted of measuring the slope efficiency of the laser for different cavity lengths at both wavelengths. The OC is the flat cleaved fiber end (4%), the high reflector was the same FBG as the one used previously. The measured cladding absorption spectrum used for the simulations is shown in Fig. 5.

Simulations were performed using standard rate equations solved with the fourth-order Runge–Kutta method and are based on fiber gain modeling [16]. All parameters that were used in the simulation, like the splice losses, background losses, core absorption, core and cladding diameter, were measured on the section of fiber used in this experiment. Figure 6 compares the experimental measurements to the numerical simulation results. For this fiber, the cladding absorption at 1535 nm is 0.57 dB/m while it is 0.17 dB/m at 1480 nm. Because of the lower cladding absorption of this all-glass fiber, the 1535 nm cladding pumped cavity used in this experiment had lower efficiency than the one we described in the first section of this Letter. On the other hand, the low efficiency at 1480 nm is due to the low absorption at this wavelength making it unsuitable for cladding pumping. It clearly appears that in-band pumping with a longer pump

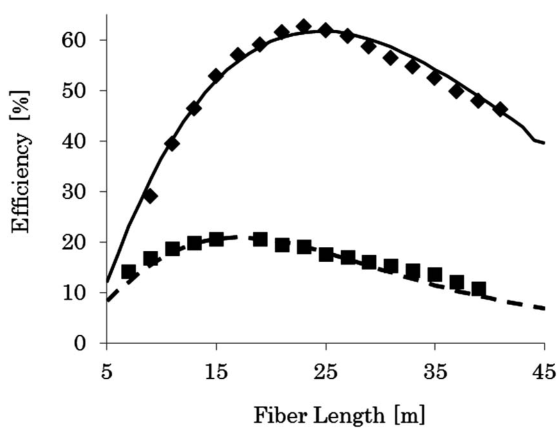

Fig. 6. Measurements and numerical simulation results of laser slope efficiency as a function of pumping wavelength, 1480 nm (square) and 1535 nm (diamonds).

wavelength for which the absorption is higher, namely 1535 nm, is a key to achieve a high-efficiency, high-power fiber laser.

In conclusion, we demonstrated that in-band pumping near the erbium absorption peak of an Er–Yb codoped fiber is an efficient scheme to obtain high-power emission near 1580 nm. The small quantum defect of this configuration also eases the cooling requirements. Although the present demonstration was performed using fiber laser pumps, it is possible to pump the same cavity using diode lasers once they become available at these wavelengths at an affordable price. With diode pumping, these fiber lasers would become competitive, in terms of efficiency, to diode-pumped Yb-doped fiber lasers but at eye safe wavelengths. Although Yb is not participating to the laser dynamics, its presence is key to reducing clustering and obtaining power scalability. Therefore, the laser performance is currently only limited by the available pump power. These laser sources with an eye safe wavelength are a promising alternative to current Yb-doped high-power fiber lasers used for industrial applications. In addition, the low atmospheric absorption at this wavelength, combined with the alignment insensitivity, light weight, and low divergence angle of a single-mode fiber laser, makes this solution very attractive to defense and aerospace applications.

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