

**High-power tunable single-frequency single-mode erbium:ytterbium co-doped
large-core fiber master-oscillator power amplifier source**

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Abstract

We present a cladding-pumped single-frequency, single-mode erbium:ytterbium co-doped fiber master-oscillator power amplifier source generating up to 151 W of continuous-wave output power at 1563 nm with 33% slope efficiency and 20 dB gain. This source was also tunable and had a stable operation range of 1546 to 1566 nm at an output power level in excess of 125 W. The doped fiber exploited a large-core design for improved power handling and mitigation of stimulated Brillouin scattering. There was no sign of having stimulated Brillouin scattering even at the highest power. Despite a large core ($V = 12$), the output beam was nearly diffraction-limited ($M^2 = 1.1$). The source showed slight roll-over at over 100 W of output power because of the onset of emission from ytterbium, centered at 1060 nm.

OCIS codes: (140.3510) Lasers, fiber; (060.2320) Fiber optics, amplifiers and oscillators

High-power, single-frequency sources with very narrow linewidths in the 1.5 – 1.6 μm wavelength range are of great interest in many scientific and engineering applications such as wavelength conversion, coherent combination, and gravitational-wave detection. Specific advantages of this wavelength range include its relatively “eye-safe” nature and its good atmospheric transmission. Furthermore, the compatibility with telecom components opens up for the use of widely available low-cost devices with superb performance, and indeed provides a route to telecom transmitters with very high power. An Er-doped fiber is the obvious choice in this wavelength range. For high-power cladding-pumping with currently available diodes at 915 – 980 nm, Yb-sensitization is required to reach sufficient pump absorption [1-3].

Unfortunately, Er:Yb co-doped fibers (EYDFs) are significantly less efficient than Yb-doped ones at 1.1 μm , and therefore much more challenging to power-scale [4,5]. Optimization of the composition of the gain medium is crucial, to obtain high efficiency and also to suppress unwanted emission from excited Yb-ions [6]. High concentrations of P, Yb, and Er are required for efficient energy transfer. This however results in a high index step relative to pure silica [2] which makes it difficult to realize single-mode EYDFs with the large core diameter required for high-power operation. Many previously reported high-power EYDFs have therefore been multimode [4,5]. In addition, stimulated Brillouin scattering (SBS) has been viewed to limit power-scaling of single-frequency beams, to the watt-level in case of standard telecom fibers, while a higher SBS limit would be expected for a large-core fiber. However, we have recently demonstrated that unexpectedly high single-frequency signal powers can be reached in fiber amplifiers [7]. The temperature variation due to large heat dissipation in high-power fibers effectively broadens the Brillouin gain. This reduces the peak gain and therefore increases the

SBS threshold. The important conclusion is that SBS need not be a substantial limitation to single-frequency amplification in rare-earth-doped fibers.

In this letter we present a single-frequency, EYDF MOPA system which is tunable from 1546 to 1566 nm at over 125 W of continuous-wave output power and emits 151 W of maximum output power at 1563 nm. We obtained a single-mode output beam. This is a key advance over earlier work. Building on our preliminary report [8], we discuss the important factors behind this result as well as limitations. This includes the power-scaling characteristics and the spurious Yb emission, which eventually limited the maximum output power, and the SBS, which was successfully suppressed. We further investigate the spectroscopy of the fiber used in the experiment in order to analyze the origin of the spurious Yb emission.

The EYDF MOPA we used is depicted in Fig. 1. An external-cavity tunable diode laser (Santec TLS-210) served as the master oscillator, providing a polarized single-frequency seed (linewidth less than 1 MHz) with up to 10 mW of power, tunable between 1530 and 1610 nm. This was followed by a polarization controller and a commercial Er-doped fiber amplifier (Southampton Photonics Inc.). This pre-amplifier had built-in isolators at both input and output terminals to prevent undesired backward propagation. It amplified the seed by ~ 23 dB to 1.8 W. The final-stage amplifier comprised a 10-m long double-clad EYDF fabricated in house using the modified chemical-vapor deposition and solution doping technique [2]. The fiber had a 30- μm diameter core with a numerical aperture (NA) of 0.2 and a 650- μm diameter D-shaped inner cladding with an NA of 0.48 with respect to the low-index polymer outer cladding. The Er:Yb co-doped core provided a core absorption of 67 dB/m at ~ 1535 nm (from the Er-doping) and an inner-cladding absorption for the pump light at 975 nm of 1.4 dB/m (from the Yb-doping). The fiber was end-pumped from the signal output end by a free-space coupled diode stack at 975 nm

with up to ~ 470 W of launched pump power. Both fiber ends were angle-cleaved to eliminate signal feedback. The signal from the pre-amplifier was launched via a free-space coupling arrangement, through a beam splitter and a dichroic mirror that were inserted to monitor the backscattered signal and to separate the residual pump and any spurious Yb-emission at $1 - 1.1$ μm from the signal beam path. With proper adjustment of the signal launch, over 85% of the incident signal power could be launched into the final-stage amplifier.

Output spectra measured at >125 W for different operating wavelengths are shown in Fig. 2. The saturated output power exceeded 125 W from 1546 to 1566 nm, corresponding to a nearly flat, saturated gain of 19 dB. At the edges of the tuning range, i.e., at 1540 nm and 1570 nm, a higher output power than 30 W was prevented by a rapid growth of the amplified spontaneous emission (ASE) outside the seed wavelength. Figure 3 shows the output power vs. final-stage pump power. Although the power characteristics were nearly identical at different wavelengths, the most efficient wavelength was around 1563 nm in terms of gain and ASE suppression. Thus, we further investigated the performance at this wavelength and reached 151 W of output power at a launched pump power of 473 W as shown Fig. 3, together with the corresponding output spectra. The ASE in a 1 nm bandwidth was nearly 40 dB down from the 1563 nm signal over the whole Er-band, for all power levels. The fraction of power within the single-frequency line relative to the total Er-band power was higher than 99.8% at 1563 nm for the highest output power. Inside the 1546 – 1566 nm tuning range the worst ratio was 93% at 1546 nm. The slope efficiency of 35% at low powers dropped to 29% at higher powers because of the onset of Yb-emission, for an average of 33%. While we did not investigate the linewidth broadening characteristics, previous investigations have shown this to be negligible relative to a 1 MHz linewidth seed [5,7].

Remarkably, the output beam was (nearly) diffraction-limited despite the high V -value of the core ($V = 12$) and long length of the fiber in the final-stage amplifier. The beam quality factor (M^2) was 1.1. Though the fiber was bent, mode-filtering effects via a differential bend-loss is not effective at NAs as high as 0.2. For the present case, the signal launch conditions were important for the beam quality. We note that even fibers with core diameters as large as $45\ \mu\text{m}$ are capable to support propagation of only the fundamental mode over significant distances [9]. Therefore, provided the fundamental mode of our amplifier can be selectively excited, the fundamental mode may propagate in the fiber without coupling to other modes. The high beam quality also implies that the beam profile was Gaussian-like. The influence of any central dip in the refractive-index profile of the core had been suppressed. Such a dip can otherwise degrade the beam quality of the fundamental mode of large-core fibers [4,5]. We recently obtained a nearly diffraction-limited output beam from a Tm:Yb co-doped fiber laser with a core-NA of 0.2 and a V -value of 8 operating at a wavelength of $2\ \mu\text{m}$ [10].

As further evidence of the pumping-induced Brillouin-gain broadening effect recently demonstrated in the case of single-frequency Yb-doped fiber MOPAs [7], there was no sign of SBS even at the highest output power. The power level of 150 W in conjunction with 10 m of fiber length and the effective mode area of $\sim 400\ \mu\text{m}^2$ for the fundamental mode should have led to a substantial Brillouin gain unless the thermal-induced Brillouin-gain broadening is considered. We monitored the backscattered signal power as shown in Fig. 4, but did not observe any SBS-induced nonlinear increase. The linearly increasing backscattered power was due mainly to the Fresnel reflection of the signal at the output end of the fiber. In fact, because of the higher thermal load, the thermal broadening effect is expected to be even more important in

Er:Yb co-doped fibers than it is in YDFs [7]. Thus, significantly higher single-frequency powers would be possible without having SBS in this wavelength range.

However, the growth of Yb emission at high powers is an issue that remains to address. It prevented us from further increasing the output power with this fiber. Even though the angle-cleaved fiber ends eliminated feedback in the Yb-gain band and hence prevented any parasitic Yb lasing, the ASE power in the Yb band still exceeded 70 W, as shown in Fig. 5. This is indicative of a high Yb gain, which could well make the system unstable if the pump power would be increased further. We measured the fluorescence decays of excited Yb and Er ions in our EYDF when excited by a 920-nm Q-switched Nd-doped fiber laser with 20-ns pulse duration. The Yb fluorescence had an intrinsic (slow) exponential decay time after a preceding fast decay ($<60 \mu\text{s}$) of 1.4 ms [3]. The Er-fluorescence lifetime was 7.6 ms. In comparison with our previous EYDF with which spurious Yb emission was well suppressed [6], the Yb-fluorescence decay time of the EYDF used here is significantly longer, approximately 2.2 times that of the fiber in ref. [6], although the compositions of the fibers are similar. The Er lifetime is also longer, by ~ 2 ms. While the longer lifetimes of the present fiber are by themselves beneficial, they also indicate that the ions are further apart, and perhaps less clustered, than they are in the fiber used in ref. [6]. Unfortunately, this would also reduce the Yb-to-Er energy transfer rate, which would explain why it was not possible to suppress the Yb-emission in this fiber. (The bottlenecking could also come from too slow de-excitation of the upper Er^{3+} level.) Thus, further improvement in the fiber spectroscopy is required in order to eliminate the Yb-emission. Our previous result [6] suggests that this is possible. Alternatively, filters can be used to suppress the Yb-emission [11].

In summary, we have demonstrated a tunable single-frequency EYDF MOPA source with a stable tuning range of 1546 to 1566 nm and with an output power in excess of 125 W and with maximum power 151 W at 1563 nm. There was no evidence of SBS even at the highest power. Despite a large core ($V = 12$), the output beam was nearly diffraction-limited ($M^2 = 1.1$) with the aid of the proper mode excitation. Although there was a slight roll-over in the final-stage amplifier at over 100 W of output power because of the onset of Yb emission at ~ 1060 nm, the final-stage amplifier still operated with a high gain of 20 dB and high slope efficiency of 33%, and the produced power levels are unprecedented for this type of source. Spectroscopic investigations suggested that the fiber contained Yb and Er ions that were not well linked. However, our previous experience with Er:Yb co-doped fibers [6] suggest that the spectroscopy can be improved, which is currently under investigation and should then enable further power-scaling of this single-frequency source configuration.

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Figure captions

Fig. 1. Experimental setup. EDFA: Er-doped fiber amplifier; DM: dichroic mirror; BS: beam splitter; ISO: isolator.

Fig. 2. Output spectra measured at >125 W of output power level.

Fig. 3. Signal power vs. final-stage pump power. Inset: Output spectra at 1563 nm.

Fig. 4. Backscattered signal power vs. signal power.

Fig. 5. Yb-emission power vs. final-stage pump power. Inset: Yb-emission spectra.

Fig. 1

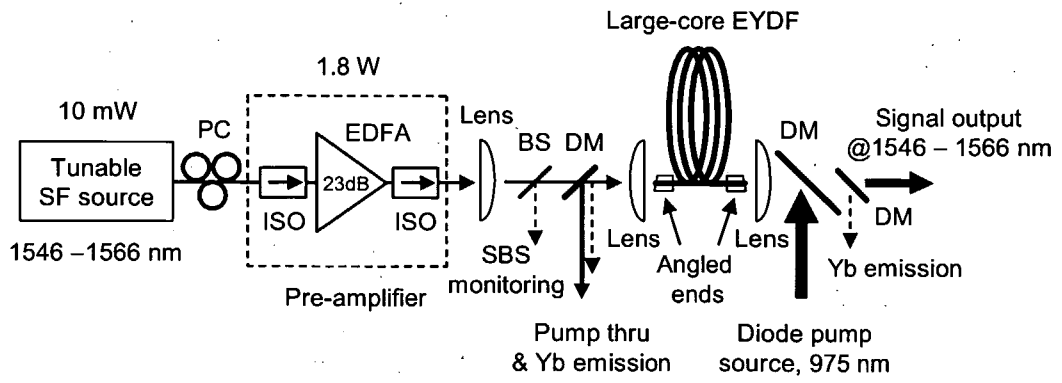


Fig. 2

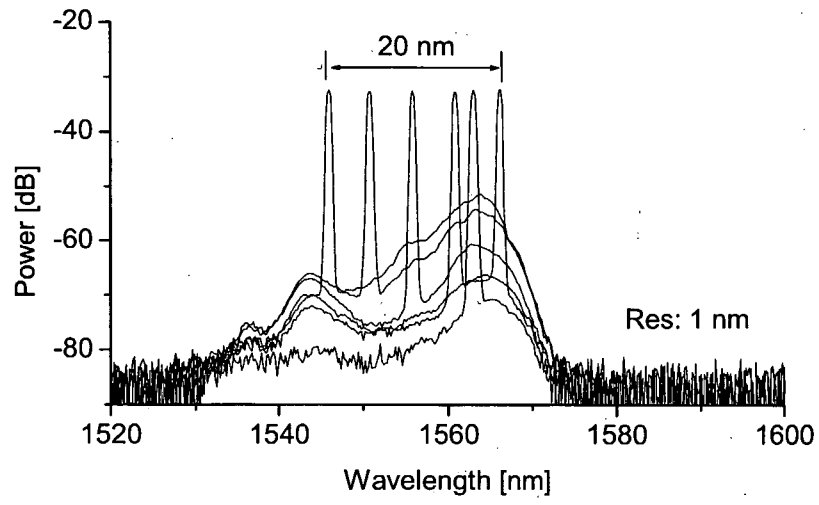


Fig. 3

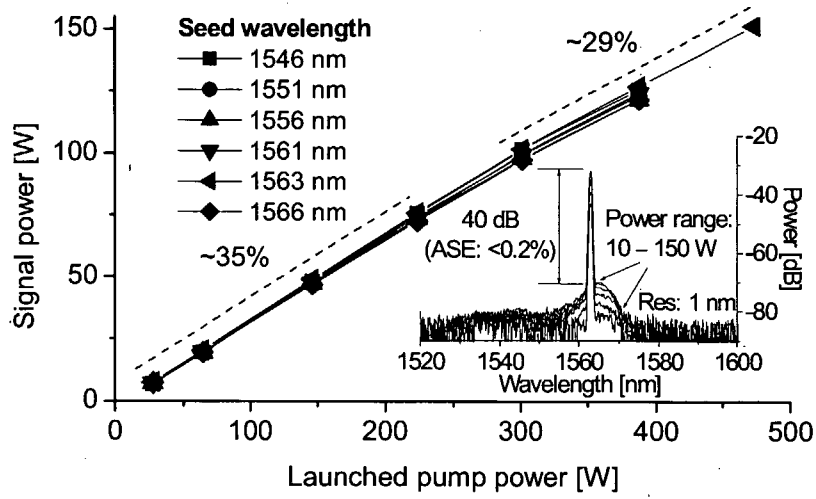


Fig. 4

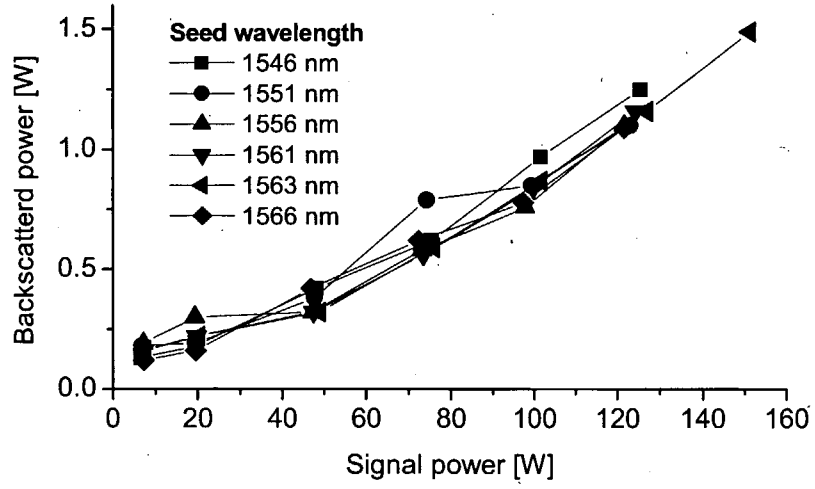


Fig. 5

