Tunable single-frequency ytterbium-sensitized erbium-doped fiber MOPA source with 150 W (51.8 dBm) of output power at 1563 nm

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Abstract: A single-frequency, single-mode ytterbium-sensitized erbium-doped fiber master-oscillator power-amplifier generated 150 W of continuous-wave output power at 1563 nm with 33% slope efficiency and was tuned in the range of 1546 to 1566 nm at >125 W.

High-power, single-frequency sources with very narrow linewidths are of great importance both in science and technology, in a wide range of applications such as wavelength conversion, coherent combination, and gravitational-wave detection. Amongst high-power fiber sources, cladding-pumped ytterbium (Yb)-doped silica fibers at 1 – 1.1 µm have received most attention because of excellent efficiency that can exceed 80% and output power that can exceed 1 kW. [1]. However, Yb-doped fiber sources are unable to address many important applications that require the use of sources in the 1.5 – 1.6 µm range, e.g., because of the relatively "eye-safe" nature of this wavelength range or because of its good atmospheric transmission. The compatibility with telecom systems further opens up for the use of widely available low-cost devices with superb performance such as modulators, and indeed provides a route to telecom transmitters with very high power. An erbium (Er)-doped fiber is the obvious choice in this wavelength range. For high-power cladding-pumping with currently available diodes at ~980 nm, Yb-sensitization is required to reach sufficient pump absorption [2]. In these, pump power is absorbed by Yb-ions and then transferred nonradiatively to Er-ions. However, Er:Yb co-doped fibers (EYDFs) are significantly less efficient than Yb-doped ones at 1.1 µm, and significantly more challenging to power-scale. In addition, the composition of the Er:Yb co-doped gain medium, with high concentrations of phosphorous, ytterbium, and erbium required for efficient energy transfer, results in a high index step relative to pure silica [3]. The large index step makes it difficult to realize single-mode EYDFs with the large core diameter required for high-power operation, and many previously reported high-power EYDFs have in fact been multimode [4,5]. In addition, stimulated Brillouin scattering (SBS) has been considered to limit power-scaling of single-frequency beams, to the watt-level in case of standard telecom fibers, while a SBS limit of 100 W has been reported for a large-core fiber [6]. So-called single-frequency linewidths are typically on the kHz to MHz scale, and in any case smaller than the Brillouin gain bandwidth of a few tens of megahertz. However, we have recently demonstrated that much higher powers than so can be reached in high-power fiber amplifiers. The large heat dissipation and temperature gradients in high-power fibers can effectively broaden the Brillouin gain. This reduces the peak gain and therefore increases the SBS threshold. Thus, we reached 264 W of single-frequency output power at 1060 nm from a Yb-doped fiber amplifier, though a simple estimate that neglected temperature broadening suggested a Brillouin limit of ~100 W [7]. The important conclusion is that SBS need not be a substantial limitation in single-frequency amplification in rare-earth-doped fibers.

Here we report single-frequency amplification in an EYDF-based cascade of amplifiers in a master oscillator – power amplifier (MOPA) configuration. The maximum output power of over 150 W is more than would be possible in the absence of SBS-suppressing effects such as thermally induced broadening. Furthermore, the MOPA is tunable from 1546 to 1566 nm at >125 W. These power levels are unprecedented for this kind of source. The last-stage amplifier operated with slope efficiency of 33% and a gain of up to 20 dB. Surprisingly, despite a V-value as high as 12, the output beam was (nearly) diffraction-limited (M^2 = 1.1).

The EYDF MOPA used in our experiment 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 a power of 1.8 W. The final-stage amplifier comprised a 10-m long double-clad EYDF fabricated in house using the modified chemical-vapor deposition (MCVD) and solution doping technique [3]. 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 / coating. 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). These values apply to the un-pumped fiber. The fiber was pumped from the signal output end by up to 470 W of launched pump power from a free-space coupled diode stack at 975 nm. 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. While the free-space launch can be replaced by a splice [5], the mode mismatch led to a degraded beam quality in this case.

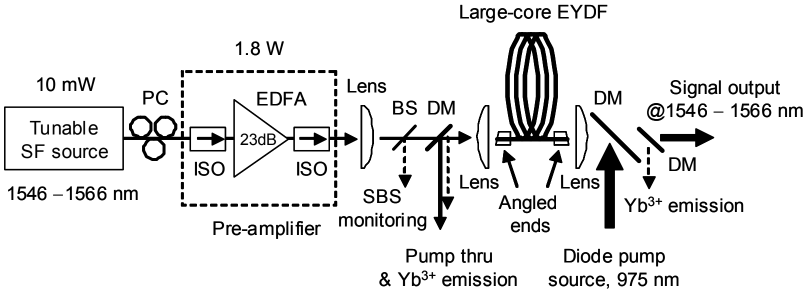

Fig. 1. Experimental setup. EDFA: Er-doped fiber amplifier; DM: dichroic mirror; BS: beam splitter; ISO: isolator.

The power characteristics of the final-stage amplifier 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. We extended the tuning range to 1540 nm and to 1570 nm, and obtained over 30 W of output; however, amplified spontaneous emission (ASE) outside the seed wavelength then grew rapidly, and prevented a further increase of the power.

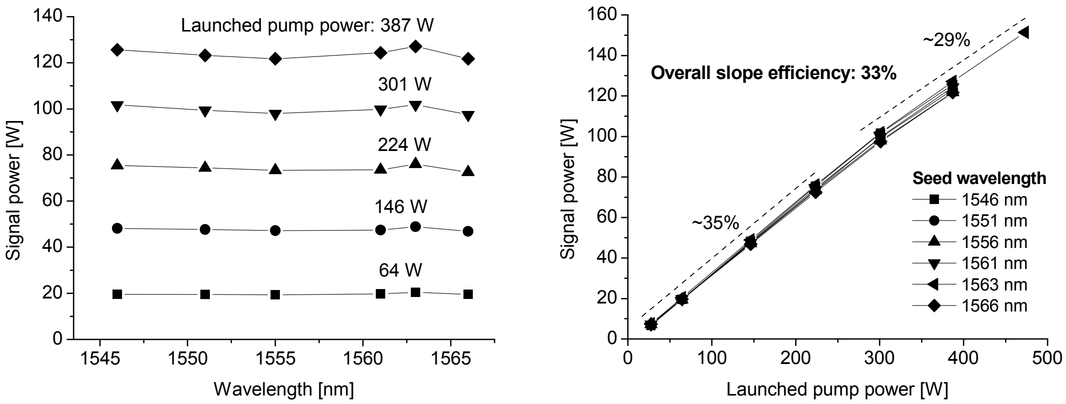

Fig. 2. Left: Signal output power vs. seed wavelength. Right: Signal power vs. final-stage pump power.

Although the power characteristics with respect to wavelengths were nearly identical, 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 (Fig. 2b). The corresponding output spectra are shown in Fig. 3. However, rapid growth of Yb emission prevented us from further increasing the output power. This is a consequence of bottle-necking in the Yb-to-Er energy transfer at high powers, as an increasing number of Yb-ions needs to be excited for a sufficiently rapid transfer of energy. The excited Yb-ions produce gain at ~1060 nm. Even though the angle-cleaved fiber ends eliminated feedback in the Yb gain band nm and hence prevented any parasitic Yb-lasing, the ASE-power in the Yb-band still exceeded 70 W. This is indicative of a high Yb-gain, that could well make the system unstable if the pump power would be further increased. On the contrary, ASE in the Er-emission range was well suppressed: 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 (Fig. 3b). 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 reliable tuning range (1546 – 1566 nm) the worst ratio was 93% at 1546 nm. The slope efficiency of 35% at the lower power dropped down to 29% at the higher power because of the onset of Yb emission, for an average of 33%. We monitored the backscattered signal power; however, we did not observe any

SBS-induced nonlinear increase even at the highest output. The backscattered power was due mainly to the Fresnel reflection of the signal at the output end of the fiber. Though the angle-cleave suppresses feedback into the core, the reflected light can still be guided back to the launch end through the inner cladding, because of its high NA. Although 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].

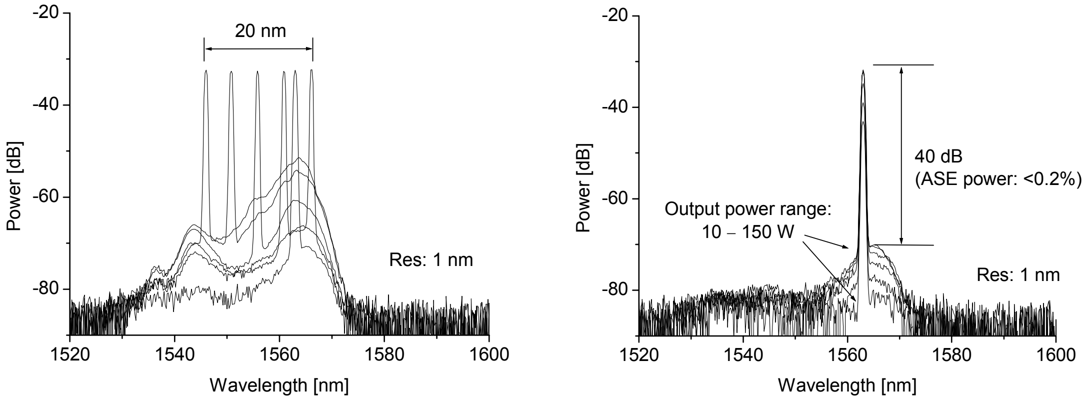

Fig. 3. Left: Output spectra measured at >125 W of output power level. Right: Output spectra at 1563 nm.

Remarkably, the output beam was (nearly) diffraction-limited despite the high V-value of the core (V = 12) and long length of the fiber: 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. This is in line with the near diffraction-limited beam quality obtained from a thulium-doped fiber laser with a V-value of 8 and an NA of 0.22 [8]. For the present case, we did find that the signal launch conditions were crucial for the beam quality. Thus, the fiber appeared to preserve the launched beam quality rather than degrade it via mode-coupling or improve it via mode-selective gain or loss. The high beam quality also implies that the beam profile was Gaussian-like. Thus, the influence of any central dip in the refractive-index profile of the core had been suppressed. A dip is likely to result in the fiber fabrication process and known to degrade the beam quality even of a single fundamental mode in large core fibers. .

In summary, we have demonstrated a tunable single-frequency EYDF MOPA source with a stable tuning range of 1546 to 1566 nm and with a record output power of over 50 dBm (maximum power 151 W at 1563 nm). The final-stage amplifier operated with a high gain of up to 20 dB gain and high slope efficiency of 33%. There was no evidence of SBS even at the highest power. The source showed a slight roll-over at over 100 W of output power because of the onset of Yb emission at ~1060 nm. Despite a large core (V = 12), the output beam was nearly diffraction-limited (M^2 = 1.1). The ability of fiber amplifiers to combine high gain, high power, and high efficiency, and the merger of such amplifiers with the convenience, reliability, and performance of telecom technology, results in sources with unique capabilities that can address a host of new applications.

References

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