High power Er,Yb-doped superfluorescent fiber source with over 16 W output near 1.55 μm

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Abstract: We report on high-power operation of a cladding-pumped Er,Yb -doped broadband superfluorescent fiber source in the 1.55 μm spectral region. Over 16 W of single-ended amplified spontaneous emission output was generated employing a simple, all-fiber geometry without the use of a high reflectivity mirror or seed source. The wavelength range spanned from ~1531 nm to 1568.5 nm with a bandwidth (FWHM) of ~17 nm and the corresponding slope efficiency with respect to launched pump power at 975 nm was 30.7%.

OCIS codes: (140.3510) Lasers, fiber; (140.3500) Lasers, erbium; (140.6630) Superradiance, superfluorescence; (140.3480) Lasers, diode-pumped.

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1. Introduction

Rare-earth doped fiber sources have attracted considerable interest over the past few years due to their excellent performances in a wide range of fields [1]. Benefit from the elongated geometry (with high surface to volume ratio) and the unique wave guiding property, fiber sources not only offer an outstanding thermal handling capability but also provide high power operation without decreasing conversion efficiency and beam quality [2]. Among the varieties of fiber sources, rather less attention has been paid to the broadband superfluorescent fiber sources (SFS, or amplified spontaneous emission, ASE) which are very useful in a number of areas requiring broad bandwidth, high brightness and low coherence. So far, high power ASE sources based on Yb-doped and Tm-doped fibers have been reported with output powers in excess of 100 W at ~1 μm and 11 W at ~2 μm [3,4]. Er,Yb-doped SFS operating around the 1.55 μm spectral region have an ever-increasing range of applications in fields such as fiber-optic gyroscopes [5,6], optical low-coherence reflectometry [7] and spectrum sliced wavelength-division multiplexing systems [8]. At present, two approaches are adopted to build a broadband fiber ASE source, one is using a low power seed in combination with one or more fiber amplifiers [9–11], the other one is employing a fiber with one end angle-polished/cleaved and the other end butted with a broadband high reflectivity mirror [12] or with both ends polished/cleaved at the same angle [13]. Although the necessity for one or more isolators between the seed source and amplifiers increase the complexity, the first approach offers high output power with less risks of resonant lasing, depending mainly on the power level of the seed, pump sources and the properties of the optical isolators [10,11]. With this approach, output power of 1.86 W at 1545 nm with a bandwidth of ~30 nm has been demonstrated [11], which is so far the highest reported superfluorescent power around 1.5 μm. Although with simpler configuration and better flexibility, the latter approach suffers from the difficulty of increasing the threshold for parasitic lasing. To date, the highest power reported using this approach is 16.85 mW centered at ~1541 nm and with a bandwidth of 18.4 nm [13].

In this paper, we present a broadband 1.55 μm Er,Yb-doped SFS with output power of almost one order of magnitude higher than the highest so far reported at this wavelength region with slope efficiency comparable to that for high-power Er,Yb-doped fiber laser oscillators by adopting a novel fiber-end termination configuration. The source was cladding-pumped by a 975 nm diode laser and generated 16.1 W of single-ended output power for 59.5 W of launched pump power, corresponding to a slope efficiency with respect to launched pump power of 30.7%. At the maximum output power, the wavelength range spanned from ~1531 nm to 1568 nm with a bandwidth (FWHM) of ~17 nm.

2. Experiments and results

The experiment setup is shown schematically in Fig. 1. The pump source is a high-power diode laser at 975 nm (DILAS) which could deliver a maximum cw output of 400 W with a bandwidth (full-width at half-maximum) of ~4 nm and beam parameter products (BPPs) of BPP_x ~25.5 and BPP_y ~24 mm·mrad in orthogonal planes. Output from the pump diode source was split into two beams of roughly equal power and launched into opposite ends of the fiber with the aid of anti-reflection coated lenses of 30 mm focal length. The launch efficiency into the fiber inner cladding was estimated to be ~85%. The gain fiber employed was a double-clad fiber with a 25

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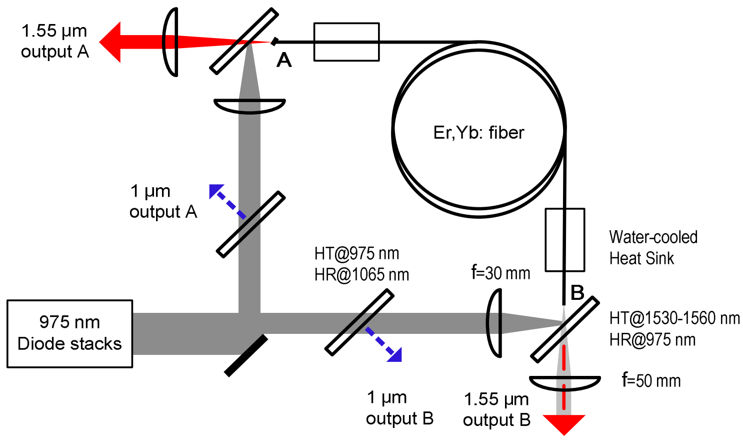

Fig. 1. Schematic diagram of the Er,Yb:fiber ASE source cladding-pumped with 975 nm diode-bars.

µm diameter (0.22 NA) Er,Yb co-doped core, a 400 µm diameter (~0.4 NA) D-shaped pure silica inner cladding, and a low refractive index UV-cured polymer outer-coating. The fiber had an Er^{3+}-doping level of 0.51×10^{20} cm^3 and Yb^{3+}/Er^{3+} doping ratio of ~17. To prevent thermal damage to the fiber coating caused by unlaunched pump power and quantum defect heating, both end sections of the fiber were carefully mounted in water-cooled V-groove heat sinks and the center part was coiled into a fan-cooled Al heat sink. Absorption coefficient of the 975 nm pump light in the fiber inner-cladding was estimated to be ~5.5 dB/m via a cutback measurement, hence a fiber length of ~4 m was chosen for efficient pump absorption. To extract the 1.55 µm ASE light, dichroic mirrors with high reflection (>99.5%) at 975 nm and high transmission (>98%) over the 1530-1560 nm band were positioned at 45° between the fiber ends and the focusing lenses. Dichroic mirrors with high reflection at 1065 nm and high transmission at 975 nm were inserted into the two pump arms to prevent any ~1 µm parasitic lasing, due to the Yb^{3+}-ion transition at high pump levels, from entering the pump diodes. Plane-convex lenses of 50 mm focal length with high transmission (>98%) at 1.5-1.65 µm were used to collimate the ASE output.

Lasing characteristics of the Er,Yb fiber was first evaluated with both ends perpendicularly-cleaved and feedback for laser oscillation being provided by the 3.6% Fresnel reflections. The 1.55 µm laser reached threshold at a launched pump power of ~2.9 W and generated 77 W of output for 209 W of launched pump power at 975 nm, corresponding to an average slope efficiency of ~37%. The laser spectrum has two peaks at 1543 and 1561 nm with a bandwidth (FWHM) of ~3 nm each. Parasitic lasing of Yb^{3+}-ion reached threshold at a lunched pump power of ~50 W and the laser started to oscillate simultaneously at both 1 µm and 1.55 µm. 41 W of laser output at 1 µm was generated at the maximum launched pump power of 209 W, corresponding to a combined optical-optical conversion efficiency of 56.5%. It is noteworthy that the 1.55 µm laser output shows a linear dependence with pump power over the whole pump range suggesting that there is scope for further power scaling by simply increasing the pump power.

For broadband superfluorescence generation, one end (A) of the fiber was angle-polished at ~8° to achieve very low feedback reflectivity while the other end of the fiber (B) kept perpendicularly-cleaved. With this arrangement, predominately single-ended output can be achieved due to the large difference in effective reflectivity of the two fiber ends [14,15]. Figure 2 shows 1.55 µm output powers from end A and B with respect to the launched pump power. It

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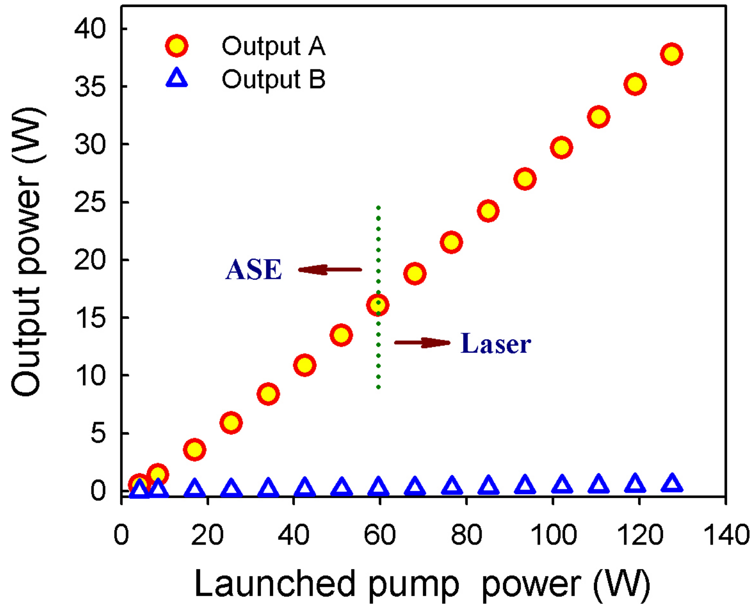

Fig. 2. 1.55 μm output power from end A and B as a function of launched pump power.

can be seen that most of the ASE output exited from end A of the fiber and predominantly single-ended operation was achieved owing to its much reduced reflectivity than the other end. At the maximum launched pump power of 127.5 W, 1.55 μm output from fiber end A and B were 37.8 W and 0.54 W respectively, resulting in a power ratio of ~70. Considering that the Fresnel reflection at the perpendicularly-cleaved fiber end was ~3.6%, the effective feedback reflectivity of the angle-polished fiber end (A) was estimated to be ~7.3×10^{-6} using $P_A/P_B \approx (R_B/R_A)^{1/2}$ [14,15], where R_A and R_B are the effective feedback reflectivities at ends A and B respectively.

Output spectra of the ASE source were monitored using a 0.55 m monochromator of 0.05 nm specified resolution at 435.8 nm (Omni-λ5005, Zolix) and the spectra from fiber end A are shown in Fig. 3 for different output power levels. It can be seen, before the system gets lasing, that all the ASE spectra span the wavelength range over 37.5 nm from 1531 nm to 1568.5 nm with the bandwidth (FWHM) almost unchanged at ~17 nm regardless of the ASE power level. In addition, both the center wavelength and spectra profile are independent of the output power level. It is worth noting that the spectra have a structure of two peaks at 1535.5 nm and 1543.2 nm, and the relative intensity of the two peaks varies with output power level. The 1535.5 nm peak is lower than the other one at low power levels, and becomes equally high at ~11 W of output power. The relative intensity of the two emission peaks reverses for ASE output powers of >11 W. This can be attributed to the bleaching of the lower laser level and hence a reduced re-absorption loss near 1535 nm at high power levels. Spectral flatness may be achieved by inclusion of a grating or other gain control element [16].

A maximum ASE output power of 16.1 W was obtained from the angle-polished fiber end (A) at a launched pump power of 59.5 W, corresponding to a slope efficiency with respect to launched pump power of 30.7%, which is comparable to that obtained in a conventional Er,Yb fiber laser system. The beam propagation factor (M^2) of the ASE output was measured with a beam profiler (Nanoscan, Photon Inc) to be less than 2.6. Further increase in pump power resulted in onset of lasing (as shown in Fig. 3) due to the residual feedback from the fiber end facets. Improvement in ASE output efficiency should be possible by operating the Er,Yb fiber system at elevated temperature to facilitate Er^{3+}-ion lasing [17]. We believe that higher ASE

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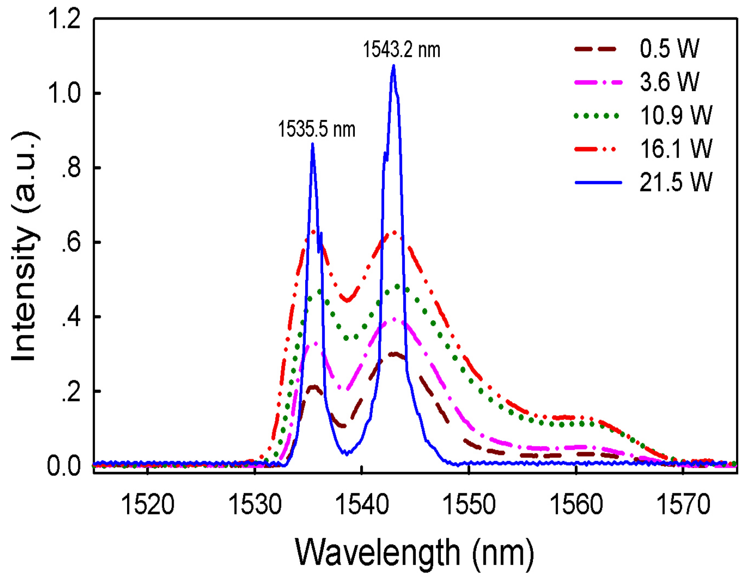

Fig. 3. Output spectra of the Er,Yb:fiber ASE source from end A at different output power levels.

output power should be achievable by increasing the polished angle (or with both of the fiber ends angle-polished but at different angles) to reduce the effective feedback and hence increase in lasing threshold.

At the maximum launched pump power of 127.5 W, the 1 μm signal output (generated by the Yb^{3+}-ion) was less than 1.6 W from the angle-polished fiber end (A) and was negligible from end B, resulting in a 1 μm to 1.55 μm output power ratio at the extraction end A of only ~4%, which is much lower than the case we described above with both fiber ends perpendicular cleaved (~34%). This suggests that the 1 μm parasitic lasing in high power Er,Yb-doped laser system may be alleviated using angle cleaved/polished fiber ends [18].

3. Conclusion

In conclusion, we have demonstrated high power, efficient and broadband operation of a cladding-pumped Er,Yb-doped fiber superfluorescent source. 16.1 W of single-ended ASE output power was obtained at a launched pump power of 59.5 W, corresponding to a slope efficiency of 30.7% with respect to the launched pump power. The bandwidth and spectra profile of the superfluorescent source are almost independent of the power level with the wavelength range spanning from ~1531 nm to 1568.5 nm and a bandwidth (FWHM) of 17 nm. Further scaling in ASE output power should be possible by further reducing the effective optical feedback from fiber end facets. The availability of high power and broadband sources with good beam quality and power-independent spectrum profile should benefit a range of applications.

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