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AN 8-CORE ERBIUM-DOPED FIBER WITH ANNULAR DOPING FOR LOW GAIN COMPRESSION IN CLADDING-PUMPED AMPLIFIERS

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Abstract

We design, simulate and characterize an 8-core cladding-pumped EDFA with annular doping. Gain compression <1.8 dB and minimum gain >12.2 dB over the C-band are demonstrated when the total input power varies between -23.1 dBm and 1.4 dBm

1 Introduction

New modulation format and elastic optical bandwidth are the two main strategies currently used to push the capacity of optical networks to their limits [1]. One of the main issues with elastic optical networks (EONs) is that the output power per channel of erbium doped amplifiers (EDFAs) is affected by its total input load, leading to gain variations when channels are added or removed [2]. To solve this issue, optical-gain-clamping and pump feedback are well known techniques for gain-control of EDFAs under changing input power conditions [2]. With their low gain compression, cladding-pumped EDFAs with annular doping have recently been proposed as a low component count alternative to traditional gain-control systems [3]. In this paper, we demonstrate the first multicore erbium-doped fiber (EDF) with an annular doping region located in the cladding (Figure 1). This fiber was designed specifically to offer low gain compression for applications in EONs. We first characterize the parameters of the fabricated fiber and present measurements of spectral gain (G) and noise figure (NF) when a single core is loaded with input channels. The extracted parameters are fed to a numerical model and simulated gain and NF are compared to experimental results.

2 Fiber fabrication and characterization

To achieve low gain compression, the EDFA must operate in an unsaturated regime. This is achieved by placing the region doped with erbium ions (Er^{3+}) in the evanescent tail of the LP_{01} mode field of the signal, i.e. where its intensity is low. Since the Er^{3+} population saturation depends on the local signal intensity, this design allows reaching higher total signal power compared to traditional core doping designs [3]. In the present design, the doped region is located in an annular region of the cladding, at a radial position between r=5.2 µm and r=8 µm. During fiber fabrication, because aluminium oxide (Al_2O_3) is incorporated in the silica glass to increase the solubility of Er^{3+}, the local refractive index of the doped region is increased. The main challenge in the optimization of this fiber then becomes to design the refractive index profile so that the signal stays strongly confined in the central part of each core, while remaining singlemode. The further the doped region will be from the core, the lower the gain compression will be, but more precision will be required during fabrication to control the mode profile and a longer fiber length will be required.

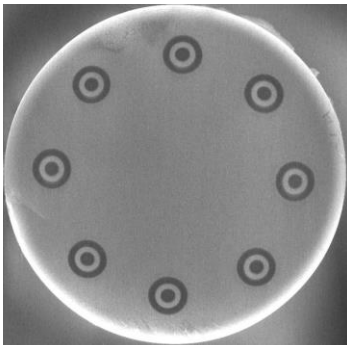

Fig. 1 Cross-section of the 8-core erbium-doped fiber with annular doping in the cladding and with a core-to-core distance of 38.25 µm

We modified the fabrication method described in [3] by incorporating an additional SiO_2 layer between the core and the doped region. Figure 2 shows the refractive index profile measured on the preform and scaled to the fiber dimension (solid blue), the Er^{3+} concentration profile measured on the preform using an electron micro-probe analyzer (solid green), and the fiber mode simulated from the measured refractive index profile using COMSOL (dashed black). The increase of the local refractive index in the doped region is clearly visible. Also shown is a fit to the Er^{3+} doping profile that is used in the simulations (dashed green).

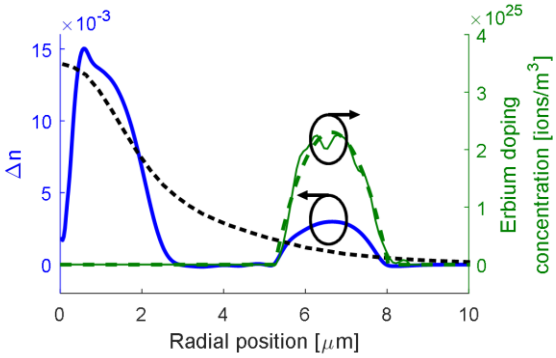

Fig. 2 Measured refractive index profile Δn (blue), measured (solid green) and fitted (dashed green) Er^{3+} doping concentration profile, and calculated mode profile at 1530 nm (dashed black)

To fabricate the multicore EDFA, the preform was cut in 8 parts of equal lengths and inserted in each of the 8 drilled holes of a silica rod. The optical fiber was drawn with a cladding diameter of 140 μm and coated with a low-index polymer (n=1.37) for cladding pumping. We characterized the absorption and emission cross-sections of each core from absorption measurements over a short fiber length (see [3] for more details). Due to the small overlap between the signal mode and the Er^{3+} doping, the measured peak absorption at 1532 nm varied between 1.86 and 2.31 dB/m, depending on the core. This variation leads to uncertainty in the calculated absorption cross-sections at 1532 nm that was estimated between 5.96×10^{-25} and 7.39×10^{-25} m^2. The pump absorption cross-section was 1.42×10^{-25} m^2 at 978 nm.

3 Numerical model

For the simulations, we used the standard EDFA set of population rate equations and power propagation equations with a radial resolution of 0.1 μm near the cores (up to a radial distance of 10 μm from the center of the cores). We considered pump absorption due to the presence of all cores as in [4]. For this fiber, we also included the impact of Er^{3+} pair-induced quenching [5]. This had to be taken into account because we used a low Al_2O_3 concentration in order to limit the refractive index change in the doped region located in the cladding.

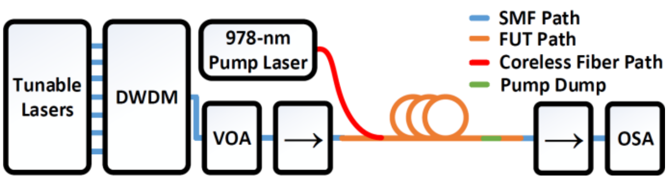

Fig. 3 Experimental setup used to measure gain and noise figure.

4 Experimental results

The experimental setup used to measure gain and noise figure is shown in Figure 3. From initial simulations, we estimated that the optimal EDF length was 23 m and used this length for the experimental setup. With active alignment, we spliced SMF pigtails at the input and output of one of the cores of the 8-core fiber. Using a 1300-nm laser source and an optical spectrum analyzer (OSA), we measured a total loss of 1.4 dB, including the two splices and connectors. The output fiber of a 978-nm pigtailed laser diode (105/125 μm) was tapered and rolled around an uncoated part of the 8-core EDF to couple the pump power into its cladding. To emulate multiple channels over the C-band, seven tunable lasers were set to seven wavelengths, evenly distributed over the C-band (1529.55, 1535.05, 1540.55, 1545.33, 1550.13, 1555.75 and 1559.80 nm). All channels had the same power and the variable optical attenuator (VOA) was adjusted to vary the total input signal power of the core under test. After the splice, considering the measured loss, the input power range was between -23.1 dBm and 1.4 dBm. Assuming an 80% coupling efficiency, the injected pump power was set to 8, 12 and 20 W. The pump power coupling efficiency was estimated by cut-back once the characterization was completed. The measured G and NF are shown in Figure 4. In order to help in extracting parameters related to pump loss, we also measured output pump power as a function of input pump power with a large area power meter placed 1.5 cm from the fiber output. We repeated this experiment with different fiber lengths as shown in Figure 5.

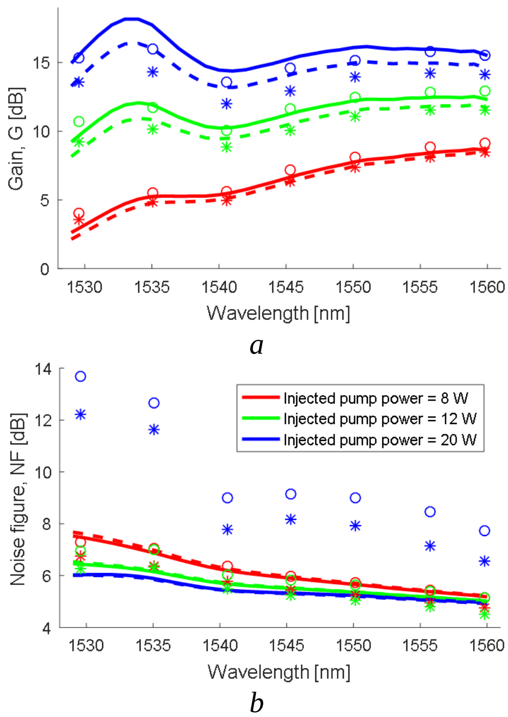

Fig. 4 Simulation/experimental results for the gain, G (a) and noise figure, NF (b) when one core is loaded with signal input power of -23.1 dBm (solid line/circle) and 1.4 dBm (dashed line/asterisk) for injected pump power of 8 W (red), 12 W (green) and 20 W (blue)

5 Simulation results

For the simulations, we used the measured profiles shown in Figure 2 to evaluate the signal and ASE overlap in the EDFA model with radial resolution. We also used the extracted absorption and emission cross-sections (absorption cross-section of 6.30×10^{-25} m^2 at 1532 nm for the core of interest). The fiber length is set to 23 m, the signal input power is swept between -23.1 dBm to 1.4 dBm, and the injected pump power is set to 8, 12 and 20 W. The lifetime of the Er^{3+} upper metastable level is set to 10 ms. In the simulations, the total signal input power is evenly distributed over 32 channels spaced by 1 nm between 1529 and 1560 nm.

Before performing simulations of G and NF, we simulated the experiment shown in Figure 5 (pump transmission without input signal power) in order to extract the pump background loss, α_p, the overlap between the pump and the doping, Γ_p, and the fraction of paired ions, k. For the overlap between the pump and the doped region, rather than uniform pump distribution, we considered that the pump power was slightly (25%) higher in the ring. This was observed using an infrared camera and a 980-nm notch filter to image the fiber output. Since the fraction of paired ions was the only parameters that had a significant impact on the gain measured with 20 W of injected pump power (Figure 4a), it was fitted to k=18%. Then, α_p was adjusted to α_p=0.052 dB/m based on the output pump power experimental results shown in Figure 5. This pump background loss is in agreement to values generally found in the literature. As discussed previously, the high value of the fraction of paired ions can be explained by the low concentration of Al_2O_3 that was used, i.e. 16000 mole ppm, which is only 32 times the Er_2O_3 concentration of 500 mole ppm. Higher aluminium/erbium ratios are usually used to lower the fraction of paired ions, i.e. a ratio of approximately 100 maintains the fraction of paired ions below 6% [6]. In ions pairs, only one of the ions can occupy the excited state leading to decreases in the gain, especially at high pump powers [5]. Ion pairs should thus be minimized but, in the present case, because the Al_2O_3/ Er_2O_3 are introduced in the cladding, there is a trade-off between quenching and index change.

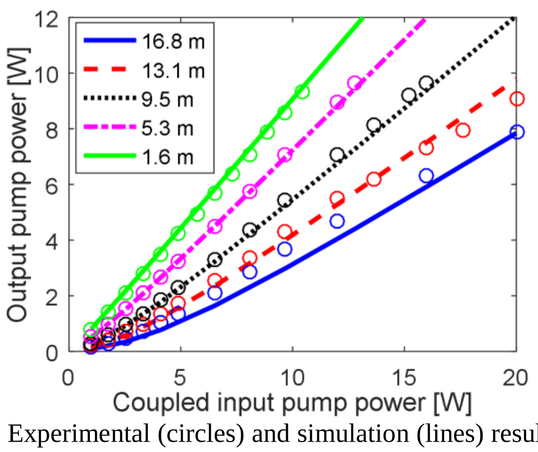

Fig. 5 Experimental (circles) and simulation (lines) results for the output pump power (without any input signals) when the injected pump power is varied between 1 and 20 W and the fiber length is varied between 1.6 m and 16.8 m.

6 Discussion

The simulations (lines) are compared to experimental measurements (symbols) of spectral gain in Figure 4a. The results are obtained with one core loaded with signal input power of -23.1 dBm (solid line/circle) and 1.4 dBm (dashed line/asterisk) for three pump power. A gain of 12.2 dB is obtained with a gain compression less than 1.8 dB with total input power up to 1.4 dBm. The spectral gain measurements agree well with simulations results with a maximum gain difference of 1.8 dB. The agreement is also good with the simulated output pump power represented in Figure 5 with a maximum output pump power difference of 0.8 W.

There is an important difference between the measured and simulated NF at 20 W of injected pump power. Note that we spliced a standard single-mode fiber (diameter of 125 µm) at an offset to the 8-core fiber (diameter of 140 µm). This creates some spurious reflections. The reason for the discrepancy is under investigation; we think that it could be related to reflections as lasing was sometime observed, or build-up of ASE in the fiber cladding.

7 Conclusion

We designed and characterized one core of an 8-core fiber with annular erbium doping. Despite a high fraction of ion pairs due to the low Al_2O_3 concentration, we demonstrate that the approach allows the EDFA to operate in an unsaturated regime over a wide range of input powers. More specifically, we achieved a minimum gain of 12.2 dB, with 1.4 dBm of total input power in the loaded core, and with a maximum gain compression of 1.8 dB over the C-band for input power varying between -23.1 dBm and 1.4 dBm.

8 Acknowledgements

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9 References

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