Characterization of an Aluminophosphosilicate Fiber with Annular Erbium Doping for Improved Performance of Cladding-Pumped Amplifiers

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Abstract A single-core fiber with annular erbium doping is investigated to improve the performance of unsaturated cladding-pumped amplifiers. Aluminophosphosilicate reduces the number of ion pairs and a modified refractive index profile slightly enlarges the mode, thus leading to smaller fiber length and improved noise figure.

Introduction

In elastic optical networks (EONs), channel rerouting often leads to large input power variations in the erbium doped fiber amplifiers (EDFAs) of reconfigurable add-drop multiplexers. Under these conditions, the use of dummy channels or feedback-controlled pumps are necessary in order to maintain a constant gain over the whole wavelength range[1]. In these systems, using integrated multi-core cladding-pumped amplifiers could be advantageous to reduce volume, component count and overall cost compared to multiple single-core EDFAs. In these integrated amplifiers, an alternative strategy to lower gain variations is to operate them in an unsaturated regime[2],[3]. This is enabled by the use of cladding pumping that provides more freedom in the placement of the erbium-doped region. In particular, an annular doped region located in the cladding, where the signal intensity is smaller, lowers gain saturation.

Recently, we demonstrated an eight-core cladding-pumped amplifier designed to decrease the gain variations in EDFAs [3]. The goal is to avoid, or reduce, the requirements of current gain-control techniques. One issue with annular doping is the need for a highly doped, low-index annular region in order to obtain sufficient gain, considering the low signal overlap with the doped region[3]. In highly doped fibers, Al_2O_3 is commonly added to silica to increase rare-earth ion solubility, which unfortunately causes an increase of the refractive index that can lead to the presence of higher order modes. In [3], we thus limited the Al_2O_3 concentration and the estimated fraction of paired ions was 18%. Another issue was a significant degradation of the noise figure (NF) compared to the simulations that was caused by the presence of ASE in the guiding cladding. In this paper, we propose to improve the fiber design by i) using aluminophosphosilicate to lower the refractive index change of the doped region while allowing a high doping concentration with a lower fraction of paired ions[4],[5],[6]; and ii) tailoring the refractive index profile to decrease the required fiber length and, consequently, the ASE in the cladding. To validate this approach, a single-core fiber with annular doping in the cladding was designed, fabricated and characterized. Its absorption/ emission properties are used in numerical simulations and results are compared to measurements of gain and NF with cladding pumping. We show that the fraction of paired ions is significantly reduced and NF is improved.

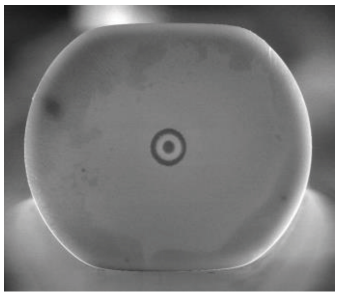

Fig. 1: Cross-section of the fabricated single-core erbium-doped fiber with annular doping

Fiber fabrication and characterization

The preform fabrication method (described in [3]), consisted of using the solution doping method for the doped region in the cladding and the modified chemical vapor deposition method (MCVD) for the core made of germanium-doped SiO_2. In the present case, P_2O_5 was added to the solution with Er_2O_3 and Al_2O_3. An electron micro probe analyzer was used on a preform sample to determine the concentration of Al_2O_3, P_2O_5 and

Er_2O_3 in the doped region: 23000 ppm, 14000 ppm and 500 ppm, respectively. In our previous work[3], these were respectively 16000 ppm, 0 ppm and 500 ppm. The addition of P_2O_5 allows to increase the concentration of Al_2O_3 without the detrimental effects of an increase in the refractive index [4],[5],[6]. The preform is polished on two sides to obtain a double-D shaped fiber (cladding diameters 105.8/122.5 μm) shown in Fig. 1. The fiber is drawn with a low-index polymer coating to allow cladding pumping.

The refractive index profile of the preform was measured using a refracted near-field analyzer (NR-9200HR, EXFO) at 657.6 nm. Knowing the diameter ratio of the preform and fiber, we calculated the mode profile at 1530 nm using COMSOL. The refractive index and mode profiles are presented in Fig.2 that compares this new single-core fiber to one core of the 8-core fiber in [3]. Due to the P_2O_5, the refractive index change of the doped region is lower, although the Al_2O_3 concentration is 1.44 times higher. Also, the core Δn was decreased to slightly increase the mode radius and the overlap with the doped region. This leads to higher gain and allows to reduce the fiber length, which decreases the amount of ASE in the cladding at the fiber output. The absorption cross-sections were measured by cutback using a filtered supercontinuum laser source (1350 nm to 1700 nm); the emission cross-sections were calculated using McCumber's equation.

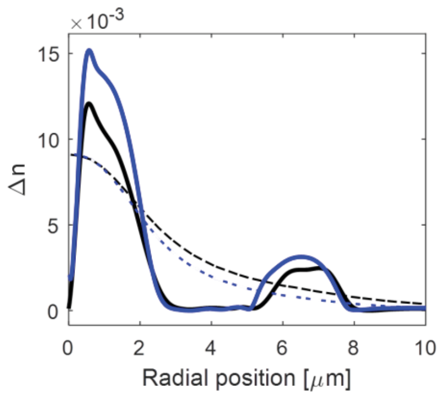

Fig. 2: Measured refractive index profile Δn (solid) and calculated mode profile (dotted) of the proposed single-core EDF (black) and of one core the 8-core fiber in [3] (blue).

Numerical model

The absorption and emission cross-sections, the mode profile, and the erbium doping concentration profile were fed into the numerical model described in [3] (considering that only a single-core is present). The pump power distribution was assumed to be uniform over the cladding.

Experimental results

The spectral gain and NF, and the output pump power were measured as in [3]. To couple the pump power into the fiber cladding, we used the half-taper method described in [7]. For the gain measurement, the experiment was first conducted with an EDF length of 15.9 m and a total input signal power of -23.0 dBm to 1.5 dBm, distributed over 8 channels between 1528.8 nm and 1563.9 nm. Then, 2.9 m of fiber was removed and the experiment was repeated with 13.0 m of fiber length. The internal gain and NF results are shown in Fig. 4 for the two fiber lengths, the two total input signal power and three pump powers (8.5 W, 12.7 W, and 21.1 W). The measured input and output splice loss was 0.7 dB. Then, without touching the half-taper pump coupler, we cut the EDF to 12.9 m, 10.1 m, 7.0 m, 4.1 m and 0.5 m to measure the output pump power in the cladding with a free-space power meter (Fig.3). The coupled input power was assumed to be equal to the output pump power measured after 0.5 m (pump coupling efficiency ~ 85%).

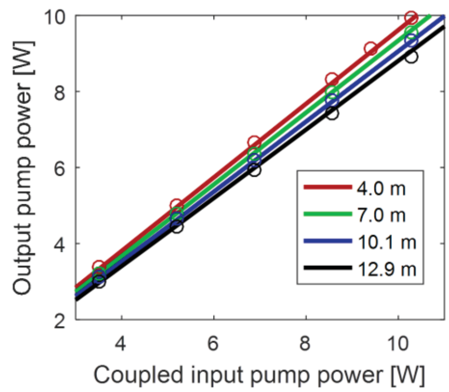

Fig. 3: Output pump power measured (circles) and simulated (lines) (without any input signals) as a function of input pump power for various fiber lengths.

Numerical simulation results and discussion

The simulations consider 36 channels uniformly distributed from 1529 nm to 1564 nm and the experimentally measured fiber lengths, coupled pump powers and total input signal powers. The pump background loss was estimated to be 0.028 dB/m by optimizing the fit between the simulations and the results in Fig. 3. A fraction of paired ions of 5% was determined by optimizing the fit of the simulations to the spectral gain measurement in Fig. 4, which is an important improvement with respect ot 18% in [3] for similar erbium concentration. This can be explained by the combination of Al_2O_3 and P_2O_5 which has been linked[4],[5] to the formation of $AlPO_4$ that has a structure and a Δn similar to SiO_2.

Experiments and simulations are in good agreement with differences <1.0 dB for NF and <3.0 dB for gain. In [3], significant NF disagreement between experimental results and simula-

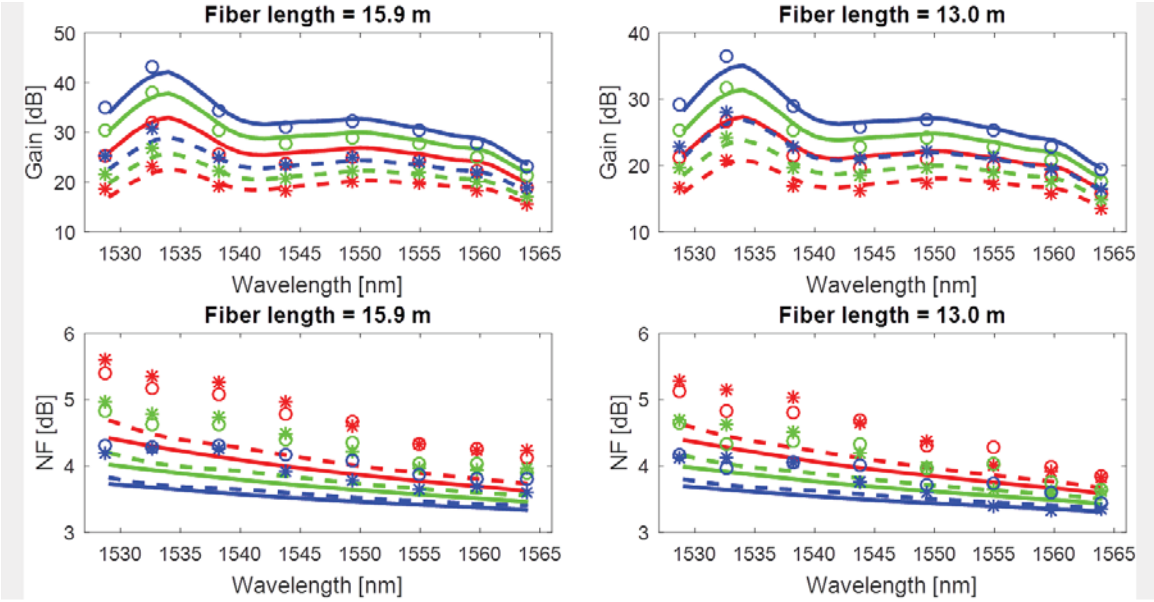

Fig. 4: Simulation/experimental results for the gain and NF when the doped fiber length is 15.9 m and 13.0 m, the core is loaded with signal input power of -23.1 dBm (solid line/circle) and 1.4 dBm (dashed line/asterisk) for injected pump power of 8.5 W (red), 12.7 W (green) and 21.1 W (blue)

tion results were observed and were associated with the presence of ASE in the cladding (NF>7 dB when the pump power is 20 W). This disagreement is not observed in the present case where NF difference between measurements and simulations <1 dB is observed even at the high pump power of 21.1 W (see Fig. 4). This improvement is mainly due to the lower core Δn that leads to a slightly larger mode and increased overlap with the doped ring. This in turn results in a shorter length of fiber being required to reach a given minimum gain over the C-Band. According to simulations, with this new fiber, the same gain compression as in [3] (<1.8 dB) would be achieved under the same scenario: 8 cores sharing 20 W of injected pump power, one core under load with an input power range of -23.1 dBm to 1.4 dBm. This scenario provided a minimum gain of 12.2 dB over the 1530 nm to 1560 nm spectral region. Thus, the higher gain compression shown in Fig. 4 results from the larger spectral region and a higher minimum gain. This paper demonstrates that the main issues previously encountered with annular doping can be addressed by careful optimization of the fiber design; both material and waveguide. We think that annular doping can be highly beneficial for many applications that require cladding-pumped amplifiers with low gain compression.

Conclusion

We fabricated and characterized a double-cladding single-core EDFA with alumino-phosphosilicate in an annular-doped region and a refractive index profile designed to reduce the NF degradations caused by ASE in the cladding. Through simulations and experiments, we show that the fraction of paired ions was significantly reduced and the excess NF caused by ASE in the cladding was reduced from >7 dB to <1 dB.

Acknowledgements

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