Experimental Validation of Highly Doped Erbium-Doped Fibre for the design of a +20 dBm, single pump and compact, WDM L-band EDFA

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Abstract *Highly doped EDFs with 13.4 to 34.7-dB/m absorption coefficients were inserted in a two-stage EDFA to enable a MSA-compliant packaging. Experimental validations led to the design of a low noise 20-dBm single-pumped WDM L-band EDFA*

Introduction

Compactness and power consumption are two important factors driving the current development of most fibre optic subsystems, including optical amplifiers. Integration of booster L-band WDM EDFAs within a MSA-compliant package (90x70 mm²) is primarily limited by the significant fibre length required for getting a low population inversion within the erbium doped fibre (EDF) [1]. Therefore the use of highly doped EDF becomes more and more attractive [2-3]. However, when used in EDFA designs, such fibres are known to degrade its efficiency due to a waste of pump photons originating from energy transfer between Er^{3+} ions known as upconversion processes [4-5], thereby requiring additional pump power to enable high gain amplification. The optimum design of a compact EDFA thus results in a compromise between fibre Er^{3+} ions concentration, coil length and number/power of pump diodes, but to our knowledge was never reached for a +20 dBm WDM L-band amplifier [6]. Recently however, 980-nm pump laser modules with kink-free output power up to 580-mW became commercially available, giving access to new designs of single pump EDFAs with highly doped EDFs.

In this paper, we report on the design of a low noise +20 dBm WDM L-band EDFA compliant with a MSA packaging and making use of a single high power single-mode pump diode at 980 nm. Double stage architecture with bi-directional pumping is chosen in order to optimise the amplifier efficiency and to achieve a low noise operation. Moreover this design enables the integration of the gain flattening filter (GFF). Two specific batches of highly doped EDFs with two different absorption coefficients each (13.5 and 21.5 dB/m, and 27 and 34 dB/m respectively) are experimentally assessed in the second stage. For each design, the pumping ratio is varied in order to optimise amplifier output power and noise figure.

Experimental Set-up

We used the generic double-stage EDFA configuration illustrated in Fig. 1a for our experimental study. The pumping scheme consisted in a co-propagating pumping in the first stage and a bi-directional pumping in the second stage thanks to the pump bypass. Different ratios of pump power were tested: 60/40, 50/50 and 40/60, where the first figure corresponds to the pump power injected in the co-propagating direction. The total power was in all cases no more than 500 mW (summed at the multiplexers' inputs).

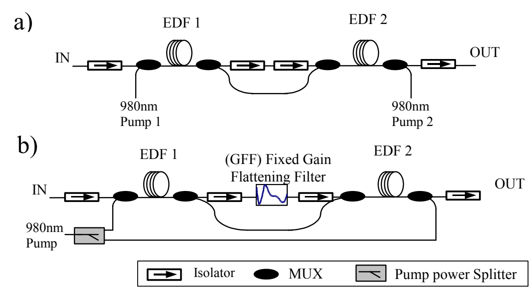

Fig. 1: Schematic diagrams of the L-band EDFA (a) preliminary design used for the experimental study - (b) final design including a single pump, a pump splitter and a GFF

The input, output and mid stage losses were respectively 0.5dB, 0.8dB and 0.8dB. On the pump path, the loss between the two stages was 0.6 dB.

The first stage consisted in a short piece of medium doped EDF providing 10-dB gain in the L-band, and four different Al/Ge highly codoped EDFs produced using MCVD technique were successively inserted in the second stage. The amplifier was tested using a WDM signal consisting in a 19-channel multiplex covering the L-band between 1569 and 1602 nm. In all cases, the signal input power was adjusted in order to achieve the 'flat gain' operation (external channel gains are equal).

First round design

We first used a commercial fibre (fibre#1) with an absorption coefficient of 13.4 dB/m at 1530 nm and inserted it into the EDFA (Fig. 1a). An output power of 20 dBm was obtained, but with a significant coil length (60m) that precluded any compact packaging possibility.

A second batch of fibre (fibre#2) with a higher absorption coefficient was then produced by increasing the Er^{3+} ions concentration, inserted into the EDFA, and its efficiency experimentally assessed with regards to the pump power ratio. Results and comparison between both fibres are shown in Fig.2 where the two fibres present a same total absorption of 811dB at 1530 nm.

Fig. 2 shows that the output power for both fibres gets stronger when the pump power ratio is moved to higher contra-propagating pump. Indeed, the conversion efficiency is better when the pump power is maximized in the region where the signal power is more important, as expected from [4-5]. However as shown in Fig.2, this pumping scheme is known to degrade the NF through ASE generation in the second stage, and there is therefore a trade-off limiting the ratio of pump power in the contra-propagating direction, depending on output power and noise figure requirements. In our case, the requirements for a +20-dBm output power and a maximum NF of 5.5-dB led to a maximum ratio of 60% for the contra-propagating pump power.

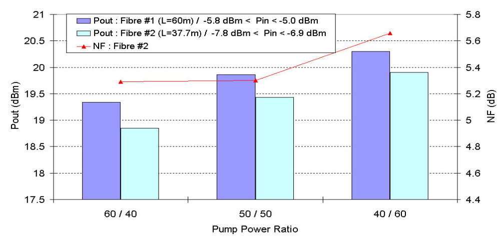

Fig. 2: EDFA maximum output power and NF with 500-mW pump power and for a flat gain operation

As can be seen on this figure, despite significantly reducing the coil length, fibre#2 could not allow to reach the required output power with the available pump, due to the higher Er^{3+} concentration degrading the conversion efficiency [4-6].

Second round design

In order to increase the absorption coefficient but with no penalty on the conversion efficiency, two batches of another type of EDF with new geometric parameters were then produced, their major specifications being detailed in Table 1. The cut-off wavelength and the core and erbium radii were modified in order to increase the overlapping of signal photons with excited Er^{3+} ions, which allowed to get a higher absorption coefficient with no significant increase in the Er^{3+} concentration.

Parameters	*Fibre #1*	*Fibre #2*	*Fibre #3*	*Fibre #4*
Peak Absorption @ 1530nm [dB/m]	13.4	21.5	27.5	34.7
Estimated erbium concentration [ions/m^3]	1.25 E+25	2.12 E+25	1.51 E+25	2.2 E+25
Effective numerical aperture	0.23	0.24	0.23	0.23
Cut-off wavelength [nm]	909	904	1420	1368
Gamma at saturation parameter wavelength	0.393	0.369	0.774	0.754
Core radius (µm)	1.51	1.45	2.18	2.21
Erbium radius (µm)	1.47	1.36	2.18	2.21
Mode field diameter (µm) @ 1553.7 nm	6.02	5.82	5.1	5.33

Table 1: Parameters of the fibres tested in the second stage.

Fibre#3 and fibre#4 were then inserted into the second stage of the L-band EDFA and their performances assessed. Results are shown on Fig. 3, where the two fibres present the same total absorption, that is again 811 dB at 1530 nm. As can be seen, fibre#3 allowed to reach the Pout and NF requirements with a further reduced fibre length. Indeed when compared to fibre#2, the lower Er^{3+} concentration was expected to reduce the upconversion processes, and thereby increase the amplifier efficiency. This was not the case for fibre#4 however, whose Er^{3+} concentration was very close to fibre#2.

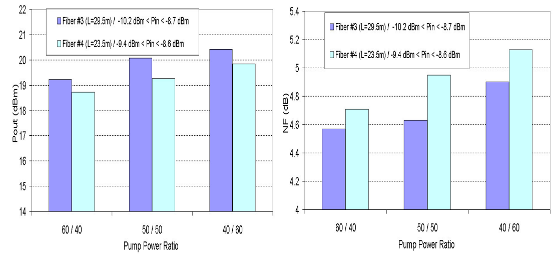

Fig. 3: EDFA maximum output power (left) and NF (right) with 500-mW pump power and for a flat gain operation

Validation setup

Based on the previous results, we implemented the fibre#3 in the final EDFA design (Fig.1b) using a home made GFF. The pump splitter had a splitting ratio of 46/54 with an excess loss for each branch of 0.4 dB. Setting a commercially available 580-mW 980-nm pump laser allowed the design of a WDM L-band EDFA with a 20.3 dBm output power and with a maximum NF of 5.2 dB as shown in Fig. 4.

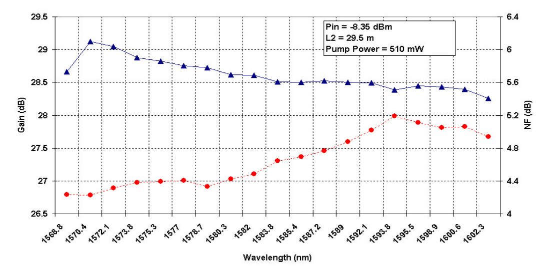

Fig. 4: Gain (triangles) and noise figure (dots) spectra of an EDFA using the fibre #3 in the second stage

Conclusion

An experimental assessment of highly doped EDF with several absorption coefficients for the design of single-pump, compact WDM L-band EDFAs has been presented. This work has led to the demonstration of a L-band EDFA with a total output power of 20 dBm, a NF lower than 5.5 dB for every WDM channel, a pump power lower than 600 mW and a coil length for the second stage lower than 30 m.

Acknowledgments

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