# Experimental Assessment of Highly Doped Erbium-Doped Fibers for WDM L-band Optical Amplifiers

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*L-band EDFAs require a low population inversion within the erbium-doped fiber (EDF) for a flat gain operation over the WDM band. When using standard EDF, this results in significant fibre lengths, increasing FWM penalties and raising issues for its packaging. Therefore, there is an interest for using short pieces of highly doped EDFs, which have been successfully used for making single channel high power C-band EDFAs and fiber lasers. We provide for the first time to our knowledge an experimental assessment of EDFs with absorption coefficients ranging from 13.4 to 34.7 dB/m (at 1530 nm) for L-band WDM amplification.*

## Introduction

The compactness becomes an important factor in the development of the fiber-optic components, notably of EDFA. For L-band WDM amplification, the fiber length is the main element limiting the minimization of the EDFA's size. Therefore, the use of highly doped EDF becomes more and more attractive. However, such fibers, when used in EDFA designs are known to damage its performances due to energy transfer upconversion between $Er^{3+}$ ions. Various experimental and theoretical studies already reported the impact of $Er^{3+}$ concentration on the performances of mono-channel C-band EDFA [1-4] and new host materials, such as lanthanum-codoped bismuth-based erbium-doped fiber [5], tellurite-based fiber [6] and phosphorous-codoped silica based fiber [7] were shown to improve the amplification performances beyond 1580 nm. However, these materials have serious problems for practical applications, such as large splicing loss and high Noise Figure (NF). Therefore alumino-silica based fiber remains an attractive host material; the optimization of doping processes such as nanoparticle technologies [8] or MCVD, allowing higher erbium concentration and a limitation of upconversions by a better control on doping uniformity. In this paper, we present an experimental assessment of highly doped EDF with several absorption coefficients for wavelength division multiplexing (WDM) L-band amplification applications. A similar experimental study was led for WDM C-band applications [9]. We compare them in terms of pump power efficiency.

## Fibers Characteristic and Experimental Setup

The Al/Ge codoped EDFs used in the experiment are commercially available and have been manufactured using MCVD technique. Their data referring were provided by Coractive and are shown in Table 1.

| ***Parameters*** | ***Fiber #1*** | ***Fiber #2*** | ***Fiber #3*** |
|---|---|---|---|
| Peak Absorption @ 1530nm [dB/m] | 13.4 | 21.5 | 34.7 |
| Background Loss @ 1200nm [dB/km] | 3 | 13.5 | 15.9 |
| Estimeted erbium concentration [ions/m$^3$] | 1.2 E+25 | 2.1 E+25 | 2.2 E+25 |
| Effective numerical aperture | 0.23 | 0.24 | 0.23 |
| Cut-off wavelength | 909 | 904 | 1368 |
| Gamma at saturation parameter wavelength | 0.393 | 0.369 | 0.754 |
| QCE @ 1532 nm (pump at 980 nm) | 74.8 | 68.0 | 73.8 |

Table 1: Parameters of the fibers tested

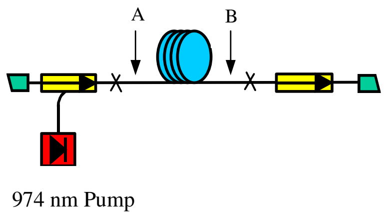



Figure 1: Experimental setup

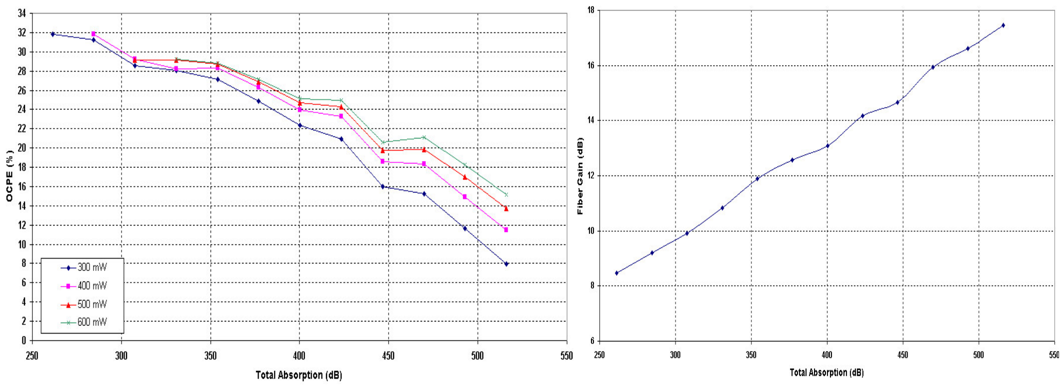
We worked on the generic experimental setup described in Figure 1. A co-propagating 974-nm diode laser pumped the fiber. We have measured the amplifying characteristics of those fibers for several lengths and pump powers. For the shake of clarity we have presented the fiber lengths in term of total signal absorption at 1530 nm. The input power was constituted of 20 WDM channels between 1569nm and 1602nm. For each total absorption and each pump power, the input power was adjusted in order to equalize the gain levels at 1569nm and 1602nm to minimize the gain excursion over the L-band. Therefore, the gain values mentioned in this paper correspond to the minimum fiber gain over the full spectral band. The fibers are compared in term of optical power conversion efficiency (OPCE) defined as

$$OPCE = \frac{P_{SigOut} - P_{SigIn}}{P_{PumpIn}}$$

Where $P_{SigIn}$ and $P_{PumpIn}$ are respectively the signal and pump powers launched into the doped fiber (A) and $P_{SigOut}$ is the signal power at the output of the doped fiber (B).

## Results and Discussion

Figure 2 shows the OPCE and the fiber gain as a function of total absorption, for four pump powers. For the shake of clarity, we have presented the results for the fiber #2, the behavior of the others fibers being very similar.



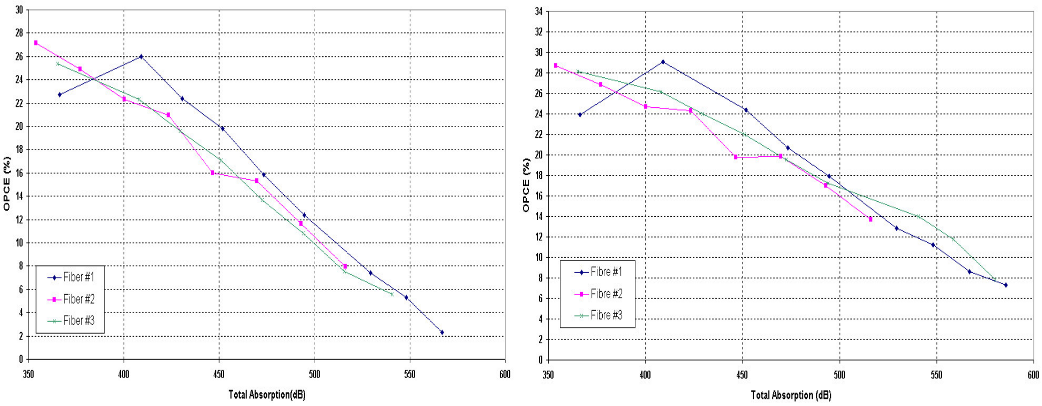

(a) (b)

Figure 2: OCPE (a) and Fiber Gain (b) of Fiber #2 as a function of total absorption for different pump powers.

We can observe that the OPCE increases when both total absorption decreases and pump power increases until an optimum length at which the OPCE is maximized. The optimum was reached only for fiber #1 but could not be reached for the other fibers due to limitied input power required to achieve flat gain operation. This behavior had already been reported by R.I. Laming et al [10], but for power amplifier in the C-band region.

We can show that the OPCE variation with pump power increases with the total absorption. Indeed, from the figure 2, we can derive the following results: at 495-dB absorption (corresponding at 16.7-dB fiber gain), the OPCE variation between 300 and 600 mW pump power is 6.6%, while at 330 dB absorption (10.8 dB fiber gain), the variation is 1% between the same pump powers.

The measured OPCE as a function of the total absorption and for the different fibers are plotted in the Figure 3. Results are shown for pump powers at 300 mW (a) and 500 mW (b). From these figures, we can notice that the fibre #1 has a better OPCE for a total absorption higher than 410 dB (13 dB fibre gain) corresponding to his optimal absorption. At this point, the variation of OPCE between fiber #1 and fiber #3 is maximized and is 3.74 % and 2.96 % for 300 mW and 500 mW pump power corresponding to a degradation in output power of 0.7 dB and 0.45 dB respectively.




(a) (b)

Figure 3: OPCE of three fibers as function of total absorption for (a) 300 mW and (b) 500 mW pump powers.

For a total absorption of 470 dB, corresponding to an equalized gain fiber of 16-dB, the fiber with 34.7 dB/m has an OPCE degradation of 1.2 % in comparison with the fiber with 13.4 dB/m for 500mW pump power. This variation corresponding to a degradation in output power of 0.26 dB. The fiber #3 offers thus a good trade-off between the reduction of both efficiency and length.

In table 1, the estimated values of erbium concentration of both fibers #2 and #3 are equivalent, but the fiber #3 has an overlap intergral more important than the fiber #2. Therefore, fiber #3 has an absorption coefficient, which is larger than fiber #2, without the upconversion process increasing. As a result of this, the OCPE is not damaged between these fibers as shown in figure 3.

Figure 4 shows the normalized gain and noise figure spectrum for three fibres. All the fibers display a flat gain and the noise figure is not damaged for a fiber with 34.7dB/m.

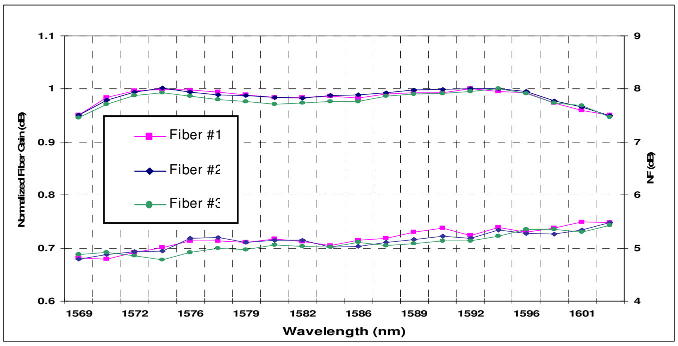



Figure 4: Normalized fiber gain and Noise Figure spectrum (pump power = 500 mW and Total Absorption = 495 dB)

## Conclusions

Measurements of OPCE for various highly doped alumino-silica fibers indicate that a fiber with 34.7 dB/m allows to shorten the fiber length without important degradation of the EDFA efficiency. Indeed, for 16 dB fiber gain, the use of 34.7-dB/m fiber instead of 13.4-dB/m allows to reduce the fiber length by a factor 2.5 with a degradation of OPCE less than 1.5 % corresponding to a degradation in output power of 0.26 dB. Reducing the fiber length is an important condition for the realization of compact EDFAs.

## Acknowledgement

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