Wideband Erbium-Doped Fiber Amplifier System Design Limitations due to C-band Signal Power Injection

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***Resumo* - Neste artigo observamos experimentalmente os efeitos do bombeamento na banda espectral C no desempenho de um Amplificador de Fibra Dopada com Érbio (EDFA) de banda L. Foi, também, implementado um amplificador para as bandas C+L numa configuração paralela de dois EDFAs, são estudadas as implicações inerentes da aplicação desta configuração a sistemas de comunicação por fibra óptica. Uma nova configuração é apresentada para resolver parte dos problemas causados pela dependência do ganho na banda L da potência na banda L.**

***Abstract* – In this paper we observe experimentally the effects of C-band pump light in the performances of an L-band Erbium-Doped Fiber Amplifier (EDFA). An amplifier for C+L-bands in a parallel configuration of two EDFAs is designed, and the inherent implications in its application to optical fiber communications systems. A new configuration is presented for decreasing the signal gain dependence in the L-band on the C-band residual power.**

I. INTRODUCTION

Speed and capacity are the nowadays-main concerns when developing a telecommunications system. The demand of high-speed transfer of a large amount of information at the same time in a unique medium requires the utilization of the low loss bandwidth of an optical fiber. That is one of the main reasons why the Wavelength-Division-Multiplexing (WDM), where we can join in the same fiber a large number of channels in different wavelengths, is a growing technology. This technique is feasible due to the 100 nm low loss fiber bandwidth around the 1550 nm telecommunications 3 rd window. But as in any medium the signal travelling along an optical fiber suffers from attenuation and the need for restoration requires the use of an optical amplifier. It is well known that one of the most used optical fiber amplifier actuality is the EDFA since its operating wavelength coincides with the third window for optical fiber communications. However, in its basic fabrication, an Erbium-Doped Fiber (EDF) can present a good gain level in the range of 1530 to 1560 nm (C-band), which is very limited if we think of all the bandwidth available in a normal fiber for signal transmission, for this reason, it is of great importance to explore other bands, namely the S-band (1480 - 1520 nm) and the L-band (1570 - 1610 nm) [1]. In the latter, we still can make use of EDF to implement gain-flattened amplifiers [2], however it works at relatively low average inversion level (30%~40%) and the Pump Conversion Efficiency is (PCE) relatively low.

L-band EDFA using auxiliary C-band pumping allows a low-noise operation as was reported by J. F. Massicot [3], while the gain could be enhanced or decreased, depending on the injected C-band laser wavelength and power [4]. In order to improve PCE of EDFA the use of Double Pass Configuration is being used [5], resulting in high-gain amplifiers with low pump power and short EDF [6], which is desirable to develop practical and affordable products.

In this perspective, a wide C+L-band EDFA can be implemented also in parallel [7] or in a serial structure [8], widening in this way the transmission and increasing the capacity in a WDM network (see Figure 2).

In parallel configurations is desirable to split (Splitter) power over the C/L bands and treat them separately to later combine them (Combiner) and obtain the power over all spectrum [9].

In this paper we present a design of a C+L-band EDFA in parallel using a C/L-band combiner/splitter, and analyze L-band limitations due to the presence of C-band signal in concatenated EDFAs systems.

II. CONCATENATED ERBIUM-DOPED FIBER AMPLIFIERS

The propagation of signal and noise in concatenated optical amplifiers is dependent on the properties of the amplifier and on the system design. Gain saturation in a EDFAs at any stage can be caused by the extraction of power from the amplifier by the Amplified Spontaneous Emission (ASE), the signal gain and the ASE from previous stages, shown in Figure 1. At the i^{th} amplifier the total output powers of the ASE and signal are given by (1) and (2) respectively, whereas the total EDFA power output is given by (3). In this equations L is the total loss in the transmission span, G_i is the gain, n_{sp} is the spontaneous noise factor, B_o is the optical filter bandwidth, ν_s is the signal frequency, and h is the Planck's constant. Note that $P_{s,0}$ is the transmitter output power and $P_{out,0} = P_{s,0}$.

$$P_{ASE,i}^{tot} = LG_i P_{ASE,i-1}^{tot} + 2n_{SP}(G_i - 1)h\nu_s B_o \qquad (1)$$

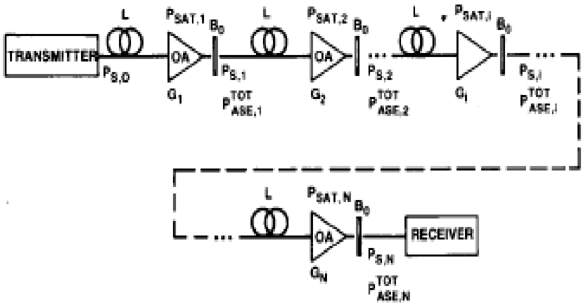

Fig. 1 - Concatenated amplifier model. Amplifier gain is G_i, saturation power is P_{sat}, the total loss in transmission span is L, and the optical filter is B_o.

$$P_{s,i} = LG_i P_{s,i-1} \tag{2}$$

$$P_{out,i} = LG_i P_{out,i} + 2n_{SP}(G_i - 1)h\nu_s B_o, i = 1, n \tag{3}$$

The amplifier gain can be written as (4), where G_o is the unsaturated gain, P_{in} is the total power at the input of the EDFA, and P_{sat} is the saturation power. In this equation when $G = G_o/2$ then $P_{out} = 0.69P_{sat}$, for $G_o >> 1$.

$$G = G_o \exp[(1 - G)P_{in} / P_{sat}] \tag{4}$$

Based on this transmission model and relationships, which could include some simplifications, it is possible to design and implement concatenated EDFA systems [10].

III. Experimental Setup

The experimental setup displayed in figure 2 consists of two EDFAs and a C/L-band combiner/splitter from TeraFiberoptics. For the C-band, we used a commercial EDFA from Photonetics FIBERAMP-BT1300, and for L-band we used a laboratorial prototype based on a bi-directional pumping scheme, with two 980/1550nm WDM to couple the signal and the pump, two 190 mW maximum output power optical pumps operating at 980 nm and one optical isolator for protection. This L band amplfier takes advantage of high erbium (Er^{3+}) concentration in the specially designed fiber from Sumitomo®, having only 30 m of fiber length while for this kind of experiment the need of at least 70 m have been reported.

For normal EDF, the absorption and emission coefficients of the fiber used were provided by Sumitomo®, being the main gain parameters described in Figure 3. It can be seen from this figure that this fiber was specially designed for L band amplification since it

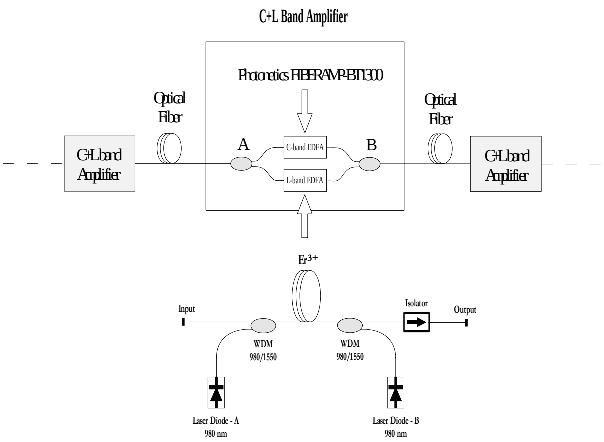

Fig. 2 - C+L band Amplifier setup; A - C/L band splitter; B - C/L band combiner.

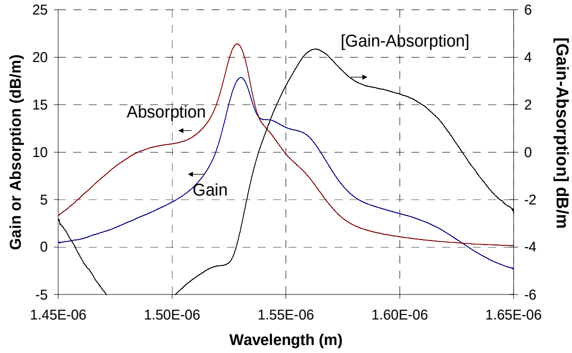

Fig. 3 - Absorption, Gain and Gain-Absorption of Sumitomo® available fiber.

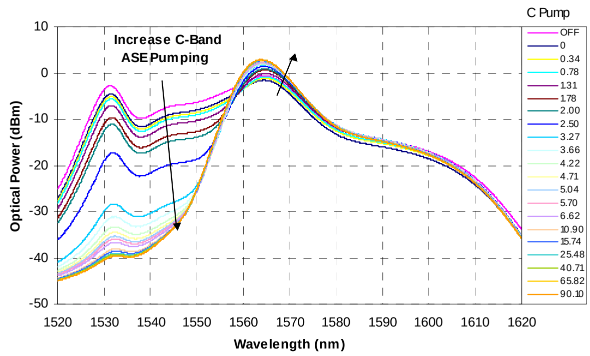

Fig. 4 - ASE spectra of the prototype EDFA for increasing C-band ASE pumping power from a commercial C-band EDFA.

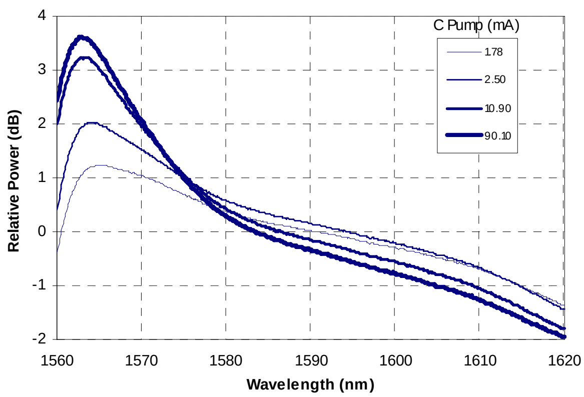

Fig. 5 - ASE in L-band relative to the spectrum without C-band pump for different C-band pump powers.

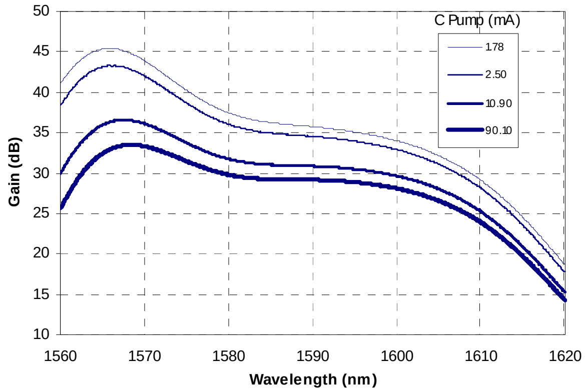

Fig. 6 - Gain in L-band for different C-band pump powers.

allows, for fully inverted population, higher gain than absorption in the 1538-1628 nm range. However, it presents a cut-off wavelength at 1460 nm, which causes a decrease in the 980 nm pump efficiency due to the multimode light propagation, and ensures low inversion. Instead of 120 dB for the 30 m fiber we will have around 20-30 dB of gain in L-band for dual pump full power pumping at 980 nm. Besides presenting a good gain level, this fiber is strongly wavelength dependent, as all EDFs usually are. Defining now the Gain Tilt as the difference between the maximum and the minimum gain in the considered wavelength range for a given fiber length, we see also from Figure 3 that there is already a ~1.5dB/m of Gain Tilt in the 1570-1600 nm range, which is quite significant.

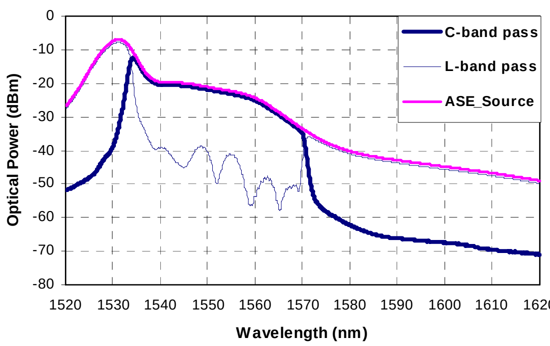

Fig. 7 - ASE source testing the EDFA for C+L-bands using a C/L-band combiner/splitter.

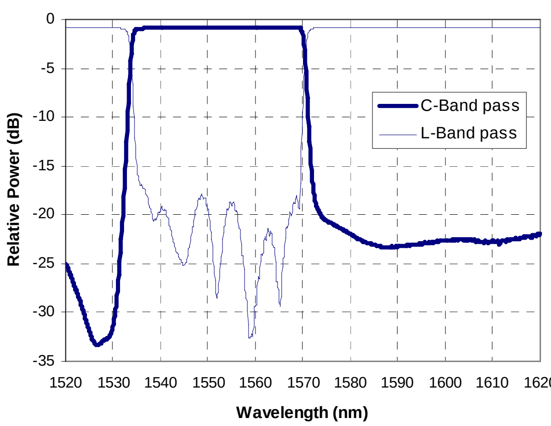

Fig. 8 - Transfer function of C/L-band combiner/splitter.

III: Results and Discussion

We begin by analyzing the dependence of C-band pumping in L-band ASE and what influence could it be in a concatenated system.

In Figure 4 we show the spectrum when C-band light is injected in our experimental L-band EDFA, for increasing power. As it can be seen, the increase of the C-band power increases ASE in the L-band. The detailed increase of ASE in L-band with respect to the spectrum without any C-band pumping is presented in Figure 5. In Figure 6 it is shown the gain saturation due to ASE increase. We can see that a decrease of 6dB in the L-band gain occur, reducing the Gain Tilt, however for concatenated EDFAs this ASE will grow faster saturating the EDFAs and degrade the OSNR.

In order to implement a wideband amplifier, we tested

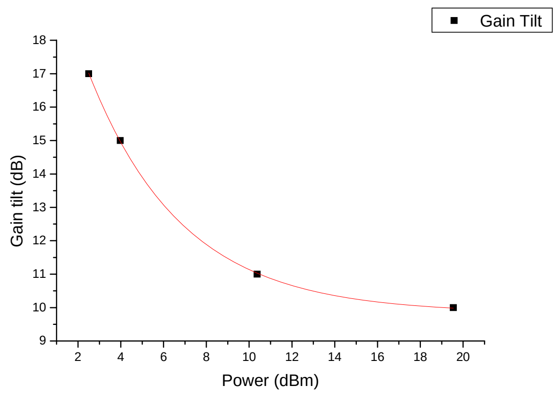

Fig. 9 - Gain tilt of the amplifier in the L-band as a function the C-Band average power.

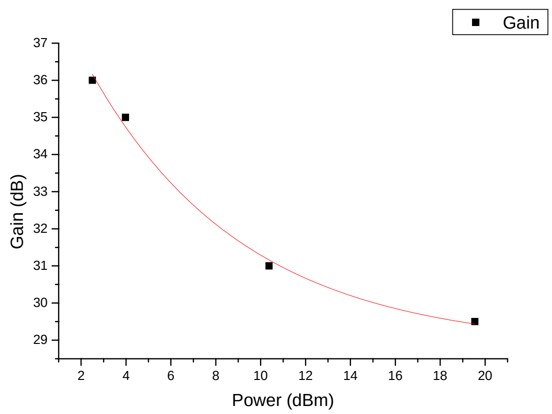

Fig. 10 - Average gain for the L-band as a function of the C-band average power.

the C/L-band combiner/splitter using an ASE source, Figure 7, and the transfer function for the combiner is presented in Figure 8, where we can see that the rejection of the C-band to the L-band pass is higher than 18 dB. To analyze the possible effect of this, or other combiner, we have characterized the change in the gain and in the gain tilt of the L-band as a function of the input power in the C-band. The results are presented in Fig. 9 and Fig. 10. As it can be observed from these graphs the increasing C-band power both the gain and the gain tilt decrease exponentially. It is important to notice, for better observation of the figures, that the power is in dBm, therefore there is a great dependence on the C-band power. So, a small amount of C-band power can cause a great change in the two parameters (gain and gain tilt). Therefore, for a system of 40 channels of 6dBm in the C-band giving a total power of 22dBm, this combiner will let pass about 4dBm in the C-band. So, with this combiner small variations in the C-band channels power, caused for example by drop of some of the C-band channels, this will cause a significant change in the gain and gain tilt of the L band amplifier due to the strong dependence of these parameters on the C-band input powers for this range of powers.

So, in order to overcome some of this difficulty, we suggest a new setup where a sample of the C-band power is fed intentionally into the L-band amplifier in order to push the operating point into a region where the dependence on the C-band power is much smaller. This is the case for C-band powers above 10dBm, where the slope (gain or gain tilt over input C-band power) is reduced more than four times, therefore the acceptable tolerances are greatly increased. There is one problem about this technique since, as it can be seen the amplifier gain is also decreased, however in terms of gain dynamics control this new system becomes simper and due to decreased gain tilt it is also easier to equalize.

IV. CONCLUSIONS

We have observed experimentally the effects of C-band pumping on L-band EDFA. By pumping on C-band, the ASE power increases saturating the amplifier in a out-of-band region causing a decrease in the Gain Tilt and on its dependence on the input power.

Special attention to the residual C-band power in this configuration should be taken, since there is strong dependence of the amplifier gain curve on this contribution. A new C+L configuration is suggested by intentionally leaving C-band power into the L-band part of the amplifier, in order to decrease the dependence of the gain curve on this residual power.

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