Highly efficient submarine C+L EDFA with serial architecture

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Abstract: This paper presents the theoretical and experimental results of an ultra-wide band C+L Erbium Doped Fiber Amplifier (EDFA). The EDFA is composed of three Erbium Doped Fiber (EDF) stages assembled in a serial architecture. Between these stages are inserted two Gain Flattening Filters (GFF) in order to achieve a balance between the control of the gain tilt and the gain bandwidth. With this strategy 70 nm of amplified bandwidth was obtained with only two pump lasers per amplifier each operating below 300 mW. The proposed architecture requires only the use of a limited number of high reliability commercially available components.

1. INTRODUCTION

With most of the long haul and ultra long haul telecommunication traffic relying on submarine networks, the maximization of the capacity of such systems is mandatory. In order to cope with the traffic growth in such networks one alternative is to focus on the expansion of the usable optical bandwidth of submarine amplifiers. Since Erbium Doped Fiber Amplifiers (EDFA) are the most widely optical amplifiers used in these networks several EDFA architectures were already proposed in the literature.

Traditional design approaches for the expansion of the usable optical spectrum typically leverage either a split band strategy, the parallel amplification of C and L bands by the amplification of the splitted and joined bands by band couplers [1] or the combination of EDFA and Raman amplifiers [2]. Going further, the use tellurite-based erbium doped fiber amplifiers can also be found in the literature [3].

In the split bands approach the traditional L band amplifiers make use of a fiber with high dopant concentration, which requires a large amount of pump power to generate a large gain [4]. Also, the band split-and-join technique does not allow one to use the spectral gap between the C and L bands imposed by the band coupler. Other alternative is the use of erbium doped telluride fiber to achieve this high bandwidth, however, tellurite-glass fiber present drawbacks related to bend radius limitations and manufacture reproducibility [5]. Finally, for the undersea environment, given the high pump powers required for Raman amplification, such as the one presented in [6], the use of such laser pumps increases the power consumption of the undersea repeater since the Raman pumps require a higher current when compared to 980 nm laser pumps.

It should be also considered that, due to high reliability demand in submarine amplifiers, it is very important the use of well know and qualified components and technologies. Also important for the reliability is to minimize the components number and use design allowing redundancy for the less reliable components.

The remainder of this paper is organized as follows: in Section 2 the architecture of the proposed amplifier is presented, in Section 3 the theoretical design of the EDFA is detailed, in Section 4 the experimental results and the comparison with the theoretical results are shown and in Section 5 the conclusions are presented.

2. AMPLIFIER ARCHITECTURE

System premises

In order to design the EDFA, the system premises for the undersea environment, were considered with the values shown in Table 1.

Table 1: System optical specifications

Parameter	Value	Unit
Fiber attenuation	0.16	dB/km
EDFA Output Power	18	dBm
Span Loss	10.2	dB
Total channel count	228	-
Target OSNR	16	dB

With the target specifications shown in Table 1 and the Amplifier Spontaneous Emission (ASE) generation model from [7], one obtains the System reach as a function of the repeater Noise Figure. This relation is shown in. In the model the ASE power generated by one EDFA is given by Eq. (1) and its accumulation through the amplifier cascaded is computed as a function of both signal and noise powers evolution along the fiber and amplifiers chain.

$$P_{ASE} = 2n_{sp}h\nu(G-1)B_o \qquad (1)$$

In Eq. (1) P_{ASE} is the ASE power generated by the EDFA, n_{sp} is the population inversion, h is Plank's constant, ν is the channel frequency, G is the amplifier gain and B_o is the reference optical bandwidth. It can be shown that, for large gains ($G > 10$), the EDFA Noise Factor (F) is proportional to the population inversion plus the input attenuation: $F=2n_{sp}A_{in}$ [8]. This way, using the model shown in Eq. (1) the reach of the system for amplifiers with different Noise Figures ($NF = 10 \log_{10}(F)$) is presented in **Erreur ! Source du renvoi introuvable.**.

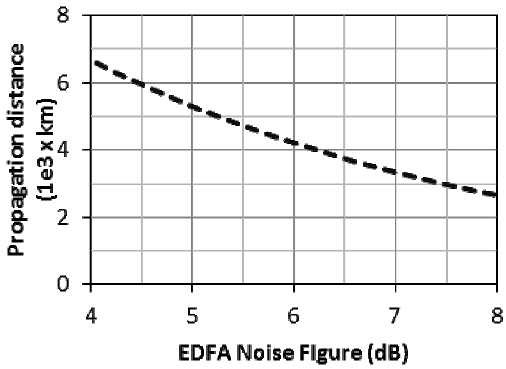

Figure 1: System reach as a function of EDFA noise figure

As can be seen in **Erreur ! Source du renvoi introuvable.**, an EDFA with a NF of 6 dB enables system to reach almost 4000 km with a span loss of 10.2 dB. In the scope of this work, such a system will be the target and its requirements for the EDFA are an output power of at least P_{out} = 18 dBm, a gain of 10.2 dB and a NF below 6 dB.

A constraint is that the 980 nm pump power output is limited to 300 mW for the available qualified suppliers in order to achieve a lifetime of 25 years for the subsea system. Another constraint is related to the amplifier bandwidth, since the target is the transmission of 228 channels with at least 37.5 GHz spacing. This way, the required specification values shall be obtained with a maximum pump power of 300 mW per laser, 70 nm of amplified bandwidth and an output power of + 18 dBm and a NF lower than 6 dB.

In addition to the performance requirements, the optical amplifier shall also incorporate a laser redundancy scheme in order to maximize the system operational life to 25 years.

Amplifier Optical Diagram

The traditional amplifier design approach using a single GFF is not useful for a C+L 70 nm wide transmission bandwidth because of the very large GFF peak attenuation that generate too high NF and to low output power. Our proposed design approach is to design a three stage amplifier with two GFF being one optimized as shape and position to work in C band and the second to work in L band. The complete optical diagram can be seen in Figure 2.

This design allow also for a minimum increase in components, only one more GFF, with respect to the parallel solution that double the components number.

One of the key steps in the design of an optical amplifier is the design of its gain flattening filter. In this specific case, which has two GFF this step is even more critical. The design variables that enable one to achieve the desired performance are the erbium lengths, the input power and the GFF attenuation profiles.

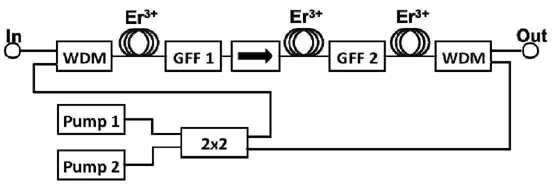

Figure 2: Optical Diagram

The proposed laser redundancy scheme makes use of both forward and backward pumping mechanisms by coupling the pump lasers with a 2x2 coupler. In order to avoid possible cavity effects in the EDF, two different laser wavelengths were used, 974 nm and 976 nm. The proposed coupling strategy of the two lasers allows them to operate in half power. In the event of a single failure, the remaining one can operate at nominal power and maintain the amplifier performance. This operation increases the lifetime of the component because it will operate in a derated mode. This architecture also enables the amplifier to have a similar performance in the event of a failure of one laser, because the change in both forward and backward pumping will be minimal because it is mainly related to the loss unbalance on the two arms of the 2x2 980 nm coupler.

Finally, the use of a serial architecture, instead of a split band one, provides a greater spectral efficiency than the parallel one that is usually found in the literature.

3. THEORECTICAL DESIGN

Gain and noise figure

After the modeling of the complete optical circuit, the search for the optimal EDF length and channel plan shall be performed.

The search consisted in choosing an appropriate EDF length and channel plan pair that minimizes the gain tilt of the amplifier and also presented a low average noise figure for the entire spectrum. This search was done by an exhaustive method and to obtain the curves the GFF was replaced by a fixed attenuation of 1 dB.

The single-mode doped fiber is modeled using the rate and propagation equations for a two-level laser medium as described in [8]. The model discretizes the total amplifier bandwidth, $\Delta\nu$, in k optical channels each one with optical bandwidth $\Delta\nu_k$ and center wavelength λ_k. To model the evolution of signal, pump and ASE powers a set of differential-integral equations, each one corresponding to one optical channel, have to be solved. The equations are shown in Eq. (2) and Eq. (3) for a 980 nm pumping scheme, in which the emission in the pump wavelength is zero.

$$\frac{dP_k}{dz} = u_k\Big((\alpha_k + g_k^*)\frac{\bar{n}_2}{n_t}P_k(z) + g_k^*\frac{\bar{n}_2}{n_t}2h\nu_k\Delta\nu_k - (\alpha_k + l_k)P_k(z)\Big) \quad (2)$$

$$\frac{dP_{980}}{dz} = u_k\left(\alpha_{980}\left(\frac{\bar{n}_2}{n_t} - 1\right) - l_{980}\right)P_{980}(z) \quad (3)$$

In Eq. (2) and Eq. (3) $P_k(z)$ is the signal power in wavelength λ_k and at distance z in the EDF; u_k represents the direction of the traveling beam being u_k=1 for the forward propagating beam and u_k=-1 for the backward propagating beam; α_k is the absorption spectrum; g^*_k is the gain spectrum; n_2 is the exited state ion population; n_t is the total ion population; $2h\nu_k\Delta\nu_k$ accounts for the spontaneous emission from the exited population in both polarisation modes; h is the Plank constant; l_k is the wavelength dependent background loss.

Design of the gain flattening filters

One of the key steps in the design of an optical amplifier is the design of its gain flattening filter. In this specific case, which has two GFF this step is even more critical. As it was highlighted earlier, the use of a single GFF is not enough to flatten the gain in the entire C and L bands, since its loss would be impractically high, eliminating thus all the gain that the amplifying stages provided.

In an optical amplifier chain, the gain profile plays a crucial role in the performance of the system. For submarine links, the gain flatness of the optical amplifiers is even more critical, given the high number of cascaded EDFAs. In order to obtain a flat gain profile for the entire C+L spectrum, an iterative technique was used to determine the optimal spectral response of the GFFs. The algorithm below describes the procedure to compute both GFF profiles. It was observed that, for diverse EDF lengths and channel plans, with a maximum number of iterations of 5 the gain tilt is not reduced significantly.

Algorithm 1 – GFF design	
Input	Channel plan and EDFA optical diagram
Output	Loss profiles of both GFFs
Step 1	Compute EDFA gain profile for EDFA with flat GFF loss profiles
Step 2	Invert gain profile and apply it to GFF 1
Step 3	Compute new EDFA gain profile
Step 4	Invert gain profile and apply it to GFF 2
Step 5	Invert gain profile, compute and differential loss profile to GFF 1
Step 6	Compute new EDFA gain profile
Step 7	Invert gain profile, compute and differential loss profile to GFF 2
Step 8	Compute new EDFA gain profile
Step 9	Return to Step 5 if max number of iterations is not achieved

Resulting optical performance

On the basis of the previously described algorithm we have implemented a numerical model for the amplifiers and performed the optimization process. On the model all optical components used are specified to operate in both C and L bands, from 1530 nm up to 1600 nm. For the WDM couplers, both the signal and pump losses are considered to be at 0.2 dB. The isolator loss is 0.5 dB and the background loss of the GFF is considered to be 0.5 dB. All splice losses are considered to be at 0.1 dB. The 2x2 980 nm coupler loss is considered to be 3.2 dB. The EDF peak absorption is at 1528.50 nm and has a value of 8.35 dB/m.

The resulting optical performance of the designed optical amplifier are summarized in Table 2. It can be seen that the system premises were achieved with this design. The resulting maximum noise figure is even 0.2 dB lower than the value considered as target. In addition, the output power obtained is 0.5 dB larger than the target output power. Both these values further enhance the reach of the system.

Table 2: Performance data of the amplifier

Parameter	Value	Unit
Output power	18.5	dBm
Gain	10.5	dB
Input power	8.0	dBm
Gain flatness at nominal gain	< 0.5	dB
Maximum noise figure at nominal gain	5.8	dB
Flat gain bandwidth	69.45	nm
Number of channels @ 37.5 GHz spacing	228	-

Input power variation

In a 25 year period, not only fiber aging but also fiber repair due to fiber cuts occur in a submarine cable and must be accounted for. Thus, the complete EDFA, with the GFFs, was characterized in terms of input power variation. The performance of the EDFA is shown in Figure 3. It can be seen that a 1 dB input power variation generates a 2 dB tilt in the gain profile. This result shows that the C+L EDFA is very sensitive to input power variation, and special care of such EDFA shall be taken into account when such system is deployed.

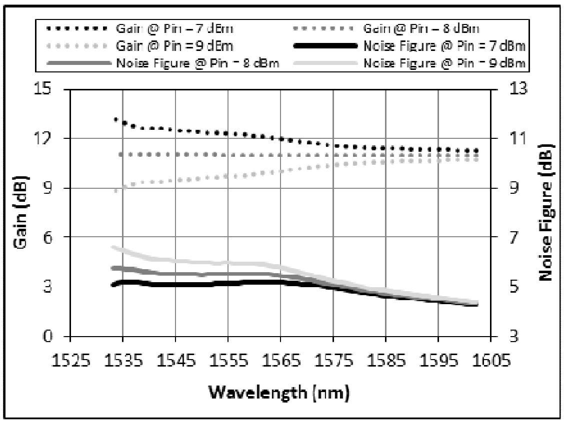

Figure 3: Gain and noise figure profiles for three different input power levels.

4. EXPERIMENTAL RESULTS

Test setup

In Figure 4, one can see the setup used to perform the characterization of the EDFA. The setup was calibrated by measuring the power differences between points *b* and *d*, which is called *Input Loss*, and the power difference between *c* and *d*, which is called *Output Loss*. The power difference between points *a* and *b* is also measured but its value is just informative and it is called *Input Monitor Loss*.

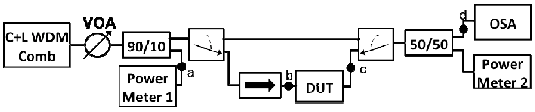

Figure 4: Experimental test setup

The optical isolator inserted before the Device Under Test (DUT) is required in order to reduce the reflection generated at the input section of the EDFA. Such a reflection might cause deflection in the ASE profile and invalidate the measurements Gain and Noise Figure measurements from the amplifier.

Test results

The experimental gain profile was compared with the theoretical results and this comparison can be seen in Figure 5. The results present a good match between the theoretical model and the experimental results.

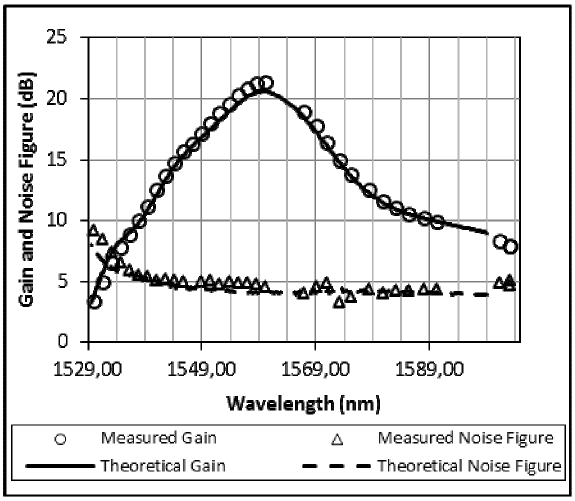

Figure 5: Theoretical and Experimental data comparison

The results shown in Figure 5 provide a good confirmation that the theoretical model is able to simulate the real saturated conditions behavior of an EDF in the C+L wavelength range. This way, it is safe to say that the optical circuit when assembled with the proper GFF profiles will provide experimentally the performance shown in Figure 3.

5. CONCLUSION

This paper presented the theoretical and experimental results of the development of a novel silica based EDFA architecture composed of three EDF stages assembled in a serial architecture. With two GFFs, one between each stage, the EDFA is able to provide a high bandwidth with a low pump power.

The amplifier was specifically designed for submarine repeater application and it was obtained 70 nm of amplified bandwidth in this architecture by using only two pump lasers operating below 300 mW. The proposed amplifier achieved an output power of 18.5 dBm by using dual pump architecture with 974 nm and 976 nm pump lasers which ensure full redundancy.

The high output power and wide amplification bandwidth from the resulting EDFA enables the transmission of up to 228 DWDM channels for up to 4000 km with at least 37.5 GHz of channel spacing and is suitable for submarine applications and the proposed architecture makes use of only a reduced number of commercially available components including silica based erbium doped fiber.

In addition, the investigation of the performance trade-offs between the average noise figure and the erbium length variation between the three stages were analysed. This fine tuning of fiber lengths enabled the design to achieve a better performance in terms of noise figure and pump power conversion efficiency.

Also, it was shown that the use of EDF fibers developed for standard C band amplification is enough and the use of EDF fibers developed for operation in the L band is not necessary. In addition, the use of a serial architecture simplifies the optical design improving reliability, and is more spectral efficient when compared to the split band one, usually found in the literature. In order to further improve reliability and space occupancy a design using passive components integrated on a single silica glass based optical chip is under development.

A good match was obtained between the theoretical model and the experimental results, which in turn enables the design and fabrication of the GFFs in order to perform a complete experimental characterization of the designed EDFA. These results also provide enough confidence that the theoretical design will provide accurate predictions of the experimental setup yet to be assembled.

Further works aims to fabricate the designed large bandwidth GFFs and completely characterize the EDFA.

6. ACKNOWLEDGMENT

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