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Radiation-Hardened Nano-particles-based Erbium-Doped Fiber for space environment

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***Abstract*—We demonstrate for the first time a radiation-resistant Erbium-Doped Fiber exhibiting performances that can fill the requirements of Erbium-Doped Fiber Amplifiers for space applications. This is based on an Aluminum co-doping atom reduction enabled by Nanoparticules Doping-Process. For this purpose, we developed several fibers containing very different erbium and aluminum concentrations, and tested them in the same optical amplifier configuration. This work allows to bring to the fore a highly radiation resistant Erbium-doped pure silica optical fiber exhibiting a low quenching level. This result is an important step as the EDFA is increasingly recognized as an enabling technology for the extensive use of photonic sub-systems in future satellites.**

I. Introduction

These last years, the space industry has shown an increasing interest for photonics, as an enabling technology to address new satellite architectures and sub-system applications. The most attractive perspectives consist in taking benefit from the ground optical communication technology, as it offers a wide range of possibilities, which are of strong interest for both civilian and defense applications. In spite of past researches, this technology is still not yet ready for space, a major lock being the availability of the so-called EDFA "Erbium-Doped Fiber Amplifier", which is strongly degraded by the harsh radiative space environment. It was clearly identified that the radiation-affected component of the EDFA is the Erbium-Doped Fiber (EDF) itself[1]. Indeed, up to now, EDFs fabricated by state of art technology do not fulfill the requirements because the radiations produce a dramatic increase of the fiber background losses. These losses lead to huge gain reduction at the end-of-life of the EDF.

II. State of the Art

The degradation of the EDFs, called "Radio-Induced-Absorption" (RIA), is not due to the insertion of the Erbium ion itself in the host matrix, but to the addition of a significant amount of Aluminum as co-doping atom in classical fabrication processes. Unfortunately, whereas Aluminum facilitates the inclusion of the Erbium ions in the glass and reduces quenching effects, it also induces structural defects in the host matrix, resulting in strong RIA levels after irradiation[2], [3].

At this time, three main approaches have been explored to reduce the amplifier gain and optical power degradation originating from the RIA.

The first one consists in fabricating shorter amplifiers [4]. Indeed, because the overall radiation induced losses grow as an exponential function of the amplifier fiber length, the first already visited way to reduce EDFA degradation has consisted in increasing Erbium concentration by means of conventional doping techniques, leading to huge concentrations of both Aluminum and Erbium. However, this approach is limited by the increase of Aluminum-induced RIA and / or by the quenching effect, which both impact optical gain and output power.

Another possibility consists in fiber hydrogenation, which is known to reduce the amount of traps in silica fibers. This way is very efficient regarding the achievable reduction of the RIA[5]. Unfortunately, it is very well known that the hydrogen reaction with the silica defects leads to the formation of hydroxyl group (OH) and sometimes hydrides (SiH). The OH overtones and combinational vibration in silica glass introduce the peak absorption in IR region. So, its impact to the background losses depends on the wavelength and it is therefore difficult to predict the resulting attenuation spectrum ; typically, 1 ppm of formed OH induces 40 dB/km of losses at 1385 nm and 1 dB/km at 940 nm[6], [7]. The resulting attenuation at both pump and signal wavelengths will obviously impact the maximum achievable gain or output power. Therefore, following this way, a tricky compromise between RIA reduction and background losses has to be reached in order to build high performance optical amplifiers that may fulfill space applications requirements.

A last well-known possible hardening possibility relies on the inclusion of Cerium in the silica matrix[8], as Cerium acts as a hole trap. However, whereas strong RIA reduction can be attained at signal wavelength[9], the insufficient RIA lowering at pump wavelength leads to complex Er-Yb double cladding optical fiber design, resulting in huge transparency power, thus to poor optical efficiency. Whereas such a fiber is suitable for specific high optical power applications, it cannot meet most satellite application requirements, in which power consumption is a key parameter.

In this paper, we explore another EDF-hardening concept that, contrary to the aforementioned approaches, is based on the accurate physical origin of standard EDFs excessive degradation ; indeed, like it has been done in the past with passive optical fibers, we look into the possibility to reduce the co-doping atoms concentration. In the frame of this work, we thus explore the opportunity to reduce Aluminum concentration in the EDFs, while increasing the Erbium quantity in order to design shorter amplifiers.

Unfortunately, following this way by means of classical fabrication techniques inherently leads to massive quenching effects that dramatically reduce the EDF efficiency[10]. For this reason, the fabrication of such an EDF relies on disruptive technologies concerning the inclusion of the Erbium in the silica glass, allowing to reduce or eliminate the Aluminum proportion while controlling the Erbium ions close neighborhood in order to minimize quenching effects[11].

In this paper, we take advantage of the glass nanostructuration to fabricate such optical fibers by means of silica or alumina Erbium-doped nanoparticles (NP) which are inserted in the glass matrix. We then compare their resistance to radiations with various EDFs fabricated by classical process, thanks to EDFA configurations and irradiation conditions chosen to approach space requirements.

III. Nanoparticles-Doped Radiation-Resistant EDFs design and fabrication

A. Fabrication of NP-doped EDF by MCVD

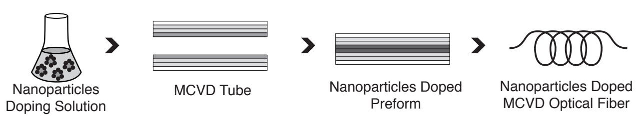

Fig. 1. Fabrication Process Steps for Nanoparticules Erbium-Doped Fibres

In this work, we take advantage of NP doping process [12], [13], [14] to manufacture rare earth doped fibers, allowing an accurate control of the rare earth doping characteristics (incorporation, dispersion, chemical environment) within the fiber core matrix. Rare earth doped NPs synthesized by soft chemical way are put in the frame of stable aqueous suspension and incorporated within optical preform through a classical liquid doping technique, whatever the chosen main core glass matrix composition.

In the context of radiation insensitive fibers, manufacturing Er-doped fibers without Al-doping (SiO_2/Er NPs) or with the minimal Al quantity (Al_2O_3/Er NPs) is now possible by involving NP doping technology. The Al_2O_3/Er NPs exhibit a determined atomic ratio Al/Er= 200, ensuring the WDM gain shape. In this case, a high Er content in the fiber can be reached thanks to a further optimization of doping porous layer capacity. Moreover, the NP process is interesting in an industrial context because it allows to perform a nanostructuration of the glass while being compatible with traditional MCVD fabrication process (fig. 1).

B. EDFs and EDFAs under test

In order to check the degradation of the EDFs, we built for each fiber a co-propagative EDFA configuration with 21 to 23 dBm pump power at 980 nm and 0 dBm 1550-nm signal power at the input. Each amplifier is simply designed by choosing the so-called "optimal EDF length", that allows to reach before irradiation the highest output power at signal wavelength for fixed pump and signal input powers. These EDFA configurations are sufficiently similar to compare the post-irradiation results in terms of gain reduction. The Erbium-doped fibers explored in this work are designed and chosen to demonstrate many points, such as the influence of Aluminum concentration and amplifier length, but also the benefits of the Erbium neighborhood control permitted by NP-CVD.

The main parameters and properties of both EDF and EDFAs before irradiation are summed-up in Table I.

IV. Irradiation Experiments, Results and Discussions

A. Irradiation Set-Up

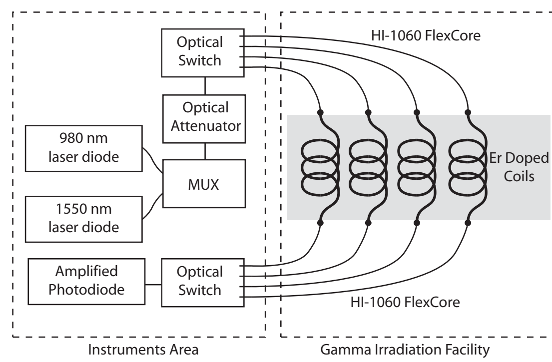

Fig. 2. Irradiation Set-up

As displayed in fig. 2, the experimental set-up is made of two distinct parts:

- the instruments area: this place contains a co-propagative pump configuration with 2 lasers, one at the signal wavelength (1550 nm) and the other one at the pump wavelength (980 nm). After the MUX, each laser light passes through an HI1060-Flexcore optical switch exhibiting transmittance fluctuations smaller than $0.2\,dB$. The EDFA configurations are tested in amplification saturation regime with $0\,dBm$ signal power and pump power exhibited in table I, whereas the RIA is tested far below the absorption saturation power. In order to reach high accuracy Noise Factor measurements, the signal laser is an Extended-Cavity Diode Laser (ECDL), which exhibits much lower Amplified Spontaneous Emission (ASE) levels than conventional DFB laser diodes. Moreover, this laser is used at the highest available power, which allows to reach a better rejection of the ASE, relatively to the laser line power ; the optical power at the input of the

Fiber Name	Al-NB	Al-LB	NP-Al	NP-Si	NP-Si+
Erbium absorption (dB/m@1530nm)	4.7	12.3	23	2	3.2
Aluminum ($wt\%$)	<1	6-8	4-6	0	0
Pump power (dBm)	23	23	21	23	21
Optimal Length (m)	25	6	2.5	45	22
Output signal (dBm)	17	18	16	17	15
RIA at 1550nm (dB/m/Gy)	5.5e-4	7e-3	5e-3	2.2e-4	2.8e-4
RIA at 980nm (dB/m/Gy)	1.2e-3	2e-2	3e-2	3e-4	3e-4

TABLE I
EDFS AND ASSOCIATED EDFA PARAMETERS, AND RIA VALUES. FIBERS "NP-AL" AND "NP-SI+" EXHIBIT LOWER OUTPUT POWER BECAUSE OF LOWER PUMP POWER. FOR 23 dBm PUMP POWER, "NP-AL" WOULD EXHIBIT OUTPUT POWER CLOSE TO "AL-LB", WHILE "NP-SI+" WOULD EXHIBIT OUTPUT POWER SIMILAR TO "AL-NB" OR "NP-SI".

fiber at the signal wavelength is then adjusted thanks to an optical attenuator.

- the gamma-irradiation facility: because the nature of radiation (X-rays, gamma, protons, electrons...) does not strongly influence the degradation[15], we simply performed gamma irradiation of all the 5 optical amplifiers. Fibers "Al-NB" , "Al-LB" and "NP-Si" were irradiated at ONERA in Toulouse (France) by means of Co^{60} source $5\,Gy/h$, and both the "NP-Al" and "NP-Si+" were irradiated at Louvain-la-Neuve University in Belgium, still using a Co^{60} source, but in the $12\,Gy/h$-$14\,Gy/h$ dose rate range.

All the EDFA measurements were performed "in-line". The coils of Er-doped fibers are linked to the instruments thanks to a set of 30 m-long HI1060 Flexcore optical fibers. The degradation of these passive optical fiber extensions can be ignored, as the RIA of passive fibers never exceeds some tens of dB/km[16] in the near to mid infrared range. This point was confirmed by post-irradiation transmittance measurements of the HI1060 Flexcore extensions.

We have also to notice that the results exhibited here are pessimistic, compared to real-space mission conditions, because each fiber was illuminated only during each data acquisition and not continuously during the whole irradiation experiments. The impact of the photobleaching is thus not taken into account in this work, and the only possible recovery may come from the room-temperature.

B. In-line Gain Measurements under Radiation

The gain decrease monitored inline for each EDFA is displayed in figure 3 as a function of the dose. These results clearly demonstrate the benefits obtained thanks to the NPCVD process. Our discussion describes two opposite ways, concerning the balance between low RIA and short amplifier length :

- following first the "ultimately low RIA Erbium-doped fiber" way to reach radiation-resistant amplifiers, the result displayed in fig. 3 is clear: the most radiation-resistant EDFA uses the less Aluminum-doped fiber with a quite short optimal length. To our knowledge, this compromise can only be obtained thanks to the NPCVD process. Indeed, reaching similar Erbium concentration with classical fabrication process requires a quite small part of Aluminum which is enough to induce a gain decrease by many dB.
- Concerning the "short-length high Erbium-concentration" radiation-resistant amplifier way, we demonstrate, once more, that NPCVD fibers are much more interesting than classically fabricated fibres. Indeed, the results obtained with "NP-Al" and "Al-LB" clearly show that, at comparable Aluminum concentration, a much stronger resistance to radiations can be obtained.

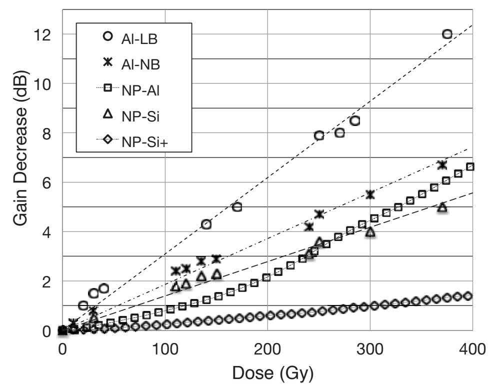

Fig. 3. Gain decrease for each EDFA configuration

We also notice that comparing fibers "NP-Si+" and "NP-Si" corroborates the design rule from A. Gusarov et al. [4], bringing to the fore that fabricating shorter-length optical-amplifiers leads to radiation-resistant EDFA. However, this rule is to be weighted with the value of the RIA. Indeed, the "short amplifier" design rule fits well with both "NP-Si+" and "NP-Si", whereas it cannot work between "NP-Si", "NP-Al" and "Al-NB", because of very different RIA values. Actually, whereas "NP-Al" allows to reach very short optimal-length amplifier (down to $2.5\,m$), both "Al-NB" and "NP-Si" based EDFA exhibit similar or better resistance to radiations, while being more than 10 times longer.

C. Pre- and Post-Irradiation Noise Factor

For these measurements, we take advantage of a low ASE ECDL (External Cavity Diode Laser). The Noise Factor was measured for both "NP-Si+" and "NP-Al" EDFA by using the

ASE interpolation technique[19] and then calculated following the IEC (International Electrotechnical Commission) definition [20], considering the signal-ASE beat as the main noise contribution in the EDFA :

$$NF = \frac{2\rho_{ASE}}{h\nu G} \quad (1)$$

ρ_{ASE} is the amplified spontaneous emission spectral density (in W/Hz), and G the amplifier optical gain. We have to notice that the shot-noise contribution $(+1/G)$ can be neglected in the NF calculation because the optical gain is still strong enough for each optical fiber after the $400\,Gy$ irradiation. The results are summed-up in fig. 4.

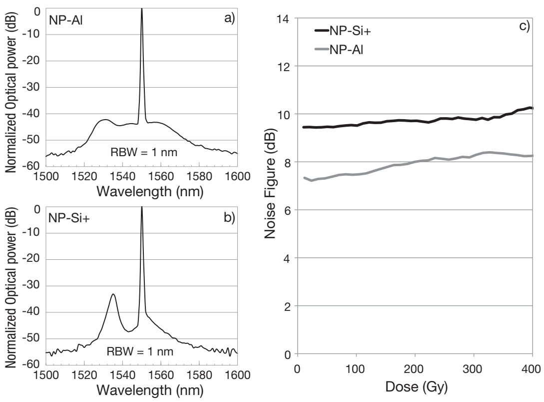

Fig. 4. Signal + ASE spectra and Noise Factor evolution as a function of the dose deposit. The spectra were obtained at $1\,nm$ Resolution Bandwidth (RBW).

Due to the lack of Aluminum, the ASE spectrum of the NP-Si+ fiber does not take advantage of the Aluminum-induced inhomogeneous broadening of the emission cross sections (fig. 4-a and -b). For this pure-silica fiber, the ASE power is thus concentrated over a narrower spectral range than the one of an Aluminum codoped fiber. For that reason, the pure silica ASE optical power spectral density (PSD) is stronger, and this impacts the noise factor value. That's what is observed in fig. 4-c. Nevertheless, we have to notice that, at this time, the NP-Si+ fiber design has not still been optimized to reduce the Noise Factor.

We also bring to the fore that the noise factor degradation itself is lower than $1\,dB$ after a $400\,Gy$ deposit dose for the two kinds of NPs. Moreover, this degradation is, once more, a pessimistic result because the fibers did not experience any optical recovery.

D. Irradiated EDFA Optimal length

It is clear that the degradation of the EDFA is due to the increase of the RIA. However, measuring simply the degradation at the output of an EDFA which optimal length is determined before irradiation is pessimistic, because the RIA acts like a strong increase of the background losses of the amplifier, which also induces a change in the EDFA optimal length once it is irradiated. In order to investigate this point, we performed cut-back operations on non-irradiated and 1300 Gy irradiated amplifiers in order to follow the evolution of the optimal length. The results of this work are displayed in fig. 5 for a highly degraded (NP-Al) and slightly degraded (NP-Si+) optical fibers. This figure shows that the optimal length

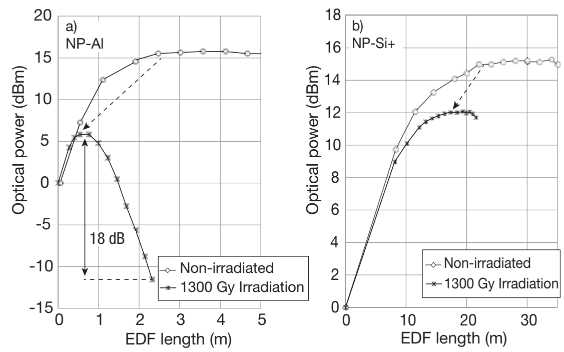

Fig. 5. Pre- and post- irradiation cut-back measurements performed for "NP-Si+" and "NP-Al" fibers.

reduction is quite small ($< 20\,\%$) for the slightly degraded fiber, whereas it reaches nearly $80\,\%$ for the Aluminum co-doped fiber, leading to huge absorption at the fiber end. Moreover, we see in fig. 5-a that the maximal power post-irradiation at signal wavelength is obtained for $\approx 0.5\,m$ fiber length and is $\approx 18\,dB$ stronger than the power reached at the end of the fiber, i.e. at the pre-irradiation optimal length. For that reason, the optimal length of a radiation-resistant optical amplifier may be choosen considering the post-irradiation optimal length instead of the pre-irradiation optimal length.

V. Conclusion

In this work, we compared the radiation-resistance performances of 5 EDFs having different chemical compositions and fabricated thanks to both classical and NPCVD fabrication processes. We measured on the one hand the optical gain and noise factor in a saturated amplifier configuration, and on the other hand the RIA for both pump and signal wavelengths, in a small-signal regime. These measurements were carried out in-line, under Co60 gamma radiation. We also performed cut-back measurements, before and after degradation.

The strongest gain-degradation is observed for the amplifier using the "standard" technology-based fiber with the highest Aluminum concentration, while the lowest gain-degradation, and also the lowest RIA levels, are noticed for the silica nano-particles based fibers, with no trace of Aluminum. Therefore, this work demonstrates for the first time the feasibility of radiation-resistant single-channel EDFA designed for space applications. This work also allows to determine an order of magnitude of the fundamental limits of the degradation permitted with an erbium-doped pure-silica fiber.

In order to target multiple-channel or low noise applications, these fibers must be enhanced concerning the inhomogeneous broadening. This can be performed by means of slight inclusion of Aluminum into the pure-silica Erbium-doped NPs, while using a minimal hydrogenation process in order to compensate the RIA.

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