Radiation hardening techniques for Er/Yb doped optical fibers and amplifiers for space application

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Abstract: We investigated the efficiencies of two different approaches to increase the radiation hardness of optical amplifiers through development of improved rare-earth (RE) doped optical fibers. We demonstrated the efficiency of codoping with Cerium the core of Erbium/Ytterbium doped optical fibers to improve their radiation tolerance. We compared the γ-rays induced degradation of two amplifiers with comparable pre-irradiation characteristics (*~19 dB gain for an input power of ~10 dBm*): first one is made with the standard core composition whereas the second one is Ce codoped. The radiation tolerance of the Ce-codoped fiber based amplifier is strongly enhanced. Its output gain decrease is limited to ~1.5 dB after a dose of ~900 Gy, independently of the pump power used, which authorizes the use of such fiber-based systems for challenging space missions associated with high total doses. We also showed that the responses of the two amplifiers with or without Ce-codoping can be further improved by another technique: the pre-loading of these fibers with hydrogen. In this case, the gain degradation is limited to 0.4 dB for the amplifier designed with the standard composition fiber whereas 0.2 dB are reported for the one made with Ce-codoped fiber after a cumulated dose of ~900 Gy. The mechanisms explaining the positive influences of these two treatments are discussed.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (350.5610) Radiation; (160.2220) Defect-center materials; (060.2330) Fiber optics communications.

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1. Introduction

Rare-Earth (RE) doped optical fibers are a key element of fiber-based systems like amplifiers or lasers with high power capabilities. Among their various applications, such active fibers and systems can be used in space missions. For this purpose, they will be exposed and will have to survive to the harsh space environment. Previous studies showed that RE-doped optical fibers are the most radiation sensitive part of amplifiers, exhibiting high radiation-induced attenuation (RIA) levels compared to Telecom-grade passive optical fibers [1, 2] when exposed to X-rays, gamma-rays or protons. As a consequence and despite the short length used for space applications, the estimation of their vulnerability to the harsh environment associated with space missions remains crucial [3].

Most of the previous studies were devoted to the characterization of their radiation responses in 1) a passive configuration (without pumping of the active ions) with the test benches used for the characterization of passive optical fibers and 2) under gamma and/or proton irradiations which lead to similar effects [1–5]. From these "passive" tests, the origin of RIA increase has been partially identified. For most of the RE-doped fibers, such as those containing aluminum (Al) or phosphorus (P) in their silica-based cores, the point defects causing the RIA are related to dopants chosen for facilitating the active ion incorporation rather than to defects related to rare-earth ions [1,6]. We also recently showed by comparing Er and Er/Yb doped samples, that the presence of the Yb^{3+} ions did not increase the fiber radiation sensitivity. So, the Yb/Er composition allows the obtaining of higher fiber gain compared to Er-doped fibers. Furthermore, we showed in [6] that the competition between the defects for the trapping of charges released by irradiation in the matrix may be used to design fibers less sensitive to radiations.

Fewer studies have been devoted to the characterization of the YbEr fiber in an active configuration, even less as part of fiber-based amplifiers. The response of actively-pumped RE-doped optical fibers and amplifiers have been discussed in [7–10]. For example M. Alam *et al.* [10] reported an important degradation of an Yb/Er amplifier output power with cumulated dose, they showed a complete darkening of their amplifier (*extinction of the amplified signal*) after a 200 Gy dose at a dose rate of 0.2 Gy/s or 400 Gy (0.1 Gy/s). Jin Ma et al. [11] also measured the complete darkening of the output power of their Yb/Er amplifier after a 500 Gy dose (0.4 Gy/s).

2. Experimental procedure

2.1. Tested optical fibers and amplifiers

The goal of this paper is to demonstrate that enhancing the radiation tolerance of fiber amplifiers is possible by improving the response of the rare-earth doped fibers. To achieve this, we optimized the composition of their host matrix to reduce the Radiation Induced Attenuation (RIA) levels at both the pump and emission wavelengths and evaluate the resulting improvement of corresponding fiber amplifiers.

To assess our technique, we designed two prototype RE-doped fibers with different core compositions including the same concentrations of Er^{3+} and/or Yb^{3+} ions. These fibers have been developed by the fiber manufacturer iXFiber SAS with bare fiber geometry and with an octagonal double-clad (DC) which is designed for easier injection of the high power laser pump into their RE-doped phosphosilicate cores. This DC is made of comparable pure-silica glass for both fibers. The structure of these fibers is illustrated in the inset of Fig. 1(a). Both are coated with double acrylate layers.

These fibers are named #1 and #2 respectively. Their main characteristics are summarized in Table 1. The main difference between them is the addition of cerium (Ce^{3+} ions) in the fiber #2 core. We expected from our previous work [12] that this element should positively affect the radiation sensitivity of RE-doped glasses without degrading its amplification properties. We also studied the influence of a hydrogen pre-loading on the radiation response of these two fibers, as previous studies reveal that such a treatment can positively act on the radiation tolerance of Erbium-doped optical fibers at least when hydrogen is present inside the fibers at the time of irradiation [13, 14]. The fibers hydrogen-loading was performed during 48h at a pressure of 192 bars and a temperature of 85°C allowing saturation of the fibers with hydrogen. This loading phase is followed by a heat treatment (85°C, atmospheric pressure) to both fix the hydrogen into the glass matrix and remove more than 90% of the hydrogen excess. Furthermore, the radiation tests were not conducted just after the completion of the treatment. As a consequence, most of the remaining H_2 molecules were diffused out of the fibers at the time of our experimentations. At the start of the irradiation tests, it is estimated that more than 99.5% of the incorporated molecular hydrogen diffuses out of the fiber. The treated fibers are respectively noted as #1H and #2H samples.

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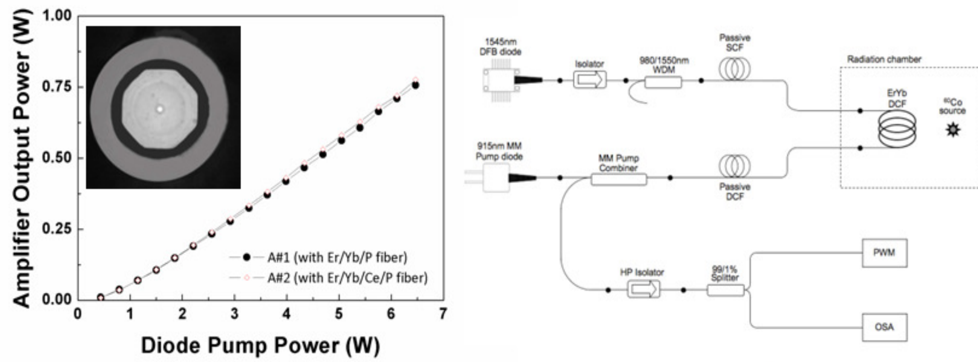
To improve our knowledge of radiation-induced mechanisms in this class of optical fibers, we also tested another DC optical fiber #3 that has been designed without Er^{3+} and Yb^{3+} ions in its core but has the same Ce-codoped phosphosilicate matrix than fiber #2. We also characterized a version of this fiber pre-treated with H_2: fiber #3H.

Table 1. Characteristics of Tested Rare-Earth Optical Fibers

Fibers	*Er^{3+} (wt. %)*	*Yb^{3+} (wt. %)*	*Ce^{3+} (wt. %)*	*P (wt. %)*	*H_2 pre-loading*
#1	0.07	1.50	-	~12	-
#1H	0.07	1.50	-	~12	Yes
#2	0.07	1.40	0.6	~12	-
#2H	0.07	1.40	0.6	~12	Yes
#3	-	-	0.6	~12	
#3H	-	-	0.6	~12	Yes



(a) (b)

Fig. 1. (a) Dependence of the amplifier output power versus the diode pump power for the amplifier A#1 based on fiber #1 (Yb/Er/P) and for A#2 based on fiber #2 (Yb/Er/P/Ce). Typical picture of RE-fibers cross section is illustrated in the inset. (b) Experimental procedure for the testing of fiber amplifiers under gamma-ray irradiation.

Based on the same length of these two active fibers and their H_2-treated counterparts, four amplifiers with comparable performances before irradiation were designed and fully characterized. The structure of these amplifiers is illustrated in Fig. 1(b). For each amplifier, we used the fixed length of 12 m of the RE-doped optical fiber to facilitate the comparison between the amplifier radiation responses. These fibers are pumped with a 915 nm multimode pump diode in a backward pumping scheme allowing an efficient amplification of the 1545 nm signal from a DFB diode.

The A#1 amplifier has been build with fiber #1 which corresponds to the standard composition, amplifier A#2 with the Ce-codoped fiber #2. Typically, the tested amplifiers exhibited a 19 dB gain with a 10 dBm input power. The output power at 1545 nm was limited to less than 1 W for these experiments but this amplifier design can easily extract up to 10 W with sufficient pump and input power available. Figure 1(a) presents the dependence of the amplifier output power versus the 915 nm diode pump power for the A#1 and A#2 amplifiers. The two amplifiers exhibit the same performances before irradiation allowing us to directly estimate the hardening effect of the Ce-codoping. Two versions of the amplifiers A#1H and A#2H have also been realized with the H_2-treated samples of fibers #1 and #2. These amplifiers present optical characteristics close to those of the amplifiers made with the untreated optical fibers.

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2.2. Irradiation tests

The gamma irradiations were performed at the CEA ^{60}Co source and at room temperature. We used the experimental setup illustrated in Fig. 1(b) to characterize the gamma-irradiation effect on the global performances of the amplifiers. Only the RE-fibers were exposed to the 1.2 MeV photons whereas the rest of the amplifier systems is deported to a radiation-free instrumentation zone with two pigtails of 30 m of single clad fibers (SCF) and double clad undoped fibers (DCF). The tested fibers have been irradiated during different runs at a dose rate of 0.003 Gy/s for total integrated doses (TID) ranging between 400 Gy and 900 Gy.

With this test bench, we were able to characterize the radiation-induced changes on the amplifier output power through a power meter (PWM) and the spectral dependence of the amplified signal through an optical spectrum analyzer (OSA). For the testing of fibers #3 and #3H, we adapted our experimental setup to record during separate irradiation runs, the radiation-induced attenuation (RIA) at both 915 nm pump and 1545 nm signal wavelengths.

3. Experimental results

3.1. Amplifier gain decrease with dose

We first recorded the radiation induced changes on the amplifier output power at 1545 nm (max emission wavelength) with the following operating conditions: room temperature, pumping at 915 nm (*max pump power of ~6.5W*). Figure 2 shows the evolution of the gain for the four amplifiers up to doses of 400 Gy for A#1 and 900 Gy for three other amplifiers. To allow a better comparison of radiation effects on these devices, the output powers have been normalized to their maximum values.

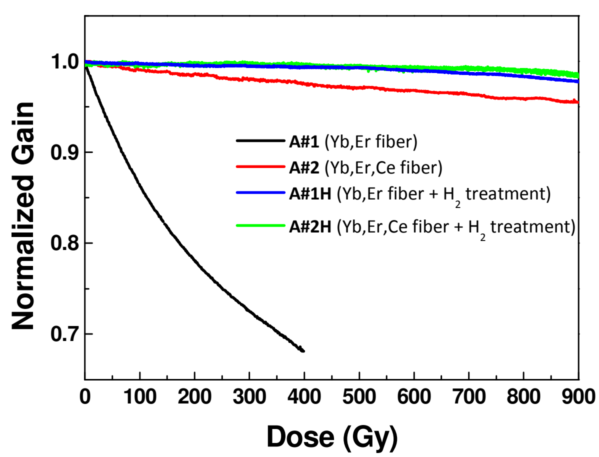

Fig. 2. Dose dependence of the gain of the four amplifiers (A#1, A#2,A#1H,A#2H) during irradiation at a dose rate of 0.003 Gy/s. The gains were normalized to their maximum values to authorize a more direct comparison between radiation effects in the different amplifiers.

Our results showed that the radiation sensitivity of the amplifiers strongly depends on the nature of the RE-doped fiber used for the signal amplification. In amplifier A#1 with the standard fiber composition, we noticed a strong decrease of the amplifier output power at 1545 nm from about ~760 mW to ~190 mW (~75% at 400 Gy). This corresponds to a 32% decrease of the gain from 19 dB to ~12.5 dB (6.5 dB) after an irradiation dose of 400 Gy. This degradation is strongly limited for amplifier A#2 which was the one designed with the radiation-hardened YbErCeP fiber #2. This A#2 amplifier presents a low gain degradation level (8%) after an irradiation dose of ~900 Gy, corresponding to an absolute gain decrease

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from ~19 dB to ~17.5 dB (1.5 dB). The two amplifiers designed with fibers #1 or #2 pre-treated with H_2 exhibit excellent radiation hardness with gain degradation of less than 1% respectively after a dose of 900 Gy. This corresponds to a limited degradation of 0.4 dB (from 19.2 dB to 18.8 dB) and 0.2 dB (from 17.3 dB to 17.1 dB) for amplifiers A#1H and A#2H respectively.

3.2. Amplifier gain decrease with input pump power

All the *in situ* tests have been performed with the pump power of ~6.5 W to facilitate the comparison. For all amplifiers, we measured very limited recovery of the amplifier gain during the first 1000 s after the end of irradiation. The point defects at the origin of the fiber degradation seem stable at room temperature.

After each irradiation run, we controlled the dependences of the amplifier output power at 1545 nm versus the 915 nm pump power and then calculate the equivalent output power losses L at 1545 nm for each possible operating pump power(> 2 W) of the two amplifiers. This loss $L(P_{pump})$ is calculated as:

$$L\left(P_{pump}\right) = -10\times\log\left(\left(P_{irr}\left(P_{pump}\right)/P_0\left(P_{pump}\right)\right)\right)$$

where $P_{irr}(P_{\mathrm{pump}})$ is the measured output power at the tested pump power P_{pump} and $P_0(P_{pump})$ the output power measured for the amplifier at the same conditions before irradiation. Results are illustrated in Fig. 3 for the two amplifiers.

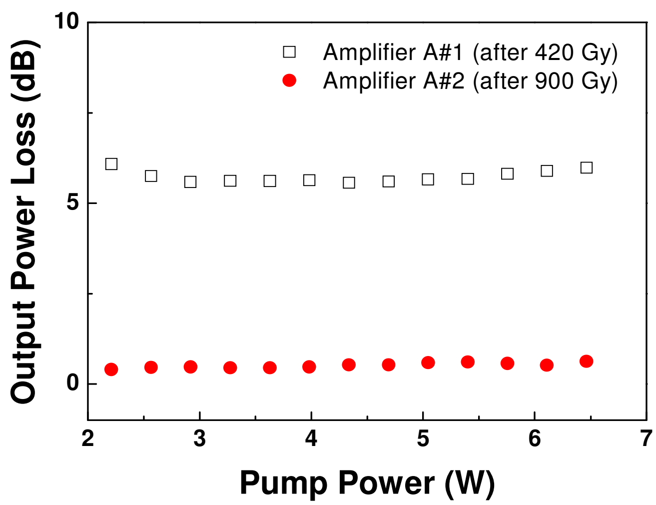

Fig. 3. Dependence of the output power loss L(I) versus the pump power for the amplifier A#1 and A#2 respectively irradiated at doses of 420 Gy and 900 Gy (dose rate of 0.003 Gy/s).

These tests confirm that, independently of the pump power, the equivalent induced losses at the signal wavelength remains constant at around 0.6 dB for A#1 and 8 dB for A#2.

3.2. Radiation-induced attenuation in fibers #3 and #3H

Under similar irradiation conditions than for the amplifiers, we characterized the RIA at both pump and signal wavelengths in the fibers #3 and #3H that did not contain Er or Yb ions. The obtained results are shown in Fig. 4.

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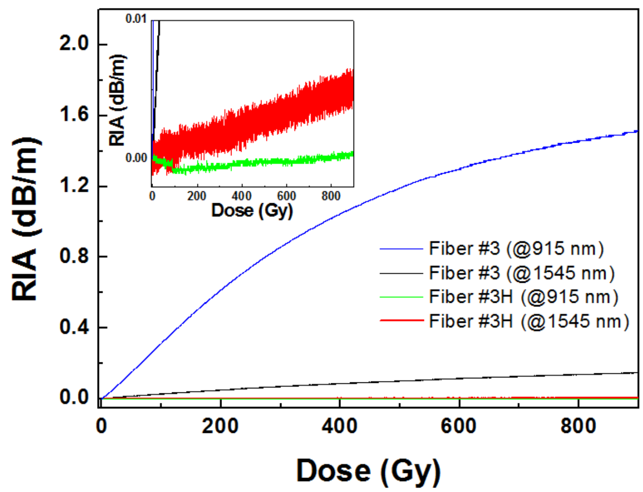

Fig. 4. Dose dependence of the radiation-induced attenuation (RIA) measured at both pump (915 nm) and signal (1545 nm) wavelengths during irradiation up to 900 Gy at a dose rate of 0.003 Gy/s (room temperature of the #3 and #3H fibers. The inset highlights the low RIA values measured for the H^2-pretreated #3H fiber.

In agreement with amplifier behaviors, these measurements reveal the strong positive effect of the H_2 pre-treatment on the fiber radiation response and this, at the two investigated wavelengths.

In the untreated sample, we measured RIA of ~1.5 dB/m at 915 nm and 0.15 dB/m at 1545 nm after 900 Gy irradiation whereas RIA is lower than 0.05 dB/m at both wavelengths in the H_2 treat sample. As expected, the RIA measured for fiber #3 at 1545 nm is quite different to the one calculated for the amplifier that can be estimated at 0.06 dB/m (for the 12 m amplifier). This can be explained by the fact that different mechanisms take place in the amplifiers A#2 and A#2H and the fibers #3 and #3H. In an amplifier, the equivalent losses at 1545 nm are related to various phenomena as the absorption from color centers at both the pump and signal wavelengths, as the absorption by rare-earth ions at these two wavelengths (*0.8 dB/m and 0.29 dB/m at 915 nm and 1545 nm in fiber #2*) whereas RIA is only caused by color centers in fibers #3 and #3H. To obtain a clear picture of these different mechanisms, simulation tools are necessary that allow calculating the light guiding and amplification along the RE-doped fiber [15, 16]. Our tests also proved that, if passive testing of rare-earth fibers can provide useful information on the radiation tolerance of a given fiber, the response of an amplifier made with this fiber cannot be easily extracted from these sole passive measurements. Active testing of amplifiers or coupled approach based on passive configuration testing in addition to simulation tools of the amplifier properties remain mandatory before integration of such system in space missions.

4. Discussion

Our radiation tests reveal different amplifier degradation depending on the RE-doped fiber choice as amplification media. In Fig. 5, we compare the radiation hardness of our amplifiers to those previously published in the literature [10, 11]

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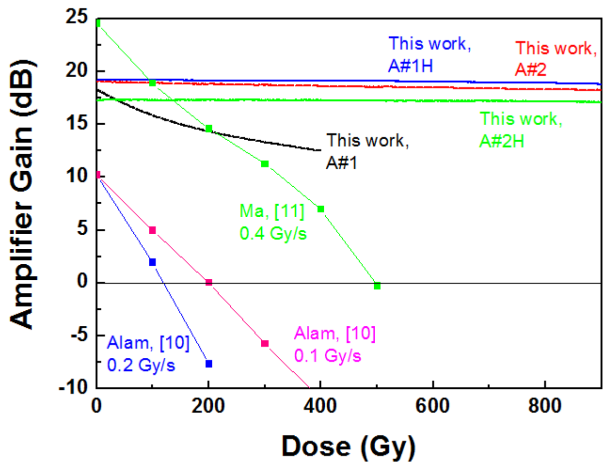

Fig. 5. Dose dependence of the amplifier gains for our four amplifiers A#1, A#2, A#1H and A#2H (dose rate of 0.003 Gy/s) and of other Yb/Er amplifiers reported in [10, 11].

This comparison clearly shows the excellent response of our amplifiers compared to those of these previous papers. Particularly, we can notice that our A#1H, A#2 and A#2H amplifiers can be considered as nearly insensitive to radiations compared to other classes of amplifiers which exhibit a strong decrease of their gains to 0 (corresponding to no amplification) or less after low or moderate doses (150-200 Gy for [10] and 500 Gy for [11]). As highlighted in this figure, the different experiments have been made with different dose rates, from 0.003 Gy/s for our experiments to 0.4 Gy/s for J. Ma results [11], the one used for our study being the more representative for space testing. In passive optical fibers without RE, the dose rate effect depends on the fiber type. RIA levels increase at higher dose rate for Ge-doped or pure-silica optical fibers as, at a given dose, the bleaching mechanism are less efficient during a short irradiation run [17]. For the case of P-doped optical fibers, the dose rate has no influence on the RIA levels in the dose range investigated in this paper [18]. This is explained by the strong stability of P-related point defects at room temperature [19], leading to this dose rate independence and to an absence of RIA bleaching after the end of the irradiation. The characterization of our amplifier behavior after irradiation from few seconds to several weeks after irradiation reveals no bleaching of the induced losses, proving the stability of the defects (certainly P-related as discussed in [6]) at the origin of the irradiation. For the case of RE-doped fibers; the published results present a more complex dose rate effect. Most of the authors provided evidence for no dose rate effects in this kind of optical fibers [16, 20] whereas a more limited number of researchers assumed that RIA levels increase at lower dose rate in certain RE-doped fibers, mainly Er-doped fibers [21]. In any case, the difference in the dose rate of the experiments discussed in Fig. 5 cannot explain the difference in the amplifier's radiation sensitivities. If there is a dose rate effect, our irradiation conditions may be less favorable than the one used in [10, 11].

Our work shows that the design of amplifiers with excellent radiation responses is now possible. Several mechanisms can be responsible for the degradation of the fiber amplifier output power, such as:

- The generation of radiation-induced point defects absorbing at around 1545 nm, the emission wavelength of the amplifier and/or at 915 nm the pump wavelength. These point defects can directly affect both the pump and amplified signals propagation. In our fibers, we have shown [6] that the radiation-induced losses are due to Phosphorus Oxygen Hole Centers [16] in the near-IR and to P1 defect centers in the IR [16]. Even if, the exact mechanisms are still under investigation, both Ce-codoping and H_2-loading

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affect the generation efficiencies or the thermal stability of these defects, resulting in a decrease of their contribution to the radiation-induced attenuation.

- The modifications of the spectroscopic properties of Er^{3+} and Y^{b3+} ions and of their cross interactions by Ce incorporation. This point is developed in [22] that investigates the natures of interactions between these different rare-earths.

Among its practical radiation-hardening use, the exact role of the Ce-codoping still needs to be investigated to authorize a more efficient control of the fiber or amplifier radiation sensitivity. Previous studies [23–25] have shown that depending on the valence states of the Ce ions incorporated into the glass matrix, its impact on the defect generation can differ. Ce ions can influence the generation mechanisms of different classes of point defects, these interactions depend on the valence states of the ions as well as on their concentration inside the glass matrix. In particular, J. S. Stroud [24, 25] showed that Ce^{3+} ions, by capturing radiation-produced holes to form Ce^{3++} centers, inhibit formation of all other kinds of centers due to trapped holes (like POHC or P1 defects); Ce^{4+} ions, by capturing electrons to form (Ce^{4+} + electron) centers, inhibit formation of all other kinds of centers due to trapped electrons. By controlling the relative concentrations of Ce^{3+} and Ce^{4+} ions, it seems possible to adjust the number of available Ce-related sites for the trapping of the holes and electrons released under irradiation.

4. Conclusion

In conclusion, we presented two different techniques to improve the radiation hardness of phosphosilicate rare-earth (Er/Yb) doped optical fibers and their associated optical amplifiers.

The first one consists in the Ce-codoping of the fiber core. We show that amplifiers based on Ce-codoped fiber can survive in the harsh environments associated with challenging space missions. A degradation of about 1.5 dB of the 19 dB gain of our amplifier is measured after an irradiation dose of 900 Gy (at 0.003Gy/s). Such radiation hardness offers very promising perspectives for fiber-based amplifier integration in future space missions.

Another technique is based on the pre-treatment of the rare-earth doped fibers with H_2. This treatment is very efficient and has been shown to drastically improve the radiation tolerance of both Ce-doped and Ce-free fiber-based amplifiers. For these experiments, the fibers were coated with acrylate and the main part of the H_2 diffuses out the fiber before the radiation tests. Furthermore, more specific studies related to the H_2 role on the amplifier behavior remain necessary to better estimate the long-term efficiency of this positive treatment. Another possibility is to use metal-coated fibers to ensure the confinement of H_2 within the fibers during the mission lifetime, as proposed in [13, 14].

Work is in progress to design more radiation-tolerant optical fibers and fiber-based systems by combining the radiation-hardened fibers presented in this paper with radiation-hardening by system through simulations of the amplifier properties taking into account the radiation effects. By combining these different hardening approaches, it appears possible to design radiation-hardened fibers for doses up to 1500 Gy in the near future.

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