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## RADIATION HARDENING OF OPTICAL FIBERS AND FIBER SENSORS FOR SPACE APPLICATIONS: RECENT ADVANCES

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### I. INTRODUCTION

In these ICSO proceedings, we review recent advances from our group concerning the radiation hardening of optical fiber and fiber-based sensors for space applications and compare their benefits to state-of-the-art results. We focus on the various approaches we developed to enhance the radiation tolerance of two classes of optical fibers doped with rare-earths: the erbium (Er)-doped ones and the ytterbium/erbium (Er/Yb)-doped ones. As a first approach, we work at the component level, optimizing the fiber structure and composition to reduce their intrinsically high radiation sensitivities. For the Erbium-doped fibers, this has been achieved using a new structure for the fiber that is called Hole-Assisted Carbon Coated (HACC) optical fibers whereas for the Er/Yb-doped optical fibers, their hardening was successfully achieved adding to the fiber, the Cerium element, that prevents the formation of the radiation-induced point defects responsible for the radiation induced attenuation in the infrared part of the spectrum. These fibers are used as part of more complex systems like amplifiers (Erbium-doped Fiber Amplifier, EDFA or Yb-EDFA) or source (Erbium-doped Fiber Source, EDFS or Yb-EDFS), we discuss the impact of using radiation-hardened fibers on the system radiation vulnerability and demonstrate the resistance of these systems to radiation constraints associated with today and future space missions. Finally, we will discuss another radiation hardening approach build in our group and based on a hardening-by-system strategy in which the amplifier is optimized during its elaboration for its future mission considering the radiation effects and not in-lab.

### II. CONTEXT OF OUR WORK

Rare-earth (RE) doped fibers and amplifiers are needed as part of optical fibers sources, gyroscopes, inter- or intra-satellites communication links for space programs [1]. For this, they present key advantages compared to other technologies but it is also known that they are very sensitive to space harsh environment [2-5] even if recent promising results on their hardening to radiations have been published [6,7]. In these components/systems, the main radiation effect concerns the radiation induced attenuation (RIA) that decreases the transmission capacity of the fiber and totally changes the amplification efficiency along the fiber used in the amplifier. For the amplifier, the main effect is a gain decrease with the deposited dose. RIA, at the origin of this macroscopic change, is related to the generation of point defects in the fiber silica-based core and cladding [8,9]. The nature and optical properties of these point defects (also called color centers), explain the different RIA levels observed at a particular wavelengths such as the pump or signal wavelengths [8,9]. The generation and bleaching mechanisms of these centers will govern the kinetics observed for the growth and decay of the RIA (or the gain) during and after the end of the irradiation. As a consequence, the RIA levels and kinetics depend on the fiber composition, design, the radiation environment characteristics (dose, dose rate, temperature,...) as well as the device profile of use (wavelength, injected power, ...) [8]. The RIA level measured in rare-earth doped optical fibers, eg. Erbium-doped fibers; is very high compared to the RIA measured in passive optical fibers like the ones used for Telecom applications [8]. Several studies demonstrated that this high sensitivity to radiations is not explained by the rare-earth ions but rather by the codopants included in their matrix to facilitate their incorporation or to optimize the amplification processes (see [4] for example). Mainly, the large RIA observed is linked to the two codopants usually added in the fiber core: the phosphorus (P) and aluminium (Al). Several solutions have been recently developed to limit the negative influence of these two elements on the fiber and/or amplifier radiation responses. For example, our group demonstrates that Cerium incorporation inside the core of a Erbium/Ytterbium (Er/Yb) doped phosphosilicate optical fibers, strongly reduces the RIA related to the P1 phosphorus-related defect that absorbs at 1600 nm near the operating wavelength of the amplifier [6,10], this will be detailed in §V. By changing the fabrication process, another group of researchers showed that it is possible to avoid the Al codoping, improving the radiation resistance of erbium-doped optical fibers [7]. A last technique working for both phosphosilicate or aluminosilicate optical fibers is the loading of the fiber core and cladding with hydrogen (or deuterium); in this case, it has been shown that the amplifier radiation response is greatly improved but the positive impact of the treatment remains time-dependent and not really adapted in its current forms to long term space missions [6,11,12].

To overcome the RIA limiting their integration and to enhance the efficiency of these already-presented radiation hardening techniques [6,7,11-13], we defined and developed a new Hole-Assisted Carbon-Coated (HACC) erbium-doped fiber (EDF) structure that permits to ensure a long-term H<sub>2</sub>- or D<sub>2</sub>- loading of the fiber core reducing the RIA (and consequently the EDFA gain degradation) compared to similar fibers without the HACC design and the H<sub>2</sub>- or D<sub>2</sub>-loading treatment. This new structure will be discussed in the following paragraph § III.

### III. HOLE-ASSISTED CARBON COATED (HACC) OPTICAL FIBERS AND AMPLIFIERS [14,15]

*This new structure has been applied together with an appropriate choice of core codopants ensuring, at the same time, optimal optical performances and lowest radiation-sensitivity. Using this new RE-doped HACC optical fiber, a 31 dB EDFA exhibits a gain degradation lower than 0.7 dB after irradiation up to a dose of ~315 krad (dose rate of 0.19 rad/s).*

#### 1. The HACC fibers

To highlight the interest of HACC-fiber structure, we compare two versions of the same erbium-doped optical fibers (EDF) made by iXFiber [16] with the same core diameter of 2.7μm and the same composition. They differ only by the presence of the HACC structure added to one of them, this one being then treated with deuterium. The core and cladding compositions used here are already optimized to strongly reduce their radiation sensitivity compared to the ones of commercial EDFs, the reference fiber is called Radiation-Tolerant Acrylated Coated (RTAC) fiber. Figure 1 illustrates the particular HACC-EDF used to design the tested amplifier. In this case, the 125μm silica cladding includes an arrangement of 6 holes that have been made to allow the H<sub>2</sub> or D<sub>2</sub> loading. This is mandatory as after the deposition of the hermetic carbon coating (thickness of 20-30nm), it is no more possible to transversally load the fiber under conventional conditions.

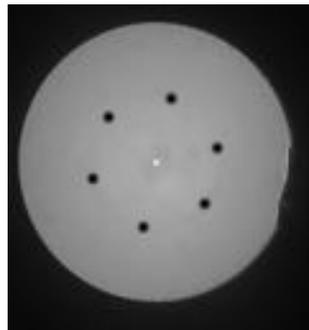


Figure 1. Hole-Assisted Carbon-Coated Erbium-doped Fiber (HACC-EDF) used to design the erbium doped optical fiber amplifier (EDFA) characterized in this study.

In the tested sample, the 3μm diameter holes were created at the preform manufacturing stage using standard glass processing techniques. It must be noticed that the hardening efficiency of the HACC structure on the EDF demonstrated here will not be affected by the choices made concerning the hole size diameter or number. Without the carbon layer, H<sub>2</sub> or D<sub>2</sub> diffuses out the silica part of the fiber within few days, eliminating the positive influence of the gas presence on the RIA [17]. After the HACC fiber loading with H<sub>2</sub> or D<sub>2</sub> through the holes, outgassing mechanisms are limited to those occurring at the hole surfaces which are ten times less efficient than those occurring in non-CC optical fibers. Another very positive possibility offered by the HACC fiber structure concerns the control of the gas loading level in the fiber. Indeed, by this method, the H<sub>2</sub> or D<sub>2</sub> level can be precisely adjusted to determine the best compromise between the radiation hardening of the fiber and its optical performances before irradiation. As long as the holes remain open at both ends of the fiber, the gas will escape more or less quickly depending on the temperature applied. Through the monitoring of the spectral changes of the attenuation, it becomes then possible to obtain the desired concentration of gas into the fiber core [17].

Then, the HACC-EDF is spliced to the other parts of the EDFA. After this step, the outgassing remains only possible through the two ends of the spliced RE-doped fiber and appears very limited. To demonstrate the efficiency of the HACC structure to keep the gas inside the fiber, we have performed on the loaded sample an accelerated thermal treatment at 80°C for more than 20 days and observed a limited H<sub>2</sub> concentration decrease

of 10%. With the HACC design, the H<sub>2</sub>- or D<sub>2</sub>- loading of EDF for long-duration space missions is now possible.

*1. Experimental characterization of HACC fibers and amplifiers radiation responses*

Two amplifiers were designed using ~10 m length of the two EDFs with and without the HACC structure and D<sub>2</sub> loading. Their gains differ, for a 100 mW pump power at 976 nm, from 31.8 dB for the radiation tolerant acrylate-coated RTAC-EDF to 31 dB for the HACC-EDF treated with D<sub>2</sub>. Comparing the optical performances of the two amplifiers (31.8 dB and 31 dB) before irradiation confirms that the used technique did not significantly affect the optical performances of the tested erbium doped optical amplifiers. To summarize, the HACC hardening technique does not significantly impact the amplifier response before its exposure to radiations and very efficient EDFAs can be designed using such fibers.

Irradiation of EDFAs has been performed using a <sup>60</sup>Co source from CEA, France. The 1 MeV photon irradiation tests were done at room-temperature. We used a dose rate of ~0.19 rad(SiO<sub>2</sub>)/s (1.9 mGy/s up to a dose of 315 krad (3.15 kGy). Such dose level exceeds the requirements for today space missions that consider usually total deposited doses below 50 krad. However, such high dose can be well-representative of the total doses expected to be deposited on materials intended to be integrated in the systems developed for future JUPITER ICy moon Explorer (JUICE) missions. Concerning the dose rate, although the one used during the ~3 weeks irradiation run was quite low, it remains higher than those associated to long (up to 20 years) space missions. During our experiments, the erbium doped fiber was the only part submitted to radiations as it was demonstrated to be the most sensitive subsystem of the EDFA to radiations [18]. For these tests, the two tested amplifiers used a continuous forward pumping configuration and were made with the RTAC-EDF or with a HACC-EDF loaded with D<sub>2</sub> during 43h at 80°C and 70 bars. For the latter, the compromise between radiation hardness and optical performances was obtained after 16h of D<sub>2</sub> outgassing at atmospheric pressure and 80°C with holes “open”. After that the fiber was spliced with the other parts of the amplifier and D<sub>2</sub> concentration remains nearly constant once a D<sub>2</sub> partial pressure equilibrium is obtained between the holes and the silica.

Figure 2 compares the radiation-induced gain degradation measured for both EDFAs versus the deposited dose.

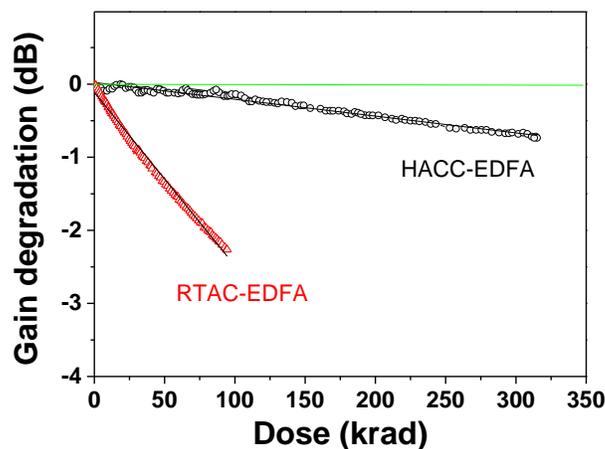


Figure 2. Gain Degradation of the EDFAs designed with a HACC-EDF and with a RTAC-EDF of same compositions.

The gain decrease remains limited for both EDFAs. For the HACC-EDFA, the gain decrease remains below 0.75 dB after a dose of ~315 krad whereas for RTAC-EDFA, the gain decrease is larger but remains below 2.4 dB after ~100 krad. For both amplifiers, our results showed that the gain decrease evolves nearly linearly with the dose and we could then extract dose dependent coefficients in dB/krad for the gain decrease. We found the coefficient  $-2.2 \times 10^{-3}$  dB/krad for the HACC EDFA to be compared to the  $24 \times 10^{-3}$  dB/krad (factor  $\times 10$ ) coefficient for the already radiation-tolerant acrylate-coated EDFA.

The HACC structure strongly enhances the radiation hardness of this class of optical fibers. We built an EDFA based on the HACC fiber and characterized its degradation under  $\gamma$ -rays up to 315 krad. The amplifier is nearly insensitive to radiations; with a mere gain change of  $-2.2 \times 10^{-3}$  dB/krad that will authorize its use even for the

main challenging applications associated with future JUICE missions. Additional tests were performed under proton exposure [15] and confirm that these HACC fibers and HACC-EDFA also resist to high fluences of 100 MeV protons without specific effects of the HACC structure in terms of dose deposition into the fiber core. In the future, the coupled simulation/experiments approach presented in [19] and detailed in §V will be applied to these amplifiers in order to enhance even more their radiation resistance by designing the amplifier parameters for optimal performances during the space mission.

#### IV. HARDENING OF ERBIUM-YTTERBIUM DOPED FIBERS THROUGH CERIUM-CODOPING [6]

##### 1. The Ce-codoped optical fibers and amplifiers

For this study, various fibers have been developed by Ixfiber SAS. The two investigated fiber structures were designed with an octagonal double-clad (DC) that is used to facilitate the high power laser pumping of the RE ions located in the fiber cores. The structure of these fibers is illustrated in Figure 3.

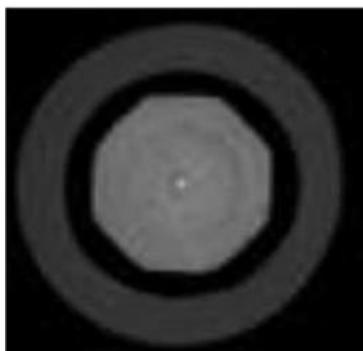


Figure 3. Illustration of the Erbium-Ytterbium fiber structure

This double clad is made of comparable pure-silica glass for each optical fiber. Both fibers have a core doped with the two rare-earth ions  $\text{Er}^{3+}$  and  $\text{Yb}^{3+}$  as well as a codoping of the glass matrix with phosphorus. For such fibers, phosphorus has been shown to be able to increase the refractive index of the silica glass and to facilitate the energy transfer from the  $\text{Yb}^{3+}$  to the  $\text{Er}^{3+}$  ions thanks to the phonons associated to the phosphorus-oxygen double bonds (P=O). Previous tests reveal that the presence of the phosphorus, if it increases the amplification efficiency of the glass before irradiation, is also responsible for the main part of the infrared radiation-induced attenuation (RIA) when they are submitted to different types of irradiations (gamma ray or protons tests). The  $\text{P}_1$  points defects related to the phosphorus that are responsible for the degradation have been identified; their structure is close to the  $\text{SiE}'$  center in pure silica. We also showed that the concentration of these defects can be affected by the presence of other codopants like aluminum. We tentatively explained this response by a competition phenomenon for the trapping of the charges released by irradiation between the different color centers associated to these codopants. This phenomenon was used in this work as we added cerium ions in the core of one of the two studied fibers, in order to compete with  $\text{P}_1$  centers and then improve the radiation tolerance. Therefore, the two tested fibers #1 and #2 have globally the same active core (phosphosilicate glass doped with erbium and ytterbium rare-earth ions) except that fiber #2 also contains cerium in its core. An important point is that the spectroscopic properties of the  $\text{Er}^{3+}$  and  $\text{Yb}^{3+}$  rare-earth ions are poorly affected by the incorporation of the cerium inside the core.

Based on the two prototype active fibers, two amplifiers (AMP#1 and AMP#2) have been designed by Ixfiber with 12 m length of active fibers. As expected, despite their difference (presence of Cerium in Fiber #2 core), we were able to obtain comparable performance for these two amplifiers. For both fibers, we were able to amplify a 10 mW signal at 1425nm to nearly 800mW by pumping the  $\text{Yb}^{3+}$  ions at 915 nm. Then, the two tested amplifiers exhibited, before irradiation, a 19 dB gain with a 10 dBm input power. It is important to notice that we limited the output power to 1W at 1545 nm for these experiments. However, this amplifier design can easily extract up to 10 W with sufficient pump and input power available.

## 2. Experimental details and results

We used a  $^{60}\text{Co}$  source to characterize the radiation sensitivity of our devices at low dose rate ( $\sim 0.3$  rad/s) and cumulative doses of up to 90 krad. All these experiments have been conducted at room temperature ( $<18^\circ\text{C}$ ). Only the active fiber is exposed to the  $\gamma$ -rays. All other equipments like diodes, lasers and detectors remain in a radiation-free instrumentation zone for this set of experiments. We used a 915 nm multimode pump diode to excite the rare-earth ions in a contrapropagative scheme. The signal from a 1545 nm DFB diode is then amplified from about 10 mW to nearly 1 W depending on the injected pump power. By using this technique, we can characterize the changes in the amplifier output power at 1545 nm thanks to a photodiode and at the same time, record the changes in the spectral properties of the amplified signal with an optical spectrum analyzer (OSA). Figure 4 presents the changes of the output power at 1545 nm of the two amplifiers with the dose. These measurements were obtained with a pump current of 7 A and are normalized in Fig.4 for a better comparison between the amplifier responses based on the two fibers.

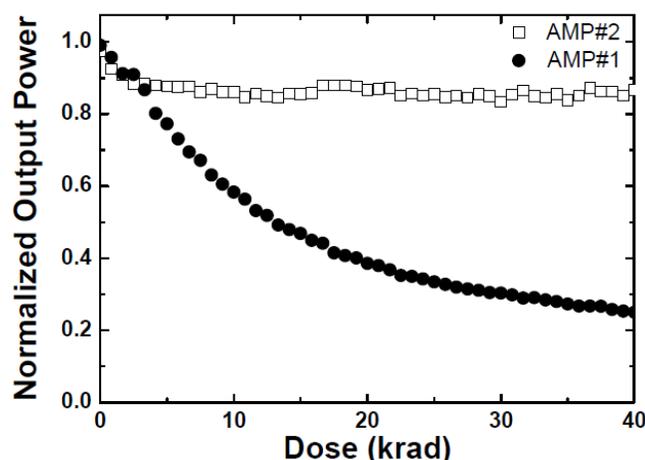


Figure 4. Dependence of amplifier output power at 1545nm versus the deposited dose (dose rate of 0.3 rad/s).

Our results showed that irradiation at only a few tenths of krad of the active fiber induces a strong degradation of the amplifier AMP#1 output power ( $<80\%$  at 40 krad) as illustrated in Figure 4. For this amplifier, the output power continuously decreases in the whole range of tested doses. However, for amplifier AMP#2 designed with Ce codoped fiber #2, only a low degradation level is observed: less than 20% of the amplifier output power is lost after a 40 krad dose. We remark that this degradation level is quickly observed after a dose of  $<5$  krad and remains stable at higher dose. Results at higher dose levels (up to 90 krad) revealed an output power decrease of less than  $<30\%$  for this amplifier. This is illustrated in Figure 5 (from [6]) that compares the performances of our amplifiers to those published in the literature [20,21]. In this figure, the positive effect of an  $\text{H}_2$  loading of the fiber on the radiation resistance of their corresponding amplifiers was also demonstrated.

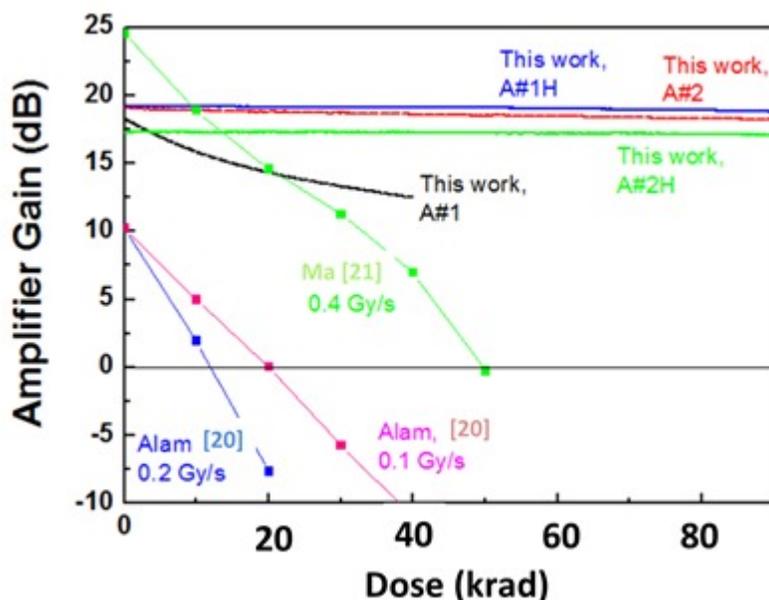


Figure 5 (from [6]) Dose dependence of the amplifier gains for our four amplifiers AMP#1(A#1), AMP#2(A#2), and their versions with H<sub>2</sub>-loaded fibers :A#1H and A#2H (dose rate of 0.003 Gy/s) and of other Yb/Er amplifiers reported in [20,21]

This comparison clearly shows the excellent response of our amplifiers compared to those of these previous papers. after low or moderate doses (150-200 Gy for [20] and 500 Gy for [21]).

#### V. THE HARDENING-BY-SYSTEM APPROACH [19, 22]

A collaboration was initiated between our different research groups to determine the possible ways to improve the radiation hardness of these very radiation sensitive devices in order to authorize their integration in future space missions. Possible ways were to work on the improvement of the fiber itself –hardening by component – or to improve the resistance of the system by changing its design to reduce the impact of the fiber degradation on its performance –hardening by system -.

In addition to our improvement of the radiation response of the fiber itself discussed in previous parts, we also work on the development of new calculations codes allowing to reproduce the behavior of the amplifier when submitted to radiations [6, 14]. A first version of the codes is now available and validated (Fig. 6 shows a comparison between the simulated and experimental results), they have been used to investigate the potential of various amplifiers configurations (in terms of fiber lengths, pumping schemes) for different applications. Such codes could also be used to optimize the performances of the amplifiers during the space missions and not only for lab-tests before the mission. We can expect to be able to propose radiation-hardened amplifiers even for the most challenging future applications.

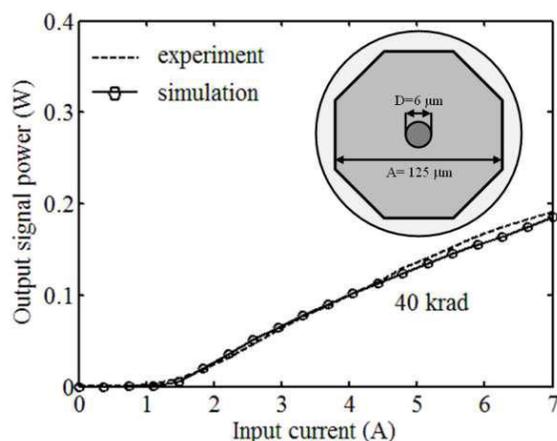


Figure 6. Radiation response of the Er/Yb-doped fiber amplifier at a 40krad dose: experimental results (dash curve), numerical results (full curve). Inset - DC structure of the simulated Er/Yb-doped fiber.

## VI. CONCLUSIONS

Recent advances are described concerning the radiation hardening of rare-earth doped optical fibers and fiber-based systems for space applications. Thanks to the new developed fibers, these systems can now survive to the constraints of today missions and are also candidates for integration in more challenging future space missions.

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