

# Radiation hardening techniques for rare-earth based optical fibers and amplifiers

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## ABSTRACT

Er/Yb doped fibers and amplifiers have been shown to be very radiation sensitive, limiting their integration in space. We present an approach including successive hardening techniques to enhance their radiation tolerance. The efficiency of our approach is demonstrated by comparing the radiation responses of optical amplifiers made with same lengths of different rare-earth doped fibers and exposed to gamma-rays. Previous studies indicated that such amplifiers suffered significant degradation for doses exceeding 10 krad. Applying our techniques significantly enhances the amplifier radiation resistance, resulting in a very limited degradation up to 50 krad. Our optimization techniques concern the fiber composition, some possible pre-treatments and the interest of simulation tools used to harden by design the amplifiers. We showed that adding cerium inside the fiber phosphosilicate-based core strongly decreases the fiber radiation sensitivity compared to the standard fiber. For both fibers, a pre-treatment with hydrogen permits to enhance again the fiber resistance. Furthermore, simulations tools can also be used to improve the tolerance of the fiber amplifier by helping identifying the best amplifier configuration for operation in the radiative environment.

**Keywords:** radiation effects, optical fibers, erbium, ytterbium, amplifiers

## 1. INTRODUCTION

The incorporation of Rare-Earth (RE), like Erbium (Er) and/or Ytterbium (Yb) doped optical fibers in radiative environments is now widely studied as these components are a key element of fiber-based systems like amplifiers or lasers with high power capabilities. This type of optical fiber was also shown to be the most sensitive part of these systems to radiation effects [1,2]. As a consequence and despite the short length used for space applications, the study of their vulnerability to the harsh environment associated with space missions remains crucial [3]. Most of the previous studies have been devoted to the characterization of their radiation response in a passive configuration (with no amplification) with setups comparable to those used for the characterization of passive optical fibers [1-5]. For most of the RE-doped fibers, such as those containing aluminum or phosphorus as codopants of the core silica-based matrix, the

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point defects at the origin of the fiber degradation, through the radiation-induced attenuation phenomenon, seem related to the glass matrix chosen for the active ion incorporation [1,6].

Other studies characterized the response of actively-pumped Er-doped optical fibers [7-9]. Fewer studies have been carried out on the Er/Yb doped amplifiers. M. Alam et al. [10] showed important degradation of an Yb/Er amplifier output power with cumulated dose; they reported a complete darkening of a Yb/Er amplifier (extinction of the amplified signal) after an irradiation dose of 20 krad (at a dose rate of 20 rad/s) or 40 krad (dose rate of 10 rad/s). More recently, J. Ma et al. [11] also reported the decrease of a Yb/Er amplifier gain from 25 dB to 0 dB after irradiation at a dose of 50 krad (40 rad/s). These previous studies demonstrate the importance of designing new types of Yb/Er optical fibers with better radiation tolerance. We previously presented [12] the radiation responses of two differently doped Er/Yb doped optical fibers. One of these fibers is radiation hardened thanks to a special composition of its fiber core. We demonstrated the high radiation tolerance of an amplifier based on this Cerium-codoped fiber through characterization of its behavior under gamma radiations. In this paper, we showed that the radiation resistance of these two fibers and associated amplifiers can be further improved by appropriate pre-treatments like pre-loading of the fiber with hydrogen or by acting on the amplifier configuration to reduce by hardening by system the relative influence of radiation on RE-doped fibers on their radiation response.

## 2. EXPERIMENTAL PROCEDURE

### 2.1 Tested optical fibers

In this paper, we present results obtained on a set of four new prototype RE-doped fibers compositions including both  $\text{Er}^{3+}$  and/or  $\text{Yb}^{3+}$  ions in their cores. These fibers have been developed by Ixfiber SAS [12]. 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. 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 ( $\text{P}=\text{O}$ ). 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 [13]. 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, as shown in [12].

Samples of these two fibers were hydrogen-loaded during 48h at the following conditions: 192 bars and 80°C. The resulting pre-treated fibers are noted as #1H and #2H. The fibers are coated with acrylate that did not allow keeping the hydrogen confined inside the fiber for a long time as metal-coated fibers do [14]. The fiber tests were done several days after irradiation meaning that most of the hydrogen should have diffused out the fiber at the time of the gamma irradiation.

### 2.2 Tested optical amplifiers

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. Figures 1a and 1b present the output power dependence at 1545nm of the two amplifiers on the pump current. As it can be noticed, for both fibers, we were able to amplify a 10 mW signal at 1545 nm to nearly 800 mW by pumping the  $\text{Yb}^{3+}$  ions at 915 nm.

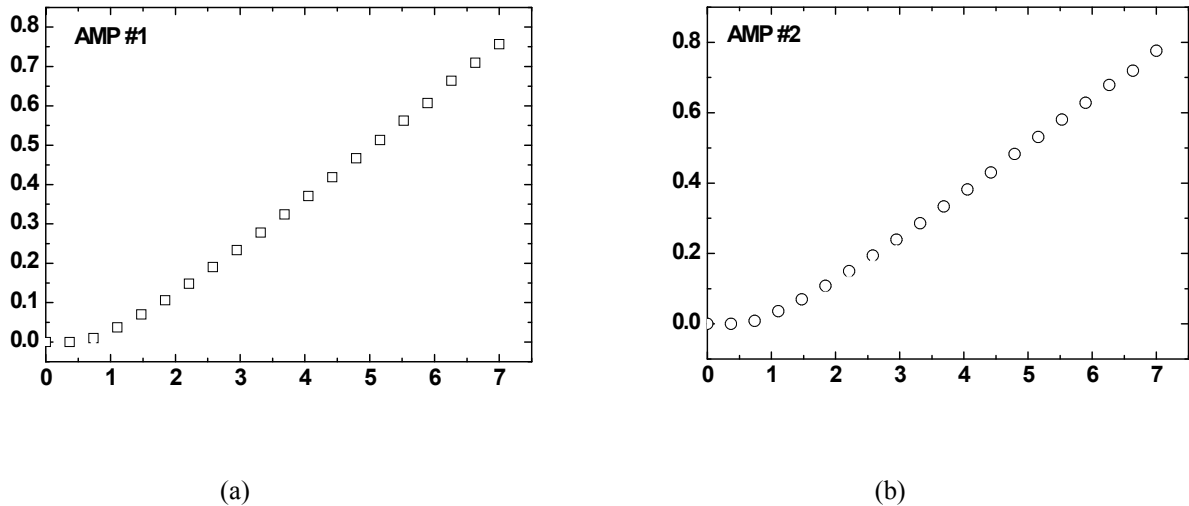


Figure 1. Dependence of the amplifier output power versus the pump current for (a) the amplifier AMP#1 based on fiber #1 (YbErP) and for (b) the amplifier AMP#2 based on fiber #2 (YbErPCe)

Then, the two tested amplifiers exhibited, before irradiation, a 19 dB gain (including a 1.4 dB attenuation of output section) 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.

Amplifiers made with the pre-treated optical fibers have close characteristics in terms of performance. A slight decrease of the output power at a given input current is observed for these amplifiers done with the #1H and #2H fibers. These amplifiers are noted AMP#1H and AMP#2H, respectively.

### 2.3 Irradiation tests

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 50 krad. All these experiments have been conducted at room temperature ( $\sim 18^\circ\text{C}$ ).

Figure 2 illustrates the experimental setup used for the online characterization of the degradation of a fiber-based Yb/Er-doped amplifier. Only the active fiber (12 m length) 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.

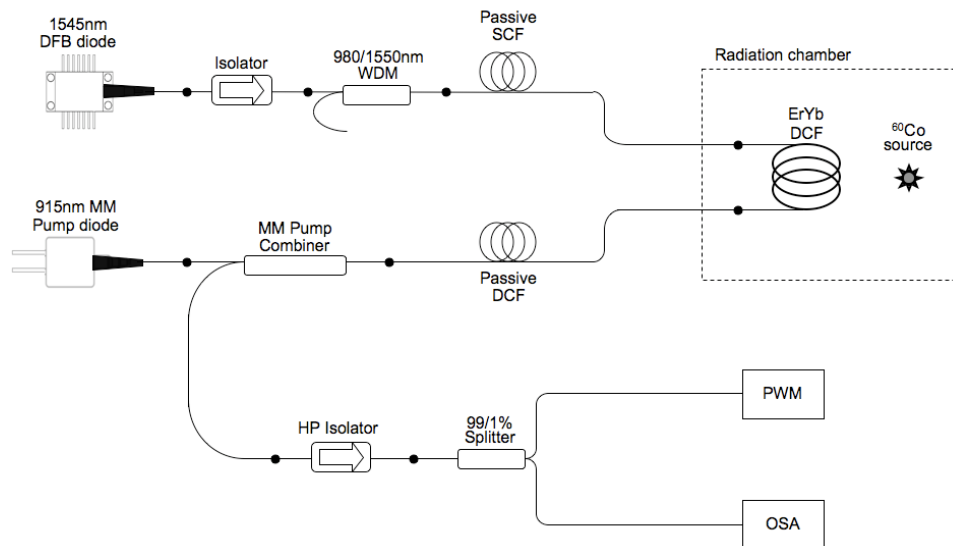


Fig.2. Experimental setup used for the characterization of RE-doped fibers in their active configuration (OSA= Optical Spectrum Analyzer, PWM= Power Meter, DCF= Double Clad Fibers, SCF= Single Clad Fiber)

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).

## 2.4 Amplifier simulation tools

We used existing models that reproduce the mechanisms leading to the infrared signal amplification in RE-doped optical fibers. These models are mainly used to optimize the performance of the amplifiers in terms of gain and noise figure without considering the radiation effects on their optical performances. To optimize amplifiers, researchers used these tools to identify the optimal amplifier design parameters (*active fiber length, pumping scheme, RE concentration, refractive-index, geometrical parameters of the fiber transversal section*) that maximize the amplification around 1550 nm. However, as the characteristics of the fiber will change with radiations, it can be clearly seen that such calculation tools, if they include radiation effects, may also be used to enhance the amplifier performance not only before irradiation but also, for example, for a space mission by a more judicious choice of these “optimal” parameters [15]. Furthermore, such an optimization of the amplifier can only be performed through simulations as it will require a too large number of samples and radiation experiments to identify the optimal system at reasonable costs.

## 3. EXPERIMENTAL RESULTS /DISCUSSION

Fig.4 presents the dose dependence of the calculated radiation-induced attenuation (RIA) measured for the 1545 nm output powers of the four amplifiers with the gamma dose. These measurements were obtained with a pump current of 7 A and the following formula:

$$\text{RIA (dB/m)} = -10/L \times \log(P(D)/P_0)$$

Where L is the fiber length used to design the amplifiers and was equal to 12m for all tested amplifiers. P(D) is the measured output power at a considered dose D and P<sub>0</sub> is the output power measured for the amplifiers before irradiation.

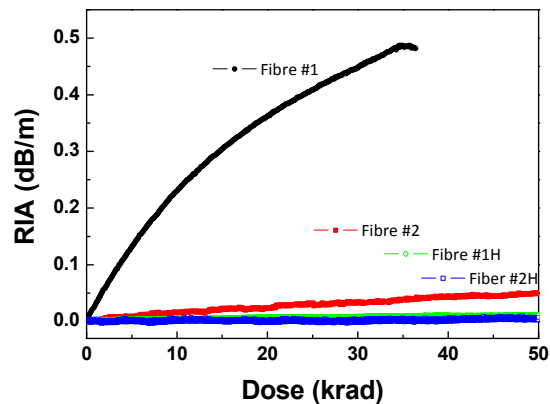


Fig.3. Dependence of amplifier output power at 1545nm versus the deposited dose (dose rate of 0.3 rad/s).

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, corresponding to 0.5 dB/m) as illustrated in Figure 3. 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. For the two amplifiers designed with the H<sub>2</sub>-loaded fibers, extremely low losses are measured and the amplifiers can be considered as unaffected by radiations. The comparison between our results and those from literature [10,11] confirm the excellent radiation tolerance of the tested optical fibers

We also used simulation tools to evaluate the hardening possibility offered by the optimization of the optical amplifier for use in a given harsh environment. Figure 4 illustrate the output power at 1545nm versus the length of fiber used to design the amplifier before irradiation and considering different doses from 7 to 70 krad. For these calculations, radiation effects have been considered taking into account the changes induced by radiation around the pump and signal wavelengths.

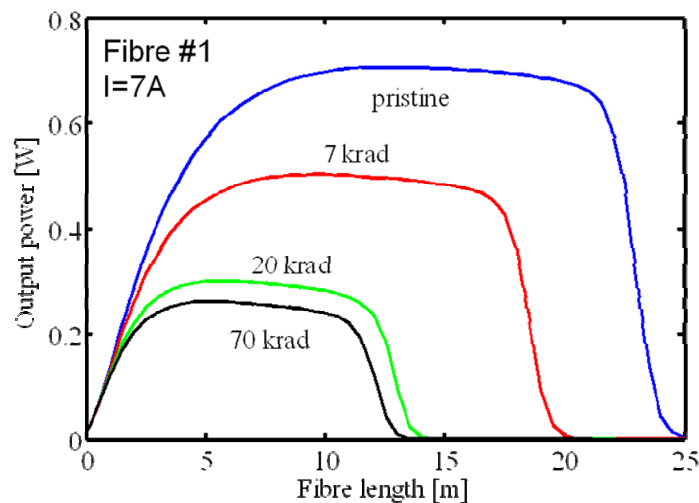


Fig.4. Simulation of the dependence of amplifier output power at 1545nm versus the fiber length at different doses.

From this comparison, it clearly appears that the more favorable length of fiber for the maximal amplification will change with the deposited dose. When the dose increases, the RIA will increase and compete with the absorption of the

pump by the rare-earth ions. In case, the RIA is so high that it results in the total absorption of the pump before the end of the used fiber length, then the gain of the amplifier will abruptly decrease. This is quickly observe for a length of 15m and will be the case, for a 12m length, if dose exceeds 70 krad from our simulation results

## 4. CONCLUSION

We have developed a new radiation-tolerant Er/Yb doped double clad optical fiber that has been used to design an amplifier at 1545 nm (gain of 20dB for an input power of 10 dBm). Our irradiation tests confirm that this amplifier is less affected by radiations than the one built with a classical phosphosilicate Er/Yb doped optical fiber. The degradation of its output power remains below 20% after an irradiation dose level of 50 krad whereas it decreases up to about 80% after 40 krad for the second one. Pre-treatment of the fibers with hydrogen allows to strongly reduce the amplifier radiation sensitivity. The exact influence of hydrogen still needs to be investigated in the future. At this time, most of the optimization of the radiative performance of our amplifier has been done by improving the radiation response of active fiber. In the future, simulations tools that are under development will be routinely used to enhance even more the behavior of our amplifiers by optimizing the amplifier parameters such as fiber length, propagative scheme ...

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