Radiation Hardening of Rare-Earth Doped Fiber Amplifiers

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***Abstract*—We investigated the radiation hardening of optical fiber amplifiers operating in space environments. Through a real-time analysis in active configuration, we evaluated the role of Ce in the improvement of the amplifier performance against ionizing radiations. Ce-codoping is an efficient hardening solution, acting both in the limitation of defects in the host glass matrix of RE-doped optical fibers and in the stabilization of lasing properties of the Er^{3+}-ions. On the one hand, in the near-infrared region, radiation induced attenuation measurements show the absence of radiation induced P-related defect species in host glass matrix of the Ce-codoped active fibers; on the other hand, in the Ce-free fiber, the higher lifetime variation shows stronger local modifications around the Er^{3+}-ions with the absence of Ce.**

***Index Terms*—Spectroscopy, Infrared Spectra, Laser Excitation, Rare-Earth Elements.**

I. Introduction

Nowadays, Rare-Earth (RE) doped fiber amplifiers have been widely deployed in many technological fields, from space to military applications. In several cases, these devices operate in harsh environments and hence the Components and Fiber manufacturers have to ensure that the devices could survive in radiative environment steadily for a long time. As a matter of fact, the performances of these devices mainly depend on the modifications induced by ionizing radiation in the RE-doped fiber glass matrix, which appears to be the most sensitive component of the amplifier system to radiation [1]. In particular, this work is focused on the analysis of the optical properties of amplifier designed for space applications. Previous studies were dedicated to identify the radiation induced centres responsible for the attenuation. Most are carried out in passive configuration [2]. Those experiments demonstrated that induced losses are principally related to radiation induced defects in the glass matrix doped in general with P and/or Al [3]. Therefore the treatments envisaged as hardening solutions should act on the host glass matrix, but up to now, the degradation mechanism of the performance and the physical action of the hardening treatments still have to be fully understood. Our experiments point out the characterization under γ-irradiation of optical fibers in active configuration (with pumping of rare earth ions (Yb, Er) during the test) as part of an integrated optical amplifier. We have analyzed the influence of Ce on the radiation response of this device, accordingly to our previous work [4] and on the basis of phenomenological studies, where most authors propose chemical composition modifications (such as the Ce-codoping) [5] as hardening solutions. We have combined with these active tests, a study in passive configuration (radiation induced attenuation (RIA) measurements), to evaluate the contribution of the glass matrix to the total attenuation. A spectroscopic study, with time-resolved luminescence measurements, is also carried out to the purpose of highlighting the optical modifications which occurred in the samples.

II. Experiment

The investigated RE-doped optical fibers were manufactured by a modified chemical vapor deposition process and were supplied by iXFiber SAS [6]. All the fibers have the same double-clad (DC) octagonal geometry, chosen to optimize the pumping mechanism. The samples are fiber prototypes elaborated *ad hoc* to highlight the role of the Ce in the amplifier response. The fiber cores were doped with P (~12 wt. %) and RE-elements (Yb, Er and Ce) by a standard solution technique. They only differ in the amount of Ce in their cores: Ce is absent in the fiber I(PYbEr) (standard active fiber), whereas its concentration is of 0.1 wt.% in fiber M(PYbErCeLow) and of 0.6 wt. % in fiber J(PYbErCeHigh). The experiments were carried out on the three optical amplifiers (A#1, A#2 and A#3), where one active fiber for each test run was integrated (fiber I, fiber M, and fiber J, respectively). Measurements were performed in active configuration: during the test, the RE-ions were pumped by a laser diode with a pump beam at 915 nm propagating inside the DC and in a counter-propagating scheme. The tested amplifiers have an indicative gain of about 18 dB. The calibrated position from the ^{60}Co source corresponds to a low dose-rate of

~3mGy/s, indicative of space radiations. We investigated the amplifier behavior up to a total deposited dose of 600 Gy for the amplifiers A#2 and A#3 and up to 400 Gy for the Ce-free amplifier A#1.

Two structurally equivalent fibers, L(PCeHigh) and N(P), were also analyzed to assess the glass matrix behavior, without the presence of active Yb and Er ions. For these latter fibers, we have carried out the RIA measurements in the near infrared (near-IR) spectral range (from 1000 to 1650 nm), within the amplifier operational emission falls; these induced loss measurements were performed with a halogen light source and a charge coupled device (CCD) detector.

Photoluminescence (PL) time-resolved measurements were performed using a pulsed laser system (Spectra Physics) with a pulse width of ~7 ns, a repetition rate of 10 Hz and a laser-line excitation of ~977 nm. The emitted light was dispersed by a spectrograph equipped with a 300 grooves/mm grating and then acquired by a semiconductor CCD camera. The acquisition was gated within a time window of 0.5 ms and with a delay time of 0.1 ms after the arrival of laser pulses.

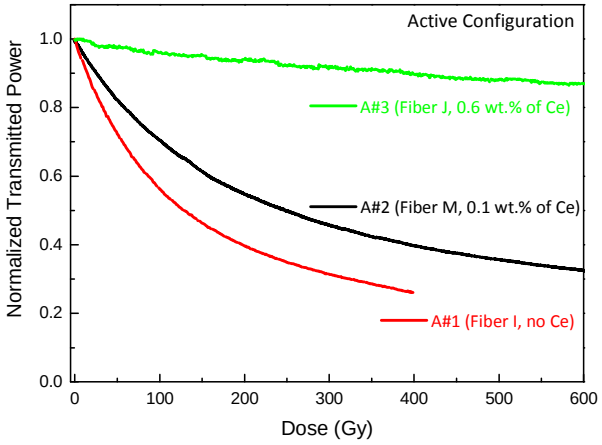

Fig. 1 Evolution of the amplifier output power at 1545 nm as a function of the γ-irradiation dose for the tested amplifiers. The curves are normalized to their maximum values to allow a direct comparison.

III. Results

Fig.1 represents the laser output power evolution of the signal at 1545 nm for the three tested amplifiers as a function of the deposited gamma dose. To better compare the radiation induced changes, the output powers were normalized to their maximum values. As shown in Fig.1, the performance of amplifiers is strictly linked to the Ce-content. Comparing the curves at 400 Gy, the output power decreases of ~75% in the standard amplifier A#1 (made with the Ce-free fiber I(PYbEr)), of ~60% in A#2, whereas the hardening effect of Ce-codoping is exploited in A#3 (based on fiber J(PYbErCeHigh)), with a degradation of ~12% up to the investigated dose of 600 Gy. From these results, we note a monotonical improvement in the radiation tolerance of the optical amplifier depending on the Ce-content (verified till 0.6 wt. %).

To improve our knowledge of the matrix degradation processes, we studied the RIA for the two structurally equivalent fibers, L(PCeHigh) and N(P). In these fibers, the absence of the active rare earth ions, Er and Yb, allows us to discriminate the contribution of the host glass combined with the only Ce-hardening codoping. The RIA curves detected by the CCD spectrometer in the near-IR signal spectral region (around 1545 nm) are reported in Fig. 2. These curves are obtained from measurements at a total deposited dose of ~300 Gy. We observe that only the fiber N(P) is affected by radiation, showing an absorbing band centered at about 1600 nm. For the Ce-codoped fiber L(PCeHigh), RIA is nearly absent.

As well as the evaluation of the Ce-codoping effect on the host glass of the active RE-ions, we also considered eventual interactions between the Ce and the Er-ions. For this purpose, we performed luminescence lifetime measurements on fiber I (standard active fiber without Ce) and fiber J (with the highest Ce content), before and after γ-ray exposure. The lifetime parameter clearly proves the ion interaction with its surroundings. In Fig. 3, we report the decay kinetics of the PL band peaked at around 1545 nm, related to Er^{3+} emission ($^4I_{13/2} \rightarrow {}^4I_{15/2}$). All the fibers present an Er^{3+}-emission IR band characterized by single exponential decay curve without dependence of the decay lifetime on the emission energy. The Ce-codoping doesn't induce variation of the lifetime value (τ = 10.3 ms) for the fiber I(PYbEr) and fiber J(PYbErCeHigh) in their pristine version. For the two irradiated fibers the results show a slight difference, with an increase in the PL lifetime up to 12.6 ms for the fiber I(PYbEr) and up to 11.4 ms for fiber J(PYbErCeHigh).

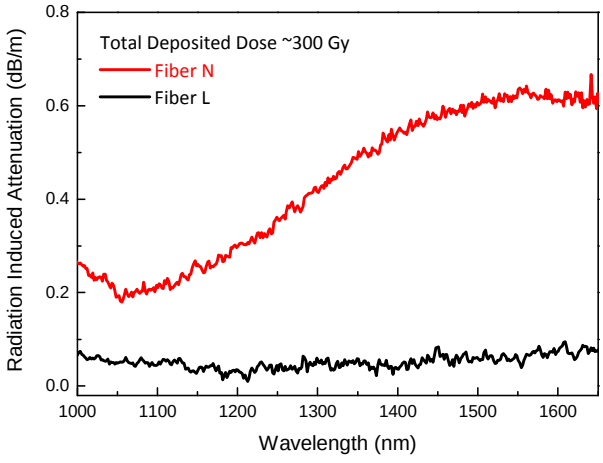

Fig. 2. RIA for fibers the N(P) and L(PCeHigh) in the NIR range. Fiber N(P) shows the typical P_1-defect absorption profile.

IV. Discussion

The radiation tests in the amplifier configuration reveal that the Ce-codoping is an efficient hardening solution for the optical amplifier based on Yb/Er doped fibers. According to the literature about the radiation hardening properties of Ce-doped silicate glasses, the common belief is based on the ability of this element of changing its valence state and this property underlies the hardening effect: the holes (electrons) generated by the γ–irradiation, otherwise involved in defect generation of the phosphosilicate glass, are easily captured by Ce^{3+} (Ce^{4+}) ions. In our works, the process is supposed through indirectly evidences. In particular, as shown in the RIA measurements in the NIR range (reported in the Fig.2), the Ce limits the presence of an absorbing center in this spectral region. We associate this absorbing defect, peaked at 1600 nm and observed in fiber N (P-doped silica core), with the P_1-center (•P≡O). In fact, it is known that the presence of Phosphorus entails P_1-formation defects under radiation, characterized by an absorbing band peaked at the same position [7, 8] of our observed defect. The P_1- defects are very stable at room temperature [8] and indeed we have checked this feature in our case with the lack of recovery after irradiation (for two hours after irradiation). Hence, we suppose that the Ce interacts with P_1 sites and/or its precursors, leading to the performance improvement of the Ce-doped optical fibers under radiations.

Moreover, we have also considered a possible influence of the Ce on the lasing properties of Er^{3+}-ion. Before the irradiation, we found that the lifetime of the IR emission of the Er^{3+} at 1545 nm is the same for the fiber I(PYbEr) and J(PYbErCeHigh), without dependence on the Ce presence.

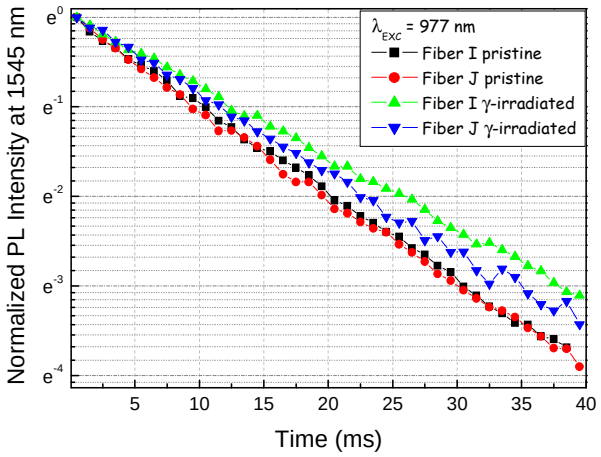

Fig. 3. Photoluminescence decay curves related to Er emission at 1545 nm (operational wavelength of the optical amplifier).

This peculiarity changes after the γ-ray exposure, with a variation higher for fiber I(PYbEr) than fiber J(PYbErCeHigh). We deduce that the local modifications of the glass structure induced by γ-ray radiation around the Er^{3+} ion are stronger in fiber without Ce than those with and this may lead to better stabilization conditions of Er^{3+} ions laser efficiency

V. Conclusions

We have shown how the Ce-codoping is an efficient hardening solution for the radiation response of optical amplifiers based on RE-doped fibers operating in space environments. The radiation induced attenuation is very low for the Ce-codoped fiber, through the limitation of defects generated at the time of irradiation and related to the host phosphosilicate glass matrix. In addition, the Ce has a role in the stabilization of the surroundings of the emitting Er^{3+}-ion under γ-ray exposure.

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