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Radiation hardened high power Er^{3+}/Yb^{3+}-codoped fiber amplifiers for free-space optical communications

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The radiation responses of different high-power Erbium Ytterbium codoped fiber amplifiers (HP-EYDFA) have been investigated up to 100 krad(SiO_2) dose levels. These devices are able to deliver 20 W of signal output power at 1565 nm by pumping at 915 nm (43 W) using radiation tolerant (Er/Yb) or radiation hardened (ErYbCe) active few mode fibers, these performances being needed for free space communications between low-orbit satellites and ground transceivers. X-ray irradiation results show that, thanks to a positive influence of the photo- and thermal- bleaching phenomena associated with such high-power operating conditions, the gain degradation levels of HP-EYDFA based on radiation hardened fibers remain below 6% after 100 krad at an accelerated dose rate of 3.4 rad/s.

OCIS codes: *(140.3490) Lasers, distributed-feedback; (060.2420) Fibers, polarization-maintaining; (060.3735) Fiber Bragg gratings; (060.2370) Fiber optics sensors.*

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Rare Earth Doped Fiber Amplifiers (REDFAs) and lasers are widely used in a broad range of applications, such as the optical telecommunication or inertial systems [1, 2]. Their high performances such as high gain, low noise figure, small volume and power budget made them a good solution for space applications too [3]. However, Telecom-grade REDFAs have been shown as very vulnerable to ionizing radiations that strongly decrease their gain [4]. It was demonstrated that the radiation induced attenuation (RIA) of the Rare Earth Doped Fiber (REDF) is mainly responsible for this gain change [5, 6]. Rather than the rare-earth ions, the RIA appeared to be due to the co-dopants such as Aluminum or/and Phosphorus that are added to the silica matrix in order to prevent ions quenching phenomena and their negative impact on the amplification mechanisms [7, 8]. The aluminum and phosphorus co-dopings lead to higher RIA levels at the pump and signal wavelengths compared to other usual dopants such as Germanium or/and Fluorine due to the specificities of their related point defects such as the P1 defect absorbing around 1.6µm and the P or Al non-bridging oxygen hole centers (Al-OHC, POHC) absorbing in the visible and strongly impacting the pump signal [9]. Various studies were carried out in order to mitigate the effect of radiations and several solutions have been suggested acting at the component level: the fiber hydrogen loading [10, 11], the Cerium codoping [12, 13] or alternative doping techniques [14]. REDFA response can also be improved at the system level by optimizing the system architecture to minimize the impact of radiations [15]. All those solutions have proved that low power (< 2W) EDFAs and EYDFAs can now withstand the dose levels associated with today (50 krad) and future (100 krad) space missions [16].

A new perspective for the REDFAs in space applications concerns their use to build satellite-ground Free Space Optical (FSO) telecommunication systems. Such photonic solution will allow to considerably increase the data transfer rate compared to actual telecommunications methods [17]. To achieve such a long distance optical link through the Earth's atmosphere, a high signal power amplification is required with an output signal power of several Watts [18]. In this case, EDFA and EYDFA appear as the best choice to amplify the signal at both the receiver and transmitter terminals. In terms of system architecture, high output power EYDFA (HP-EYDFA) can be achieved using a multistage amplification scheme such as the one described in Figure 1. A Low Power EDFA (LP-EDFA), acting as a preamplifier provides an output signal power of hundreds of mW at 1565 nm with a low noise figure and supporting low signals inputs powers of few mW. The output of this preamplifier is subsequently used as the input signal for EYDFA boost-amplifier that provides an output power reaching 20 W in the third window of telecommunication.

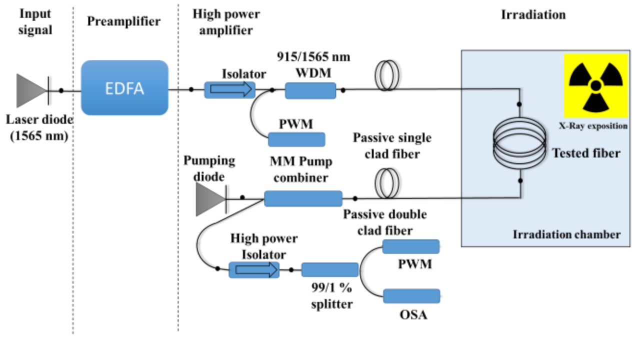

Fig. 1. HP-EYDFA architecture and scheme of the irradiation test setup. As explained in the text, the sole ErYb-codoped fiber is exposed to the X-rays.

In [10], we demonstrated that the performances of LP-EDFA designed with radiation-hardened hole-assisted carbon coated (HACC) Er-doped fibers are almost unaffected by γ-rays, with a gain reduction below 0.2 dB after 100 krad(SiO_2) for an initial gain of ~31 dB. This demonstrates that radiation hardened preamplifiers already exist. As a consequence, in this work, we focused our investigation on the study of the radiation effects on the booster EYDFA of our multistage system. To our knowledge, the radiation vulnerability of HP-EYDFAs associated with such high pump (915 nm, 50 W) and signal (1565 nm, 20 W) powers has never been investigated in literature. The radiation impact on the EYDFA gain depend on the nature and concentration of the point defects responsible for the RIA. The concentration and nature of these defects depends on numerous parameters (fiber composition, irradiation conditions, temperature, application parameters) [19]. Increasing the pump and signal powers is expected to strongly change the defect equilibrium in phosphosilicate EYDF. First, consideration of such high powers, the fiber core temperature increases up to hundreds of degree Celsius [20]. It was shown that the combined temperature-radiation effects are difficult to predict as both the defect generation and bleaching efficiencies are affected [3], even more in P-doped glasses where point defect conversion mechanisms exist between POHC and P1 defects absorbing at our wavelengths of interest [9]. Other effects, such as photobleaching, photodarkening ones or RIA impact on the fiber temperature increase are not known today and makes it impossible to predict the vulnerability of such HP-EYDFA booster under irradiation.

In this letter, we experimentally study X-ray irradiation effects (comparable to γ-rays for such fibers) on three HP-EYDFAs designed either with a radiation tolerant or with radiation hardened ErYb-codoped fibers. The amplifiers were tested in the ON-configuration (pumped during the whole irradiation run) up to 110 krad dose which is exceeding the needs for expected Satellite-Ground FSO telecommunications applications. In order to investigate the influence of the system profile of use, fibers have been irradiated in OFF mode too (passive configuration without pumping) and used post irradiation to build LP-EYDDA allowing to evaluate the impact of high pump and signal powers. For this work, three Er/Yb codoped phosphosilicate fibers have been produced by iXBlue [21] with a double clad octagonal geometry and a 12 µm core diameter. These fibers are illustrated in Figure 2a). The chosen core diameter provides a good compromise between the allowed number of guided modes at 1565nm and the achievable maximum output power for the HP-EYDA. The first sample, noted as #ErYb corresponds to a phosphosilicate fiber doped with the two rare-earth ions, representative of radiation tolerant fibers for space applications. The samples #ErYbCe and #ErYbCe+ have been codoped with two different levels of Cerium in addition to the Er^{3+} and Yb^{+3} ions (level2 > level1), and correspond to state-of-the-art radiation hardened ErYb fibers. Figure 2b) illustrates the spectral attenuation of the three fibers measured before irradiation, highlighting that the cerium codoping of the glass does not strongly change the spectroscopic properties of the Er and Yb ions, as we previously showed in [22]. Main available characteristics about the samples are reported in Table I.

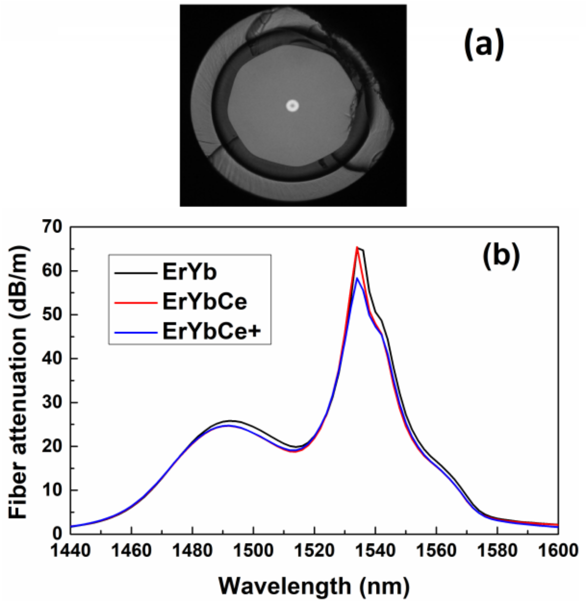

Fig. 2. a) Illustration of the three tested fiber geometries. b) Spectral attenuation of the 3 fibers in the IR domain before irradiation.

Table I. Characteristics of tested RE-doped fibers

Parameter	#ErYb	#ErYbCe	#ErYbCe+
Core diameter (µm)	12	12	11,5
1st Clad diameter (µm)	125	125	125
2nd Clad diameter (µm)	170	170	170
P (wt. %)	9	9	9
Er ($x10^{25}$ Ions/m^3)	2.4	3,3	2,9
Yb ($x10^{25}$ Ions/m^3)	37	43	39
Ce (Ions/m^3)	none	level 1	level 2
SM α @ 1.536 µm dB/m	63	58	55
MM α @ 0.915 µm dB/m	2.9	3.3	2.8

We build and test in an ON-configuration three different HP-EYDFAs using the three fibers. To obtain the 20 W output power, we selected a backward pumping configuration at 915 nm, the operating conditions described in Table II and the setup of Figure 1. As discussed, only the booster-doped fiber is exposed to radiations.

Table II. HP-EYDFA booster parameters

Parameter	values
Signal wavelength	1565 nm
pump wavelength	915 nm
Signal input power	80 mW
Operating pump power	43 W
Active fiber length	~ 5 m

The irradiation was performed at Hubert Curien laboratory in Saint Etienne, France using the X-ray machine MOPERIX delivering ~40 keV photons. The dose rate was about ~3.4 rad(SiO_2)/s, allowing for a ~ 8h30 long irradiation run to accumulate a dose of ~105 krad(SiO_2). All the irradiations were performed at room temperature and the accumulated dose was selected in order to exceed the predicted needs for targeted applications. For the post irradiation measurements, 5 m samples of each fiber were irradiated at different doses (40, 75 and 110 krad) and the same dose rate. After the irradiation, these samples were tested in a low power EYDFA configuration (~ 11 W of pumping power) in order to evaluate the impact of photo and thermal bleachings in place in the HP-EYDFA during in-situ operation test.

The performances of the three HP-EYDFA have been monitored before irradiation as a function of the 915 nm pump power. The comparison between the obtained results is reported in Figure 3. As it can be seen, despite the use of different fiber compositions, and in agreement with previous results at lower pump levels, all the amplifiers present similar behaviors, reaching ~20 W of output power at a pump power of about 43 W at 915 nm.

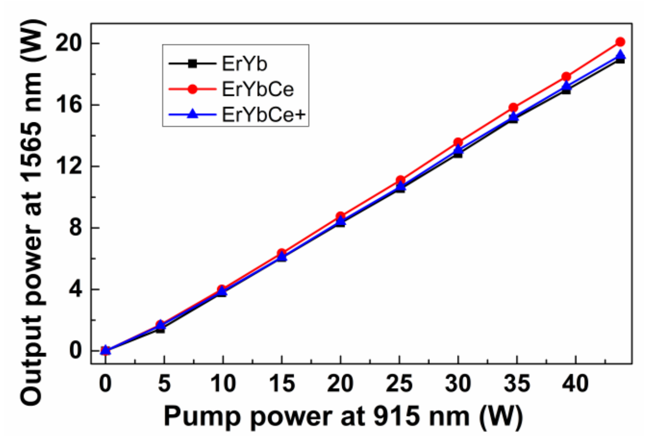

Fig. 3. Output power at 1565 nm as a function of the pump power at 915 nm for the three tested HP-EYDFA based on the three selected ErYb-doped fibers.

The gains of the three amplifiers have been monitored under irradiation in the ON configuration. For this, ~ 43 W of constant pumping power at ~ 915 nm is injected in the double clad fiber during the whole irradiation and Figure 4 gives the dose (or time at constant dose rate of 3.4 rad/s) dependence of the HP-EYDFA gains. To better compare the degradation kinetics, the gains have been normalized, the absolute values being given in Figure 4.

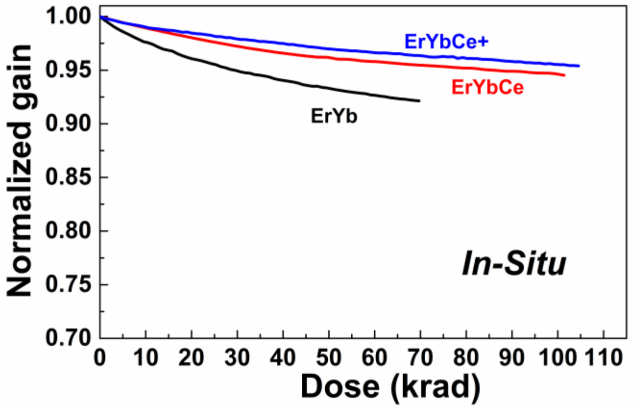

Fig. 4. *In-situ* normalized gain degradation as a function of the total accumulated dose for the HP-EYDFA designed with the #ErYb sample (black line), #ErYbCe (red line) and #ErYbCe+ (blue line) fibers

For all HP-EYDFAs, we observed a small (<10%) but clearly resolved decrease of the gain with the dose. As expected from previous studies on LP-EYDFA, the HP-EYDFA based on Ce-doped #ErYbCe and #ErYbCe+ fibers are more radiation tolerant than the amplifier made with the Ce-free #ErYb fiber. The gain degradation of about 5 and 6 % at the maximum dose (~105 krad) for the HP-EYDFA based on the #ErYbCe+ and #ErYbCe respectively, instead of ~ 8 % for the system using the #ErYb fiber at a lower dose of ~70 krad.

It is important to notice that the radiation resistance of all these HP-EYDA appears larger than the one we could expect from results available in the literature in the case of LP-EYDFAs. In particular, for a conventional LP-EYDFA based on a radiation tolerant fiber comparable to #ErYb, in [13], a gain degradation exceeding 30 % was measured for a 45 krad dose at 10 W pumping. This degradation difference is explained by a positive impact of the combined photo- and thermal-bleaching effects for the tested compositions of fibers that should reduce the impact of the POHC defects on the pump and of the P1 defects on the signal propagation [19]. This assumption is comforted by the experiments done ex situ using the active fibers irradiated in OFF configuration (passive mode) at different doses. Weeks after irradiation, the various fiber samples have been used to build LP-EYDFA and their gains are characterized under a reduced pump power of 11 W (instead of 43 W for the *In-situ* measurements). This LP-EYDFA configuration was selected to highlight the contribution of the thermal- and photo-bleaching effects on the good response of our HP-EYDFA. Fig. 5 represents the normalized gain as a function of the total accumulated dose in the *Post-Irradiation* configuration.

These test confirm that the two EYDFAs based on the Ce-doped active fibers are more radiation resistant than the one based on the Ce-free fiber and that the one made with the #ErYbCe+ fiber is also slightly more resistant than the one using the #ErYbCe fiber. Also, gain degradation levels at 110 krad are increased by a factor of 2-3 compared to ON-configuration tests. Then, for these fibers, photo and thermal bleaching effects have a major impact on the fiber behavior and then the EDFA radiation responses. During irradiation, and for such phosphosilicate fibers, the induced losses are mainly due to POHC and P1 centers. Several mechanisms are competing to establish the HP-EDFA behavior.

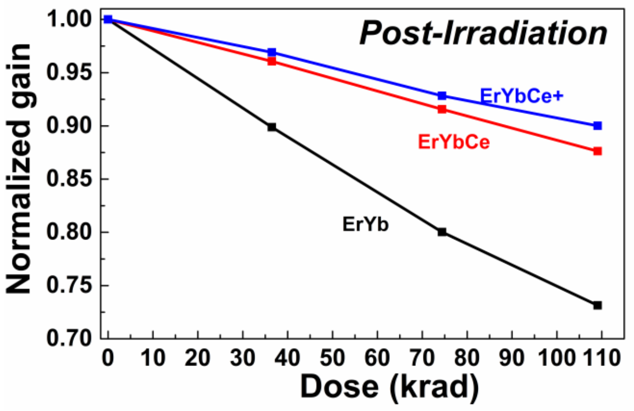

Fig. 5. *Post-Irradiation* normalized gain degradation as a function of the total accumulated dose for the LP-EYDFA designed with the #ErYb sample (black line), #ErYbCe (red line), and #ErYbCe+ fibers (blue line)

At high powers, we could expect that the RIA caused by the X-rays will enhance the thermal effects, resulting in a faster increase of the fiber temperature and then a possible accelerated gain degradation under irradiation than at room temperature. By increasing the fiber core temperature, radiation induced POHCs will become less stable [9], and one could expect lower RIA levels at the pump wavelengths to decrease if their generation efficiency is not increased [19]. For temperatures below 300°C, the POHC are bleached through conversion into P1 centers that absorb at signal wavelengths. If the core temperature remains below 300°C, RIA at the signal wavelength could increase (and the gain being affected) whereas at higher temperature, both POHC and P1 are unstable and should less contribute to RIA at the spectral domains of interest. In addition to the pure thermal effects, the high 915nm and 1565nm powers could also have some bleaching effects helping metastable defects to recover. Even if phosphosilicate fibers are not known as very sensitive to photobleaching, none study has been done at such powers, so a positive contribution of this phenomenon cannot be totally avoided.

The results obtained in this work show the positive effect of the high power on the amplifiers responses during the irradiation due to photo and thermal-bleaching phenomena. The radiation hardened sample undergoes less than 6 % of gain degradation after a total accumulated dose of about 100 krad with a dose rate of ~ 3.4 rad/s. According to those primary results, we assume that the EYDFAs could be used in harsh environments and in high power configuration. However, the other amplifier components radiation response need to be investigated to validate the whole system radiation resistance.

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