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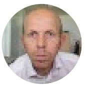

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Radiation-hard erbium optical fiber and fiber amplifier for both low- and high-dose space missions

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We present a new structure for erbium-doped optical fibers [hole-assisted carbon-coated, (HACC)] that, combined with an appropriate choice of codopants in the core, strongly enhances their radiation tolerance. We built an erbium-doped fiber amplifier based on this HACC fiber and characterize its degradation under γ-ray doses up to 315 krad (SiO_2) in the ON mode. The 31 dB amplifier is practically radiation insensitive, with a gain change of merely -2.2×10^{-3} dB/krad. These performances authorize the use of HACC doped fibers and amplifiers for various applications in environments associated with today's missions (of doses up to 50 krad) and even for future space missions associated with higher dose constraints.

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Radiation-hardened rare-earth (RE)–doped optical fibers and amplifiers are needed for current and future space programs. For example, different types of applications have been recently identified for operations at 1.55 μm by the European Space Agency, such as loss compensation in optical cross connects for microwave photonic repeaters, boosting photonics to low orbit for distribution to antennas in repeaters, a *geostationary* Earth orbit/gateway optical feeder link, optical image telemetry, intersatellite bidirectional links, and low Earth orbit to ground links [1]. For this, RE-doped fibers and fiber-based systems like amplifiers present key advantages compared to other technologies, but their integration remains limited by their high sensitivity to space radiation [2,3]. Furthermore, the investigated dose range for today's space missions remains typically below 50–100 krad; higher doses (up to 500 krad) are expected for future missions, like the Jupiter icy moon explorer. Their high radiation sensitivity is not related to the RE ions themselves but rather to the complex nature (aluminum, phosphorus-doped) of the glass matrix properties usually used in the core to enhance the RE optical amplification properties [4,5]. Radiation creates point defects related to Al or P, causing an excess of linear attenuation, called radiation-induced attenuation (RIA) at both the pump and signal wavelengths. RIA decreases the amplification efficiency (or gain) of amplifiers based on these fibers, whereas the effects of radiation on the spectroscopic properties of RE ions exist but, up to now, have been shown to have little effect on the device performance [6,7]. For a few years, different approaches have been proposed to overcome this issue. One of the most efficient ones consists in adding cerium into the RE-doped core, exploiting the competition between the generation mechanisms of the various point defects to strongly reduce the contribution of those impacting the spectral domain of interest around the pump and signal wavelengths [8,9] without degrading the amplification properties of other RE ions [10]. In this way, our research group demonstrated the high radiation tolerance of an Er/Yb-doped fiber amplifier with its 15 dB gain degradation of less than 0.2 dB after 90 krad (γ-rays, dose rate of ~1 krad/s) [8]. For applications needing low power, Er-doped fiber amplifiers (EDFAs) may be preferable, especially to reduce energy consumption. In this case, a new nanoparticle doping process (NDP) allows the incorporation of erbium in an Al-free matrix, resulting in a lowered γ-ray RIA and a gain decrease of 11% for a 15 dB erbium amplifier [11]. A last technique consists in loading the RE-doped fibers with hydrogen (H_2) or deuterium (D_2) before irradiation. Such treatment is very efficient in limiting the impact of radiation effects, but its efficiency during the space missions (up to 20 years) cannot be guaranteed with standard optical fiber coatings due to the gas outdiffusion with time [12,13]. However, carbon-coated fibers permit the gas to be kept inside the fiber [12,13], but their incorporation requires high temperature treatments (>300°C), resulting in a poor control of the gas concentrations in the fibers, which leads to optical performance degradation. In this Letter, we defined the new hole-assisted carbon-coated (HACC) erbium-doped fiber (EDF) illustrated in Fig. 1 to solve this issue.

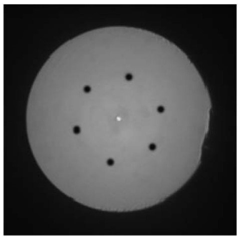

Fig. 1. HACC fiber structure.

Two versions of the same EDF, with core diameters of 2.7 µm, have been made by iXFiber SAS [14] starting from a unique preform. Core composition includes amounts of Ce to strongly reduce radiation sensitivity, as will be demonstrated in this letter by comparison with literature results. The hole-free fiber is called radiation tolerant acrylate coating (RTAC) fiber. The 125 µm silica cladding of HACC fiber includes an arrangement of six holes allowing an efficient and homogeneous loading of the fiber with H_2 or D_2 after the deposition of the hermetic carbon coating (20–30 nm). The holes were created at the preform manufacturing stage using standard glass processing techniques. In the studied fiber, the hole diameter was 3 µm, but neither hole diameter size nor hole number plays a critical role in the HACC positive impact on EDFA radiation resistance.

This is an innovative and impactful technique that solves the problem of gas-loading of fibers through hermetic carbon layers that degrades the erbium ion lasing performances at the same time it reduces the fiber radiation sensitivity. Without the carbon layer, H_2 or D_2 are diffused in a few days outside the silica part of the fiber, eliminating the positive influence of the gas presence on the RIA. After the HACC fiber loading with H_2 or D_2 through the holes, outgassing mechanisms are limited to those occurring through the walls of the axial channels running along the fibers and then out of the fiber ends, being 10 times less efficient than those occurring in non-carbon-coated optical fibers. Finally, after both ends of the EDF are spliced to the passive components of the EDFA, outgassing only remains possible through the two ends of the RE-doped fiber and appears very limited. To quantify this, we applied to a 5 m H_2-loaded sample an accelerated thermal treatment at 80°C for more than 440 h followed by a five-month period at room temperature (~25°C). We estimated the H_2 presence by monitoring the attenuation around 1250 nm related to one of the well-known H_2 absorption bands [15]. The obtained results are illustrated in Fig. 2. We observe an important decrease in the H_2 content during the first step of measurements. This is explained by the fact that during the fiber splicing at both ends for loss measurements, the holes become H_2-free. After closing the fiber, a partial pressure equilibrium is quickly obtained between the holes and the silica by diffusion of H_2 from the silica part to the air holes. After this equilibrium is achieved, the H_2 concentration decrease in the core slows down with a 10% decrease after more than 420 h at 80°C (in a fully saturated standard fiber, this decrease is observed in about 3.6 h). After five months at room temperature, a limited diffusion of less than 10% of the H_2 is observed. From these tests, we estimate that we reduce the kinetics of gas outdiffusion by a factor of more than 100. This factor can probably be increased with appropriate fiber structure and by using a greater length of EDF than 5 m. This structure greatly improved the long term positive impact of H_2 or D_2 loading.

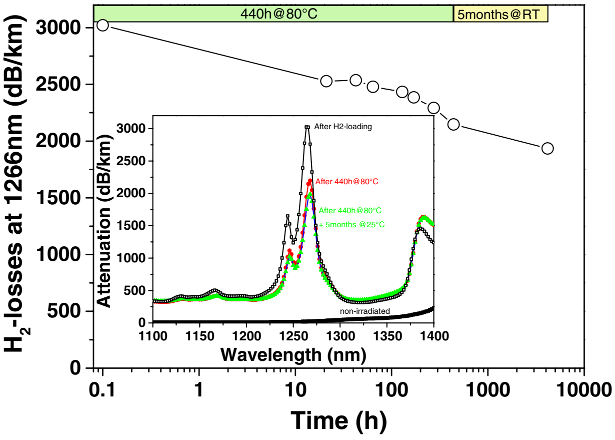

Fig. 2. Evolution of the H_2-related absorption band at 1266 nm in the HACC optical fiber submitted to different thermal treatments at 80°C and 25°C. Inset illustrates the spectral dependence of the attenuation measured in this fiber before loading and at different times after the gas loading.

Another advantage of this HACC fiber structure is that the H_2 or D_2 level can also be precisely adjusted to determine the best compromise between the radiation hardening of the fiber and its optical performances before irradiation. This is done through the monitoring of the H_2- (1240 nm) or D_2-related (1720 nm) absorption bands in the infrared part of the spectrum and its impact on the background losses of the EDFA. Indeed, optimizing the H_2 (D_2) content before and even during the space missions becomes possible.

Two amplifiers have been designed with ~10 m of the two EDFs. Their gains vary for a 100 mW pump power at 976 nm from 31.8 dB for the RTAC-EDFA to 31 dB for the HACC-EDFA (input power of −20 dBm in both cases). For the results presented in this Letter, the HACC fiber was treated with D_2 for 43 h at 80°C and 70 bar. For this fiber, the compromise between radiation hardness and optical performances was obtained after 16 h of D_2 outgassing at atmospheric pressure and 80°C with holes "open"; after that the fiber was spliced with the other parts of the amplifier. The HACC hardening approach does not significantly impact the amplifier response before its exposure to radiation, and very efficient EDFAs can be designed using such fibers.

Irradiation of EDFAs was performed using the ^{60}Co source from CEA, France. The tests were done at room temperature with a dose rate of ~680 rad/h up to a dose of 315 krad. Our experimental setup is illustrated in Fig. 3. The EDF is the only part submitted to radiation; all other EDFA parts are located in an instrumentation zone. The tested amplifiers used a continuous forward pumping configuration and were made with the RTAC-EDF or with the D_2-loaded HACC-EDF.

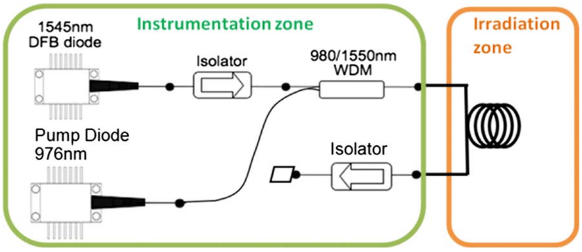

Fig. 3. Experimental setup used for the characterization of the radiation response of the HACC and RTAC fiber-based amplifiers.

Two test configurations were used. The “ON” mode corresponds to a continuous pumping of the active EDF during the whole irradiation campaign (several weeks), which will maximize possible photobleaching effects [16] and is the most realistic compared to a space profile of use. In the “OFF” mode, the pumping of the fiber under test is only achieved at the time of the gain measures whereas between these measurements the active fiber is not pumped, resulting in the influence of photobleaching. One interest of this OFF mode is to provide a worst-case estimation of the amplifier vulnerability, and another one is to allow us to compare the obtained results with those from literature acquired in these conditions.

Figure 4 compares the γ-ray induced gain degradation measured for both EDFAs versus the deposited dose in the ON mode (room temperature, dose rate of 680 rad/h).

The gain decrease remains limited for both EDFAs and evolves nearly linearly with the dose. From the data, we can extract a dose dependent degradation coefficient of -2.2×10^{-3} dB/krad for the HACC EDFA, which is almost 10× better than that measured for the RTAC EDFA (-24×10^{-3} dB/krad). To better evaluate the radiation hardness of these fibers and EDFAs, we compared our obtained results to those published in [11], which to our knowledge represent the current state of the art for radiation tolerant EDFs and amplifiers. Their results were obtained in an OFF mode, and for their fibers, they also observed a quasi-linear dose dependence of the gain degradation with dose. We show in Fig. 5 the results they obtained for their best (NP-Si+, Al-free by NDP) and worst (Al-doped, typical of commercial erbium fibers) EDFA as well as our results obtained in the OFF mode. Before irradiation, the amplifiers exhibited very different gains (about 15–18 dB for [11] instead of 30–31 dB for this work), so we compared the percentage gain decrease observed for each fiber. A 100% gain decrease corresponds to no amplification of the input signal.

The first important result can be evaluated from the comparison between the RTAC and the NP-Si+ fiber-based amplifiers. Percentage gain decrease is significantly lower in the RTAC-EDFA than in the “radiation-hard” NP-Si+ amplifier, confirming the very good radiation tolerance of the amplifier based on the optimized composition core (dose rate effects can be neglected in the used range [11]). Furthermore, this radiation tolerance is, as for the ON configuration, greatly improved for the HACC-EDFA, with an extrapolated degradation of the gain below 10% at 300 krad. We summarized the results of the ON and OFF configurations below, providing evidence of a positive photobleaching effect related to the pumping.

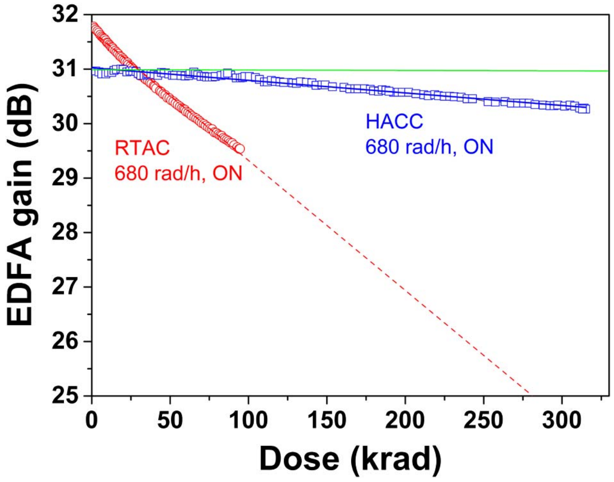

Fig. 4. Degradation in the gain of the EDFAs designed with a HACC-EDF and with a RTAC-EDF of same compositions. Configuration test was ON mode, room temperature.

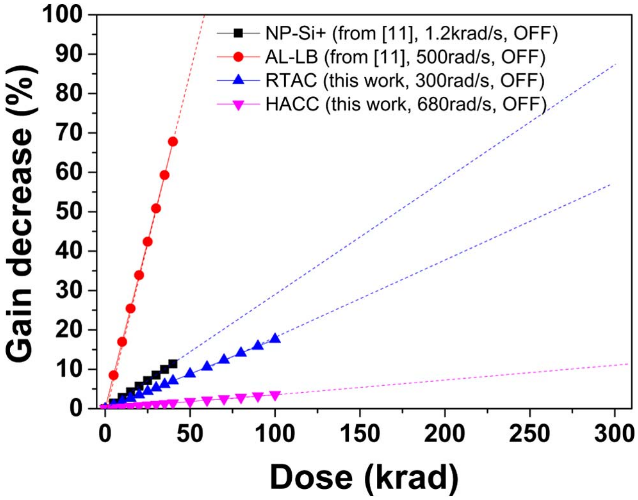

Fig. 5. Comparison between the EDFAs’ gain decrease (%) designed with a HACC-EDF and with a RTAC-EDF measured in the OFF mode with the results presented in [11] for the best and worse tested fibers. Symbols represent best linear fits of experimental results; dashed lines represent extrapolation to higher doses.

For the RATC-EDFA, the gain decrease in the OFF mode is of -56×10^{-3} dB/krad instead of -24×10^{-3} dB/krad for the ON mode. For the HACC-EDFA, the gain decrease in the OFF mode is -11×10^{-3} dB/krad instead of -2.2×10^{-3} dB/krad for the ON mode.

In conclusion, a new structure for erbium-doped optical fiber (HACC) is shown to strongly enhance the radiation hardness of this class of optical fibers. Such a fiber, in addition to an optimized Ce-doped composition in the core, leads to the construction of a high-performance EDFA with a gain of 31 dB. We characterized its degradation under γ rays up to doses of 315 krad. The amplifier is minimally sensitive to radiation, with a gain change of merely -2.2×10^{-3} dB/krad in the ON mode up to this dose (-11×10^{-3} dB/krad in the OFF mode, up to ~100 krad) that makes this technology an excellent candidate for the most challenging applications associated with future low- and high-dose space missions. Future work will focus on the complete characterization of the HACC structure influence on spectroscopic properties of RE ions and on the amplifier design improvement by the coupled simulation/experiments approach we recently validated on Er/Yb-doped amplifiers [17].

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