Recent Advances on Radiation-Hardened Optical Fiber Technologies

Sylvain Girard[1], Thierry Robin[2], Adriana Morana[1], Gilles Mélin[2], Alexandre Barnini[2], Aziz Boukenter[1], Benoit Cadier[2], Emmanuel Marin[1], Laurent Lablonde[2], Arnaud Laurent[2], Youcef Ouerdane[1]
1. *Univ Lyon, UJM-Saint-Etienne, CNRS, Graduate School Optics Institute, Lab. Hubert Curien UMR5516, Saint-Etienne, F-42023,France*
2. *iXblue Photonics, Lannion, F-22300,Lannion, France*
Author e-mail address: sylvain.girard@univ-st-etienne.fr

Abstract: Silica-based optical fibers possess key advantages for integration in radiation-rich environments as parts of communication systems, laser sources, optical amplifiers, diagnostics and point or distributed sensors. We reviewed how the understanding of the basic mechanisms of radiation effects can be exploited to optimize their tolerance to the most challenging environments.© 2020 The Author(s).

1. Fiber-based applications in radiation environments

The potential of optical fiber-based technologies has been investigated for a variety of environments associated with very different radiation constraints. Fig.1. classifies them using three parameters: the dose (*deposited energy in the material, expressed in Gy with 1 Gy=1 J/kg*), the dose rate (*speed of energy deposition, in Gy/s*) and the temperature [1,2]. For all these environments (*space, nuclear industry, fusion-related facilities, high energy physics*), optical fibers have been considered for high-speed, high-bandwidth communications and sensing. For space, a very important application concerns the development of free space optical communications that require the qualification of tolerant rare-earth doped optical fibers for the building of laser sources or optical amplifiers [2]. For high energy physics facilities and nuclear industry (*in core monitoring, dismantling operations, waste repository*), numerous studies [3,4] are today conducted to implement fiber-based distributed sensing solutions with the goal to multiply the number of sensing points, reduces the intrusiveness and increases the performances of the monitoring sensor network; ultimately reducing the sensor associated nuclear wastes.

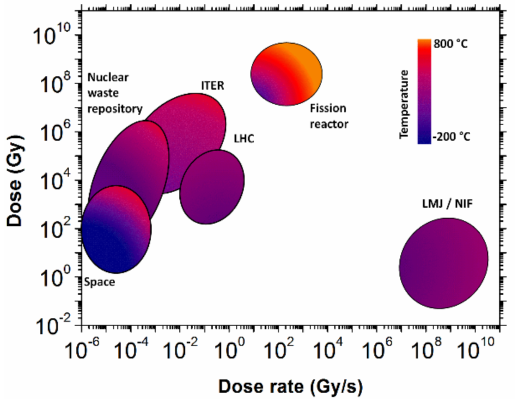

Fig. 1. Radiation environments of interest for implementation of optical fiber sensing technologies

2. Radiation effects on optical fibers

At the macroscopic scales, radiation leads to three main changes in the properties of single-mode (SMF) or multimode (MMF) optical fibers. The radiation induced attenuation (RIA) decreases the waveguide transmission capacity. RIA levels, growth and decay kinetics during and after the irradiation depend on several parameters some are intrinsic to the fiber (*composition, production processes,…*), while others are extrinsic: environmental parameters (*type of radiations, dose, dose rate, temperature*) or the fiber profile of use (*operating wavelength, injected light power, …*) [1]. As an example, when the SMF28© fiber from Corning is exposed, at room temperature (RT), to a high dose rate X-ray pulse (> 1 GGy/s, 100 Gy) representative of those expected during fusion by inertial confinement experiments, its attenuation at 1.55 µm can increase from 0.2 dB/km before the shot to up to 2×10^3 dB/km during the irradiation, then decreasing seconds later to a few tenths of dB/km after the X-ray pulse [1]. During steady state X-ray irradiation at lower dose rate (~6 Gy/s) but higher doses (1 MGy), the RIA at 1.55µm of the most radiation hardened optical fibers (*pure silica core or F-doped core*) is of is around of ~10 dB/km, whereas it's ~250 dB/km for the one of germanosilicate fibers and very high, above 10^4 dB/km, for fibers containing either P or Al dopants [5]. The RIA is caused by radiation induced point defects, also known as color centers, in the silica network. These defects are associated with optical absorption bands peaking in the silica transmission windows. Most of the absorption bands are located in the ultraviolet and visible parts, explaining that, usually, the RIA levels decrease at larger wavelengths [5]. Depending on the nature of dopants (*Ge, P, F, Al, N…*) used to design the fiber refractive-index profile, point defects are generated with various optical and structural properties as well as thermal stabilities, explaining the very different observed fiber RIA levels and kinetics. Some of these defects also present emission properties, leading to the so-called radioluminescence during the fiber exposure. In addition to the possible contribution of Cerenkov light, the radiation induced emission (RIE) can decrease the signal-to-noise ratio. Numerous studies have been conducted to identify mitigation solutions to limit the RIA and RIE impact. However, both RIA and RIE can also be exploited to build very efficient radiation detectors and dosimeters [2]. Finally, radiation, especially very high fluences of neutrons change the refractive index of the silica through the radiation induced compaction phenomenon [6]. This last effect, less studied, could particularly affect the sensor performances.

3. Radiation effects on passive SMFs and MMFs: towards radiation hardened fibers for high doses

As illustrated in Fig.1, numerous applications require radiation-hardened SMFs for data transfer at the IR Telecom wavelengths at doses exceeding 100 kGy(SiO_2). In particular, huge research was conducted to identify and qualify a SMF allowing to fulfill the CERN requirements in terms of optical performances and radiation tolerance [7]. Since this work, additional studies have been done to extend the application range of such radiation hardened SMFs from the communication to the sensing domain to ensure their compatibility with the existing distributed sensing technologies (Rayleigh, Brillouin and Raman) able to operate under such harsh constraints. In particular, the surface plasma chemical vapor deposition (SPCVD) technique sounds very promising to design radiation hardened SMFs with low IR-RIA [8]. Furthermore, the impact of radiation on the fiber mechanical strength has been investigated in order to determine the most appropriate coating type (acrylate, polyimide, metal) according to the experienced temperature of the irradiated fiber [8,9]. Fig.2 (left) shows the 1.31 µm RIA growth kinetics of such radiation-hardened SMF at different dose rates of γ-rays while Fig.2 (right) illustrates the Weibull tests of a polyimide-coated radiation hardened SMF before and after its 10 MGy irradiation at 90°C. Those results pave the way towards safe operation of distributed fiber sensors over several hundred meters under extreme dose environments

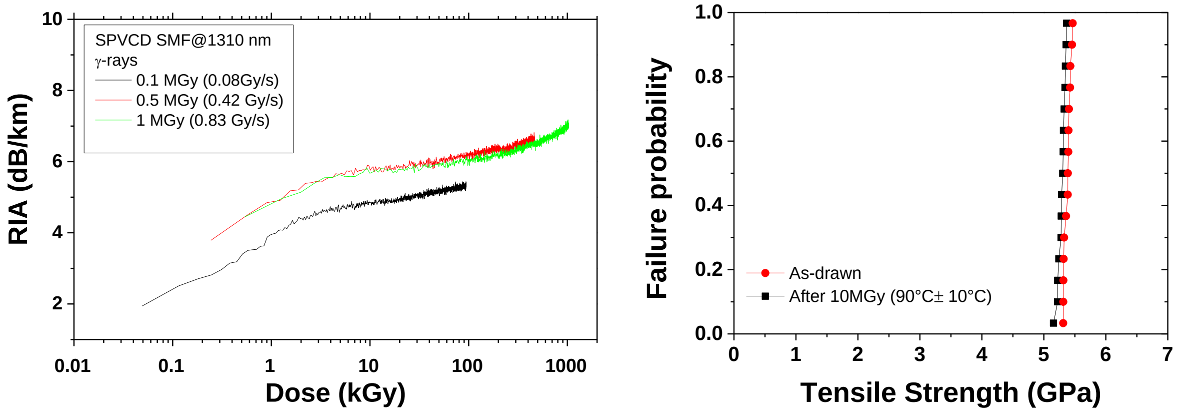

Fig. 2. left) γ-ray RIA at 1310 nm (RT) in radiation hardened SPCVD SMF [8] right) Tensile strength versus failure probability before/after 10 MGy(90°C) irradiation of a polyimide coated fiber (see [8] for more details).

Radiation hardened MMFs, especially those operating in the UV and visible, are needed for the plasma diagnostics of ITER and the laser diagnostics of Megajoule class lasers [1]. For these applications, studies showed that pure and F-doped core MMFs are good candidates but the achievements of low RIA levels imply to work on their impurity levels and on the glass stoichiometry or to treat the fibers with hydrogen or deuterium gases [10].

4. Radiation effects on active optical fibers: towards radiation hardened optical fibers for space needs

Different classes of optical fibers are today used in space: telecom grade SMFs and MMFs, polarization-maintaining optical fibers, rare-earth doped optical fibers (REDFs). Among them, the standard versions of Er and ErYb-doped fibers used in optical amplifiers are the most radiation sensitive, having RIA levels at the pump and signal wavelengths sufficiently high to strongly degrade the amplifier gain during irradiation. The vulnerability of REDFs is explained by the codoping of their cores with either Al or P, in order to enhance the signal amplification process. To overcome this limitation, radiation hardening approaches have been proposed, acting first at the material level. It has been shown that the Cerium codoping of the REDF core greatly reduces the RIA levels in ErYb-doped optical fiber and that a pre-loading of both fiber types with H_2 or D_2 gases ensures to maintain the low power (<2 W) amplifier gain during irradiation. To enhance the efficiency of this last technique, specific fiber structures have been suggested: the hole-assisted carbon coated (HACC) optical fibers [2]. Fig.3 illustrates the gain decrease of an Erbium doped fiber amplifier (EDFA) designed with such HACC fiber loaded with D_2 showing that amplifiers are available for the most challenging future missions, eg. to the Jupiter moons [2]. Today, the remaining challenge is to ensure a good radiation resistance of high power (>10W around 1550 nm), for which the radiation effects will combine with the thermal constraints associated to the use of high pump and signal powers.

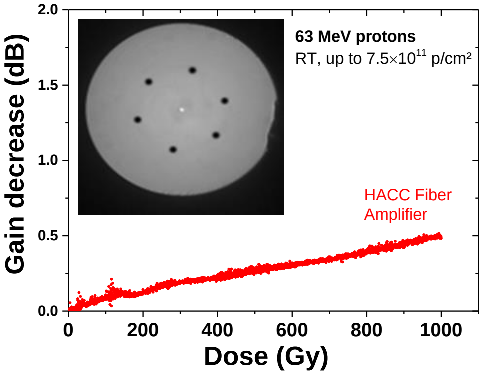

Fig. 3. Radiation induced gain decrease in an EDFA (gain of 27 dB before irradiation) designed with a HACC Er-doped fiber (loaded with D_2) under 63 MeV proton exposure up to 7.5×10^{11} p/cm² a t RT.

5. Conclusions

Optical fibers and fiber-based sensors present key advantages for operation in radiation environments compared to the alternative microelectronic technologies. Even if radiation affects their optical properties through radiation-induced attenuation or radiation-induced emission, hardening techniques have been identified ensuring that radiation hardened SMFs and MMFs are today available for data transfer, diagnostics and sensing applications.

6. References

[1] S. Girard, J. Kuhnhenn, A. Gusarov, B. Brichard, M. Van Uffelen, Y. Ouerdane, A. Boukenter and C. Marcandella., "Radiation Effects on Silica-Based Optical Fibers: Recent Advances and Future Challenges," in IEEE Transactions on Nuclear Science," **60** (3), 2015-2036 (2013).
[2] S. Girard, A. Morana, A. Ladaci, T. Robin, L. Mescia, J-J. Bonnefois, M. Boutillier, J. Mekki, A. Paveau, B. Cadier, E. Marin, Y. Ouerdane and A. Boukenter, "Recent advances in radiation-hardened fiber-based technologies for space applications," J. Optics **20 (**9), 093001 (2018)
[3] S. Delepine-Lesoille, S. Girard, M. Landolt, J. Bertrand, I. Planes, A. Boukenter, E. Marin, G. Humbert, S. Leparmentier, J-L. Auguste and Y. Ouerdane, "France's State of the Art Distributed Optical Fibre Sensors Qualified for the Monitoring of the French Underground Repository for High Level and Intermediate Level Long Lived Radioactive Wastes," Sensors **17**, 1377 (2017).
[4] D. Di Francesca, G. Li Vecchi, S. Girard, A. Morana, I. Reghioua, A. Alessi, C. Hoehr, T. Robin, Y. Kadi, and M. Brugger, "Qualification and Calibration of Single-Mode Phosphosilicate Optical Fiber for Dosimetry at CERN," J. Lightwave Technol. **37**, 4643-4649 (2019)
[5] S. Girard, A. Alessi, N. Richard, L. Martin-Samos, V. De Michele, L. Giacomazzi, S. Agnello, D. Di Francesca, A. Morana, B. Winkler, I. Reghious, P. Paillet, M. Cannas, T. Robin, A. Boukenter, Y. Ouerdane, "Overview of radiation induced point defects in silica-based optical fibers," Reviews in Physics **4**, 100032 (2019).
[6] L. Remy, G. Cheymol, A. Gusarov, A. Morana, E. Marin and S. Girard, "Compaction in Optical Fibres and Fibre Bragg Gratings Under Nuclear Reactor High Neutron and Gamma Fluence," IEEE Trans. Nucl. Sci. **63** (4) 2317-2322 (2016).
[7] T. Wijnands, K. Aikawa, J. Kuhnhenn, D. Ricci and U. Weinand, "Radiation Tolerant Optical Fibers: From Sample Testing to Large Series Production," Journal of Lightwave Technology **29** (22), 3393-3400 (2011).
[8] G. Mélin, A. Barnini, A. Morana, S. Girard, P. Guitton and R. Montron, "Combined effect of radiation and temperature: towards optical fibers suited to distributed sensing in extreme radiation environments," Poster PE-1, 30th Conference RADECS 2019, September 2019.
[9] G. Mélin, P. Guitton, R. Montron, T. Gotter, T. Robin, B. Overton, A. Morana, S. Rizzolo, S.Girard, "Radiation Resistant Single-Mode Fiber With Different Coatings for Sensing in High Dose Environments," IEEE Trans. Nucl. Sci. **66** (7), 1657-1662 (2019).
[10] B. Brichard, A.L. Tomashuk, H. Ooms, V.A .Bogatyrjov, S.N. Klyamkin, A.F. Fernandez, F. Berghmans, and M. Decréton, "Radiation assessment of hydrogen-loaded aluminium-coated pure silica core fibres for ITER plasma diagnostic applications" Fusion Engineering and Design 82, 2451-2455 (2007).