Official URL: https://doi.org/10.1109/RADECS.2015.7365653

To cite this version :

Rizzolo, Serena and Boukenter, Aziz and Périsse, Jocelyn and Bouwmans, Géraud and El Hamzaoui, Hicham and Bigot, Laurent and Ouerdane, Youcef and Cannas, Marco and Bouazaoui, Mohammed and Macé, Jean Reynald and Bauer, Sophie and Girard, Sylvain Radiation Response of OFDR Distributed Sensors Based on Microstructured Pure Silica Optical Fibers. (2015) In: 2015 15th European Conference on Radiation and Its Effects on Components and Systems (RADECS), 14 September 2015 - 18 September 2015 (Moscow, Russian Federation).

Radiation Response of OFDR Distributed Sensors Based on Microstructured Pure Silica Optical Fibers

S. Rizzolo, A. Boukenter, J. Périsse, G. Bouwmans, H. El Hamzaoui, L. Bigot, Y. Ouerdane, M. Cannas, M. Bouazaoui, J-R Macé, S. Bauer and S. Girard, *Senior Member, IEEE*

***Abstract*- Temperature sensors based on microstructured pure silica optical fibers are investigated by OFDR and RIA performed during X-ray irradiation up to 50kGy dose. The results evidence that the temperature measures are poorly influenced by irradiation (the error being less than 0.3 °C). Such a radiation tolerance is relevant for the use of these Rayleigh based sensors in harsh environments.**

***Index Terms*—Optical fiber sensors, radiation, Rayleigh scattering.**

I. INTRODUCTION

FIBER-BASED applications such as sensors, diagnostics…, have recently attracted much interest for their use in harsh environments associated with nuclear power plants, space or high energy physics facilities. Fast response, reduced volume and weight and electromagnetic immunity are some advantages obtained from their employment, in addition to the possibility to monitor several environmental parameters such as temperature, strain and radiation dose by replacing punctual sensor technologies with one sensor exploiting the optical fiber sensitivity to external changes.

In the panorama of fiber-based distributed sensing techniques [1]-[3], Optical Frequency Domain Reflectometry (OFDR) is one of the most promising because it offers the best spatial resolution of few µm over 70 m of fiber length [4]. Before integration of the OFDR -based systems in harsh environments, their tolerance to the constraints associated with the presence of high levels of radiations has to be demonstrated. Indeed, it is well known that irradiation induces point defects along the optical fiber core and cladding thus leading to the transmission degradation along the fiber length through radiation induced attenuation (RIA) phenomena [5]. For fiber-based distributed sensors, RIA affects the sensing range of the device; it depends on different parameters, a crucial one being the nature of the dopants used to modulate the refractive index profile of the fiber core and cladding [6]-[7].

The development of microstructured optical fibers (MOFs) is one of the most innovative progresses in the field of optical waveguides. These fibers present wavelength scale structures with a refractive index contrast that provides them unusual properties [8]. Two types of MOFs are usually distinguished: photonic bandgap (PBG) MOFs in which the light remains confined in a low index core thanks to a PBG cladding and high index core fibers in which light is guided via modified total internal reflection (MTIR).

PBG MOFs are very promising for radiation environments because they exhibit lower RIA than other fiber types [9]-[10], but several issues limit their employment such as the fiber reliability, the fiber splicing with other fibers, sources or detectors and also their higher costs. On the other hand, MTIR MOFs are easier to handle and present several useful properties that could be exploited to design new laser or plasma fiber-based diagnostics. Another possible advantage, under irradiation and for fiber sensing, consists in their homogeneity in terms of glass properties. Such fibers can be made using a unique glass composition, without dopants addition to limit the fiber transmission degradation [5] or with limited residual strain occurring from the different properties of core and cladding glasses.

In this work we study steady state effects on Rayleigh radiation response of MOFs for distributed temperature sensors up to 50 kGy(SiO_2) dose levels. We compare the temperature changes monitored during irradiation by a thermocouple and through an OFDR sensor interrogating the MOFs. A characterization of spectral RIA is also reported to evaluate the limitation of the employment of this kind of fiber in harsh environments.

II. MATERIAL AND METHODS

A. Investigated samples

Two air/silica MOFs have been fabricated by the PhLAM laboratory in Lille (France) by the stack and draw technique. Both fibers present the same micro-structuration with a hole

Serena Rizzolo is with Université de Lyon, Université de Saint-Etienne, Laboratoire Hubert Curien UMR CNRS 5516, F-42000 Saint-Etienne, France, and also with Dipartimento di Fisica e Chimica, Università degli Studi di Palermo, 90100 Palermo, Italy (e-mail: serena.rizzolo@univ-st-etienne.fr).
A. Boukenter, Y. Ouerdane, S. Girard are with Université de Lyon, Université de Saint-Etienne, Laboratoire Hubert Curien UMR CNRS 5516, F-42000 Saint-Etienne, France.
G. Bouwmans, H. El Hamzaoui, L. Bigot, M. Bouazaoui are with PhLam Laboratory, Université de Lille, Lille, France
M. Cannas is with Dipartimento di Fisica e Chimica, Università degli Studidi Palermo, 90100 Palermo, Italy.
J. Perisse, J-R Macé and S. Bauer are with AREVA, France.

diameter of 1.8 μm and a pitch Λ =3.85. MOF1 is entirely made of pure-silica glass F300 tubes with a special procedure to ensure a limited concentration of OH group at the tube surfaces that is known to cause an excess of optical losses. MOF2 fiber core originates from a Sol-Gel silica containing as well a low OH concentration (<1ppm) [11]) and is combined to Hereaus silica capillaries for the cladding region.

B. *Irradiation facility*

The irradiations are performed using the X-ray source facility (MOPERIX) at the Laboratoire Hubert Curien (Saint Etienne, France). The dose-rate is (4.5±0.2) Gy/s during Rayleigh measurement and the reached dose is ~50 kGy(SiO_2). Temperature during irradiation is measured by a T type thermocouple and a Picolog temperature reader.

C. *Distributed measurements*

Distributed sensing measurements were done thanks to an Optical Backscatter Refectometer (OBR) 4600 from Luna Technologies. In all measurements described below the laser source was tuned over a range of 21 nm centered around 1550 nm (with a wavelength accuracy of 1.5 pm), yielding to a nominal spatial resolution of the Rayleigh scatter pattern of 40 μm along the investigated optical fiber propagation axis. *In situ* OBR measurements are performed under X-rays on ~1 m -long fiber spooled on an aluminum plate in a circular zone of constant dose rate with a diameter of 8 cm. The acquisition is made every 5 sec and temperature is monitored by the comparison with data from a thermocouple data stuck on the same plate inside irradiation zone and close to the fiber.

D. *RIA measurements*

The fibers were characterized with another setup allowing measuring the temporal (5 s time resolution) and spectral dependence (900-2200 nm) of the RIA during and after the X-ray irradiation. To this aim, we used a laser-driven light source (EQ99 from Energetic) and a near-IR spectrophotometer NIRQuest 512. Here again, the temperature is monitored during the measurements.

III. Experimental Results

To investigate the transient radiation effect on OFDR, we irradiated our samples up to a total dose of ~50 kGy at a dose rate of (4.5±0.2) Gy/s through 3 hours run duration. In Fig. 1 (a) and (b) are reported the obtained results.

We followed at the same time temperature evolution with a thermocouple placed near the fiber in the irradiation zone. By comparing the temperature measured by OBR and the thermocouple we highlight the differences caused by the fiber irradiation. The direct comparison of rough data is also reported in the inset of Fig. 1 (a) and (b) for both irradiations.

We observe that, in both samples, there is no evidence of an error induced by radiation on OFDR sensor: indeed temperature difference remains stable during all the run time. In the case of MOF1 these differences varies between -0.1 °C and 0.2 °C while in MOF2 we observe changes between -0.3 °C and 0.1 °C. These differences in both cases remain within 3σ range around the mean values during the whole run, as shown by dotted lines in the graphs.

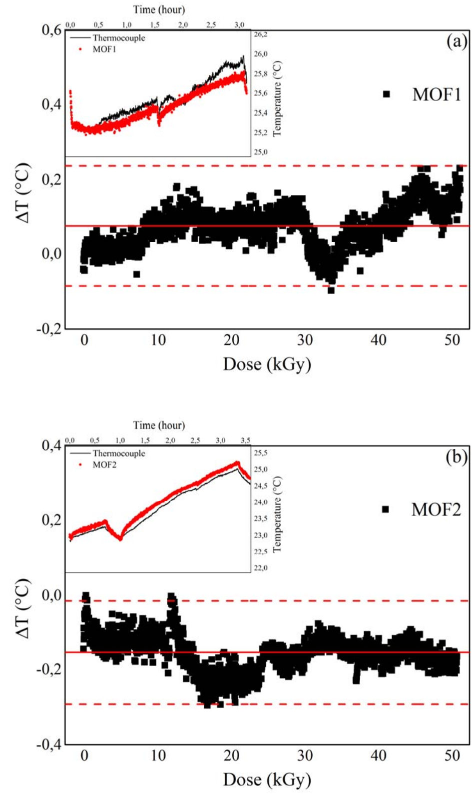

Fig. 1 Temperature differences between OFDR and thermocouple measurements as a function of irradiation dose in (a) MOF1 and (b) MOF2 fiber. Space within dotted lines represents the variation of 3σ with respect the mean value indicated by solid red line. Insets report the temperature during irradiation as a function of time measured by microstructured fibers (red circles) compared with thermocouple measured temperature (black line).

IV. Discussion and conclusion

These results show that OFDR-based sensors exploiting MOFs are not affected by radiation-induced errors as it is the case for Brillouin [1] sensors with the Radiation Induced Brillouin Shifts (RI-BS) and Raman [2]-[3] sensors (by the differential absorption Δα affecting the ratio between scattered intensities at Stokes and Anti-Stokes wavelengths).

For this sensor technology and at least up to 50 kGy, the limiting factor will be the RIA that will limit the sensing range. To evaluate the performances of OFDR we performed RIA measurement on our samples. At the total reached dose the RIA spectrum as a function of wavelength is reported in Fig. 2 for both samples. We obtain at 1550 nm attenuation values of ~15 dB/km in MOF1 and ~130 dB/km in MOF2.

For our 70 m sensing range, considering the OFDR system dynamic that is 10 dB, we can conclude that the employment of MOF1 as distributed Rayleigh sensor is possible, being radiation induced losses over the whole range ~ 1 dB. The case is different for MOF2 where the attenuation at 1550 nm is higher and comparable with the maximum OFDR permitted losses (~140 dB/km for the parameters specified above). The use of this fiber can be possible but has to be calibrated to the application in terms of sensing range and environment constraints (total reached dose, dose rate…).

This first study reveals the potential of OFDR sensors, especially one using radiation tolerant MOF, for operation in harsh environments.

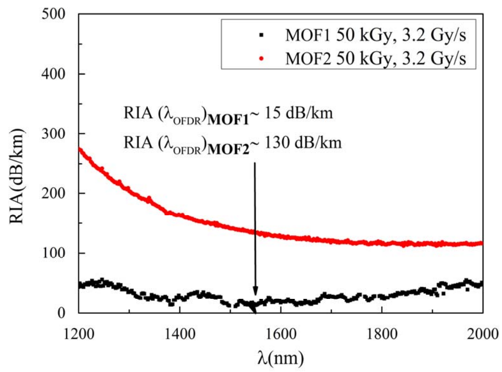

Fig. 2 Radiation induced attenuation spectra in the infrared region for MOF1 (black squares) and MOF2 (red circles) at the total reached dose of 50 kGy. RIA values at the operating OFDR wavelength are highlighted in the graph and result ~15 dB/km for MOF1 and ~130 dB/km for MOF2.

REFERENCES

[1] X. Phéron, S. Girard, A. Boukenter, B. Brichard, S. D. Lesoille, J. Bertrand, and Y. Ouerdane, “High γ-ray dose radiation effects on the performances of Brillouin scattering based optical fiber sensors,” *Opt. Express,* vol. 20, no. 24, pp. 26978-26985, 2012.

[2] C. Cangialosi, S. Girard, A. Boukenter, M. Cannas, S. Delepine-Lesoille, J. Bertrand, P. Paillet, Y. Ouerdane, “Hydrogen and radiation induced effects on performances of Raman fiber-based temperature sensors,” *J. Lightwave Technol.,* vol. 33, no. 11, p. 1558-2213, 2015.

[3] C. Cangialosi, Y. Ouerdane, S. Girard, A. Boukenter, S. Delepine-Lesoille, J. Bertrand, C. Marcandella, P. Paillet, M. Cannas, “Development of a Temperature Distributed Monitoring System Based On Raman Scattering in Harsh Environment”, IEEE Transactions on Nuclear Science, vol. 61 (6), 3315 – 3322, 2014.

[4] B. J. Soller, D. K. Gifford, M. S. Wolfe and M. E. Froggatt, "High resolution optical frequency domain reflectometry for characterization of components and assemblies," *Opt. Express,* vol. 13, no. 2, pp. 666-674, 2005.

[5] 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,” IEEE Trans. Nucl. Sci., vol. 60, no. 3, pp. 2015 - 2036, 2013.

[6] S. Girard, J. Keurinck, Y. Ouerdane, J.-P. Meunier, and A. Boukenter, “Gamma-rays and pulsed X-ray radiation responses of germanosilicate single-mode optical fibers: influence of cladding codopants,” *J. Lightwave Technol.,* vol. 22, no. 8, p. 1915–1922, 2004.

[7] E. J. Friebele, P. C. Schultz, and M. E. Gingerich, “Compositional effects on the radiation response of Ge-doped silica-core optical fiber waveguides,” *Appl. Opt,* vol. 19, no. 17, p. 2910–2916, 1980.

[8] P. St. J. Russell, “Photonic-crystal fibers,” *J. Lightwave Technol.,* vol. 24, no. 12, p. 4729–4749, 2006.

[9] S. Girard, J. Baggio, and J.-L. Leray, “Radiation-induced effects in a new class of optical waveguides: the airguiding photonic crystal fibers,” *IEEE Trans. Nucl. Sci.,* vol. 52, no. 6, p. 2683–2688, 2005.

[10] G. Cheymol, H. Long, J. F. Villard, and B. Brichard, “High level gamma and neutron irradiation of silica optical fibers in CEA OSIRIS nuclear reactor,” *IEEE Trans. Nucl. Sci.,* vol. 55, no. 14, p. 2252–2258, 2008.

[11] H. El Hamzaoui, L. Bigot, G. Bouwmans, I. Razdobreev, M. Bouazaoui, and B. Capoen, “From molecular precursors in solution to microstructured optical fiber: a Sol-gel polymeric route,” Opt. Mater. Express, vol. 1, no. 2, pp. 234-242, 2011.