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Serena Rizzolo, Emmanuel Marin, Marco Cannas, Aziz Boukenter, Youcef Ouerdane, et al.. Radiation effects on optical frequency domain reflectometry fiber-based sensor. *Optics Letters*, 2015, 40 (20), pp.4571-4574. 10.1364/OL.40.004571 . hal-01211197

HAL Id: hal-01211197

<https://hal.science/hal-01211197v1>

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To cite this version :

Rizzolo, Serena and Marin, Emmanuel and Cannas, Marco and Boukenter, Aziz and Ouerdane, Youcef and Périssé, Jocelyn and Macé, Jean Reynald and Bauer, Sophie and Marcandella, Claude and Paillet, Philippe and Girard, Sylvain Radiation effects on optical frequency domain reflectometry fiber-based sensor. (2015) Optics Letters, 40 (20). 4571-4574. ISSN 0146-9592

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Radiation effects on optical frequency domain reflectometry fiber-based sensor

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We investigate the radiation effects on germanosilicate optical fiber acting as the sensing element of optical frequency domain reflectometry devices. Thanks to a new setup permitting to control temperature during irradiation, we evaluate the changes induced by 10 keV x rays on their Rayleigh response up to 1 MGy in a temperature range from 40°C up to 75°C. Irradiation at fixed temperature points out that its measure is reliable during both irradiation and the recovery process. Mixed temperature and radiation measurements show that changing irradiation temperature leads to an error in distributed measurements that depends on the calibration procedure. These results demonstrate that Rayleigh-based optical fiber sensors are very promising for integration in harsh environments.

OCIS codes: (060.2370) Fiber optics sensors; (350.5610) Radiation; (290.5870) Scattering, Rayleigh.

<http://dx.doi.org/10.1364/OL.40.004571>

Integrating optical fiber based devices in a radiation environment has drastically increased during the last decades; fast response and immunity to electromagnetic fields are some advantages for their employment, as well as the possibility to monitor temperature, strain, or radiation dose by replacing numerous punctual sensors with an unique optical fiber [1–3]. In the panorama of fiber based sensing techniques optical frequency domain reflectometry (OFDR) is one of the most promising because it offers spatial resolution from a few micrometers over several meters to a few centimeters over a few kilometers of fiber length [4,5]. Integration of OFDR based systems in harsh environments will be possible if the optical response, used for monitoring the environmental parameter changes along the fiber, is well controlled within a high dose level of radiation. Recently, a systematic

characterization on a large panel of γ ray pre irradiated fibers has shown that Rayleigh temperature and strain coefficients used to calibrate distributed measurements remain unaffected one month after a 10 MGy dose [6]. However, OFDR sensor performances are affected by the radiation induced attenuation (RIA) phenomena that limit their sensing length, which can be reduced to a few meters for the most sensitive fibers.

The aim of this Letter is to explore the presence of radiation transient effects and their possible impact on OFDR measurements during irradiation. To our knowledge this up to date aspect is only partially investigated in the literature; a study was performed at low doses of γ irradiation [up to 2 kGy(SiO₂)] [7] or using radiation sensitive optical fibers for dosimetry application [8]. Thus, our work is focused on *in situ* measurements up to 1 MGy on a germanosilicate commercial SMF28 single mode optical fiber composed of a Ge doped core (~5 wt. %) [9], a pure silica cladding, and an acrylate coating able to operate up to 85°C. The vulnerability of this fiber guide was deeply evaluated for applications in space or nuclear reactors revealing an acceptable RIA level in the near IR (above 1 μ m) [10]. Furthermore, it is the fiber commonly used with OFDR systems for structural health monitoring [11]. Rayleigh temperature and strain responses of this fiber, characterized in [6], give temperature a coefficient C_T of $6.77 \pm 0.0310^{-6} \text{C}^{-1}$ in nonirradiated fiber after a thermal treatment up to 80°C and a strain coefficient C_ϵ of $0.743 \pm 0.001 \mu\epsilon^{-1}$. As reported in [7], *in situ* OFDR experiments are affected by fiber installation. Indeed, this can introduce errors on temperature or strain evaluation caused by vibrations or dilatation of the fiber support that change the calibration curve of studied systems and may be difficult to control at irradiation facilities. To overcome these problems we have developed an original setup reported in Fig. 1 to control simultaneously both the irradiation conditions and the temperature level of the fiber inside the irradiation chamber. The tested fiber is set on an aluminum plate with a diameter of 15 cm on which is engraved a square groove (300 μ m deep) to create a path where the fiber is fixed with

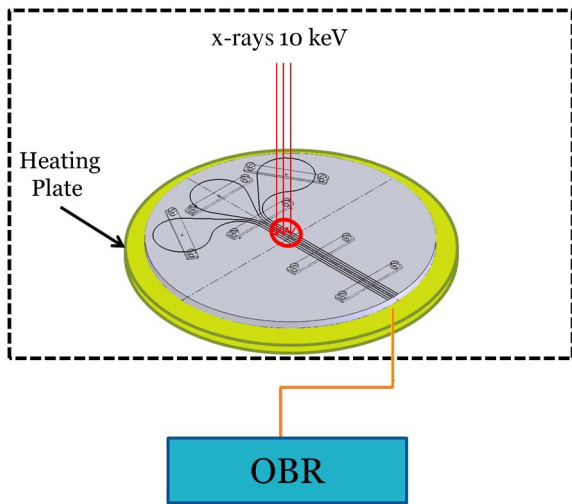


Fig. 1. Experimental setup used for temperature distributed measurement under x ray irradiation.

diverse aluminum bridles; such a designed path is thought to avoid bending losses due to the curvature. The plate is positioned on a heating chuck of the same diameter permitting us to irradiate at different controlled temperatures. The 10 keV x ray irradiation was performed at CEA, DAM, DIF (Arpajon, France), with the ARACOR machine [12]. The dose rate is 40 Gy/s for 25,000 s leading to a total dose of 1 MGy (SiO_2); the irradiation beam of diameter about ~ 2 cm is centered on the setup plate.

Distributed temperature measurements are performed with an optical backscatter reflectometer (OBR) 4600 from Luna Technologies. Rayleigh response to radiation is first investigated at a constant irradiation temperature of 50°C , which is reduced at room temperature at the irradiation end. In Fig. 2

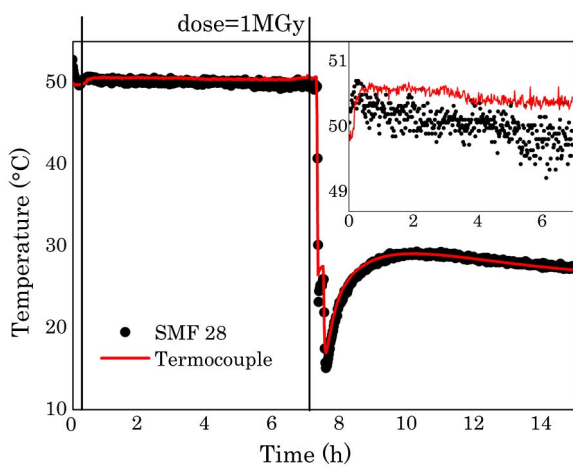


Fig. 2. Temperature evolution as a function of time measured by OBR on SMF28 fiber during irradiation at 50°C (solid black circles) and by thermocouple temperature (red line); irradiation period is highlighted by two straight vertical lines (duration 25,000 s, dose: 1 MGy). The inset shows a zoom during irradiation and the temperature is reported as a function of time in irradiated fiber (black circles) and thermocouple (red line).

the measured temperature as a function of the time during the experiment is reported. As we can notice, detected thermocouple temperature reproduces well the OBR response during the whole sequence: irradiation at 50°C up to 1 MGy, and recovery. The inset highlights the small temperature differences between the OBR and thermocouple responses during irradiation.

Since we observe the same trend both in the thermocouple and in the irradiated fiber we can affirm that no significant radiation effects affect the Rayleigh distributed temperature measurements; the only observed effect is, indeed, a slight warming up due to x ray beams.

Then we study radiation and temperature combined effects, as it was recently shown that the two constraints can enhance the radiation induced degradation of fibers [13]. The experiment is divided in two runs: (i) first, we characterize the fiber response to the temperature inside its setup plate performing 10 steps of ~ 42 min each between 40°C and 75°C , (ii) then, without changing fiber installation, we characterize mixed temperature and radiation sensibility making the same temperature steps procedure during irradiation at a constant dose rate of 40 Gy/s. The acquired spectral shift values during the first run allow a calibration of our system (fiber + plate) finding a C_T of $(7.71 \pm 0.15) \cdot 10^{-6} \text{ }^\circ\text{C}^{-1}$. We use this coefficient to obtain temperature as a function of time, which fits well with the thermocouple responses and is reported in Fig. 3(a). This temperature response is used as a reference to investigate the combined radiation and temperature effects reported in Fig. 3(b) for the second run. As pointed out before, we are able to follow the temperature in all the steps even during irradiation. It is useful to highlight that the fiber sensor response is very quick (less than 60 s) as temperature is well evaluated during some brutal changes happening during the run (see, e.g., curve around 2.5 and 5 h).

Figure 4 shows the comparison of temperature evolution between the two runs. Temperature differences normalized with thermocouple values (ΔT) between the two runs are reported in the inset and we demonstrated that no significant error on the OBR temperature is caused by radiations. ΔT values show that, except for the first point at 0°C where ΔT is $(5.1 \pm 0.5)^\circ\text{C}$, differences of calculated temperature between the first and second runs are between 0.6°C and 2.1°C .

These ΔT are linked to the installation setup and calibration procedure. As shown in [7], distributed temperature and strain measurements are, in fact, strongly dependent on the fiber packaging. The presence of coating or metallic components can introduce errors in C_T determination, which is an issue that can be solved by calibrating the whole system and by optimizing the fiber packaging or reducing the external constraints. However, this sensor optimization will be specific to a given fiber sensor and to a given industrial environment.

For harsh environment applications, the long distance probing fiber length is a key aspect to investigate as these sensors are affected by the RIA phenomena that limit their sensing length and degrade the signal to noise ratio. Radiation, indeed, induces point defects that degrade optical fiber response, which depend, e.g., on the nature of the irradiation, the total reached dose, the dose rate, and the optical fiber core/cladding composition [1]. We reported in [6] an extended study on five classes of optical fibers from radiation resistant to radiation sensitive ones that points out that for OFDR measurements RIA is a critical mechanism in the sense that it will reduce the sensing

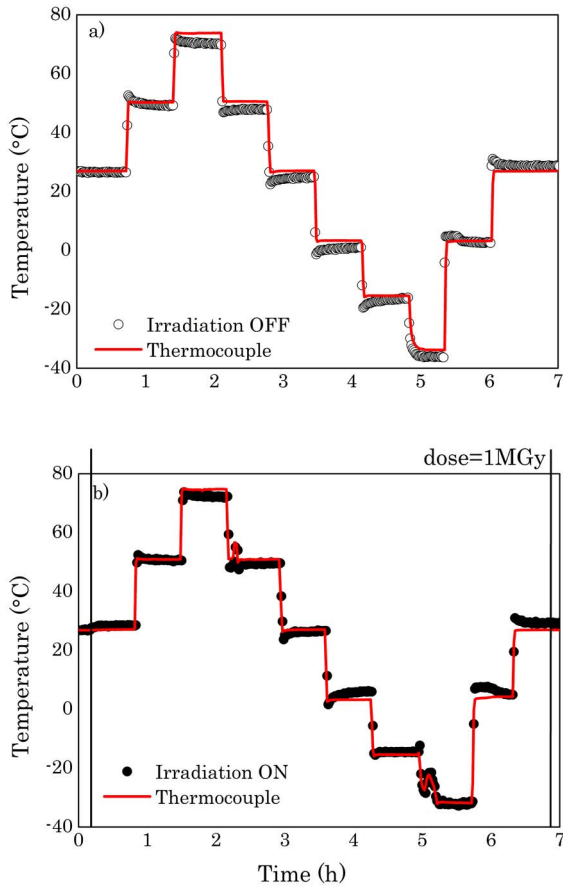


Fig. 3. Temperature evolution as a function of time measured (a) without radiation and (b) with radiation. Open black circles indicate temperature calculated by Rayleigh measurements in absence of radiation (a), solid black circles represent temperature values under irradiation and red line measured thermocouple temperature. In (b) irradiation window is highlighted by two straight vertical lines, 1 MGy dose is reached after 25,000 s of irradiation.

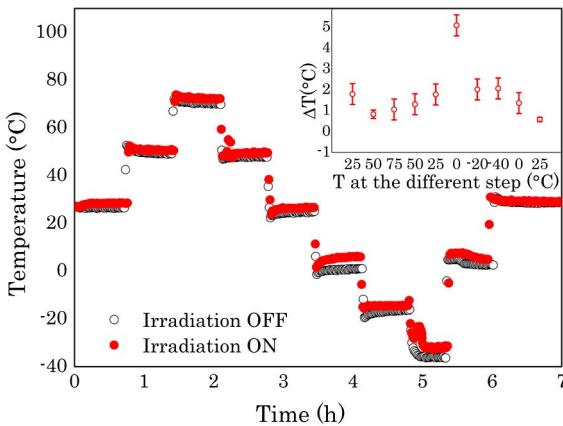


Fig. 4. Comparison of temperature responses as a function of time measured without radiation (open black circles) and during irradiation (solid red circles). The inset represents temperature differences between irradiated and nonirradiated corrected with temperature fluctuation of thermocouple data.

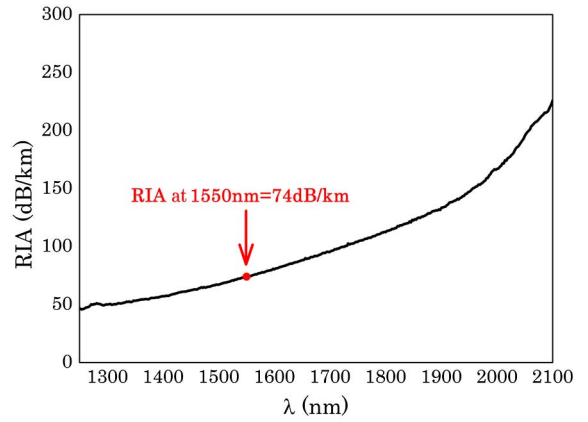


Fig. 5. Infrared RIA of SMF28 irradiated at 1 MGy.

length from several kilometers in radiation resistant fibers to a few meters when the fiber is radiation sensitive. Moreover, irradiation temperature is also a crucial parameter for optical fiber performance: Girard *et al.* in [13] show that there is a complex combined influence between this parameter and the radiation (dose, dose rate). To better understand the role of RIA in our measurements we investigated the fiber behavior with an experimental and simulation approach in terms of RIA.

Figure 5 reports the spectral losses in the infrared region after an irradiation dose of 1 MGy. Attenuation of 74 dB/km is reported at the wavelength of interest (1550 nm). This value level is acceptable when short irradiation fiber lengths are involved.

As longer optical fiber lengths have to be integrated in harsh environments, it is important to evaluate in these conditions the capability of the employment of the OFDR technique. To this aim, by using the power law defect growth kinetics of RIA as a function of the radiation dose described [10] and [14] for Ge doped optical fibers, from the maximum device length of the OFDR and its optical budget, we evaluate dose rate and dose range that can be investigated with OBR 4600 and SMF28 fiber. Obtained results are shown in Fig. 6 for a device length

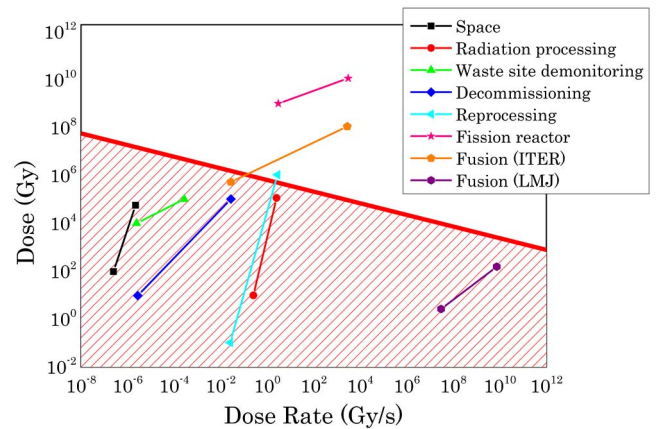


Fig. 6. OFDR possible dose and dose rate ranges calculated [10,14] in condition of RIA = 0.14 dB/m (straight red line) and (D', D) couples associated with various projects and natural radiation environments where the integration of optical fibers is investigated [1].

of 70 m (that preserve the OFDR spatial resolution measurements of 20 μm) and an optical budget of 10 dB. By varying the dose rate we calculate the dose corresponding to a RIA of 0.14 dB/m, which defines our investigation region. Couples (D', D) below this straight line permit the study with OFDR in specified conditions; however, a higher RIA level limits the device length, preventing the investigation.

In Fig. 6 the dose and dose rate ranges, associated with various projects and natural radiation environments where the integration of optical fibers is considered, are also reported. Thus, OFDR optical fiber sensors can be employed in monitoring applications in several harsh environments, even using a commercial germanosilicate fiber. This range will be extended using radiation hardened pure silica core or fluorine doped optical fibers.

In summary, we evaluate radiation effects on a germanosilicate optical fiber which can be employed in monitoring applications in several harsh environments, as shown by a coupled experimental and simulative approach. By developing a new setup permitting to control temperature during irradiation we show that *in situ* distributed temperature measurements up to 1 MGy are successful during both irradiation and recovery processes. Results on combined temperature and irradiation effects show that changing irradiation temperature can lead to an error (typically $\sim 2^\circ\text{C}$) in distributed measurements that is partly related to the fiber packaging. The understanding of these effects by varying fiber composition and in particular on radiation resistant fibers will be done in future work, as well as complementary investigations on fiber packaging during measurements and on coating contributions examining a large range of possible fiber coatings.

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