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Coating Impact and Radiation Effects on Optical Frequency Domain Reflectometry Fiber-based Temperature Sensors

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ABSTRACT

Temperature response of radiation-tolerant OFDR-based sensors is here investigated, with particular attention on the impact of coating on OFS. By performing consecutive thermal treatments we developed a controlled system to evaluate the performances of our distributed temperature sensor and to estimate the radiation impact. We show an important evolution of the temperature coefficient measurements with thermal treatments for non-irradiated fiber and that the amplitude of this change decreases increasing radiation dose. As final results, we demonstrate that sensor performances are improved if we performed a pre-thermal treatment on the fiber-based system permitting to monitor temperature with an error of 0.05°C.

Keywords: DTS, OFDR, high temperature, radiation, optical fibers.

1. INTRODUCTION

Optical fiber sensors (OFSs) have attracted intensive research interest for several decades. They have already shown a superior advantage over their conventional electrical counterparts because of their distributed capabilities. A fully distributed OFS usually operates by measuring the surrounding environment changes along the length of the sensing fiber. Several techniques have been successfully applied to fulfill this kind of measurement, such as Brillouin[1], Raman[2], as well as Rayleigh scattering[3]. On the other hand, among a large amount of physical and chemical parameters that OFSs could measure, temperature and strain are the most widely studied, since many applications requiring accurate measurement of these two parameters operate in space, military or high energy physics harsh environments. An OFS based on Rayleigh or Brillouin scattering is sensitive to both strain and temperature, normally being unable to discriminate between them. This effect which exists in almost all the OFSs, including distributed ones, would introduce errors when monitoring one of these two parameters even with optimized packaging. Increasing demand for OFS is observed in the last years mostly for operation in radiation environment such as future nuclear facilities. The integration of OFSs in harsh environments may be possible if these sensors resist to the combined environmental constraints such as the presence of high levels of radiation and temperature. In this abstract, we study the response of fluorine (F)-doped radiation resistant fiber; this fiber possesses an acrylate coating resisting up to 80°C. In the final paper, fibers with diverse coatings (polyimide, metallic ones) will be presented to investigate their effects on calibration procedure and temperature measurements. This will be the first study on this topic to our knowledge and will help in identifying the various issues associated with such constraints and suggest solutions that permit to overcome them.

2. MATERIALS AND METHODS

For the presented part of our study we use a temperature sensor based on a single mode fiber (SMF) developed by iXBlue manufacturer with a fluorine (F)-doped core of ~10µm diameter; the fluorine concentration is about 0.2 wt.% in the core and ~1.8wt.% in the cladding.

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We investigate the properties of non-irradiated fiber and γ-irradiated ones up to dose of 10 MGy. The γ-ray irradiations are performed using a ^{60}Co source facility (BRIGITTE) in SCK-CEN (Mol, Belgium)[5]. The dose-rate varies between 10 and 30 kGy/h, whereas the temperature ranges from 30°C to 50°C during the irradiation run. The total deposited dose varies from 1 MGy up to 10 MGy.

Temperature measurements are performed in an oven (Binder) equipped with a K type thermocouple thanks to an Optical Backscatter Refectometer (OBR) 4600 from Luna Technologies with spatial resolution of 1 cm on ~15 m total long segment of fiber composed by the different samples non-irradiated and irradiated spliced to each other. Each sample is 3 meter long and formed by a coated part followed by a similar uncoated one obtained thanks to chemical treatment to avoid a mechanical stress induced by stripping the fibers. We evaluate the temperature sensitivity of our sensor making 11 steps at different temperatures ranging from 30°C to 80°C to extract the temperature coefficient of our F-doped fiber before and after irradiation. At each temperature step (of 5°C) , the chamber is stabilized for more than half an hour; the last value (80°C) is related to the maximal temperature the acrylate coating can resist without impacting the fiber optical properties. To test coating resistance to high temperature we perform four consecutive heating sequences; each thermal treatment took one day to be performed and it is followed by a slow cooling during the night.

3. RESULTS AND DISCUSSION

Response of our distributed temperature sensor (DTS) after calibration procedure is shown in Figure 1, where temperature measured by OBR as a function of thermocouple temperature is reported. The plots are obtained by using the temperature coefficient corresponding to the first thermal treatment to calculate the temperature during the second one. A linear fit of these data allows estimating the efficiency of DTS; the linear correlation, indeed, gives the error that is introduced by calibration procedure, calculated estimating the discrepancies between the best-fit slope and the unitary slope obtained in case of 100% of DTS efficiency. We obtain an error that decreases with increasing the radiation dose and that varies from 7.5% in non-irradiated fiber to 0.1% in 10 MGy one.

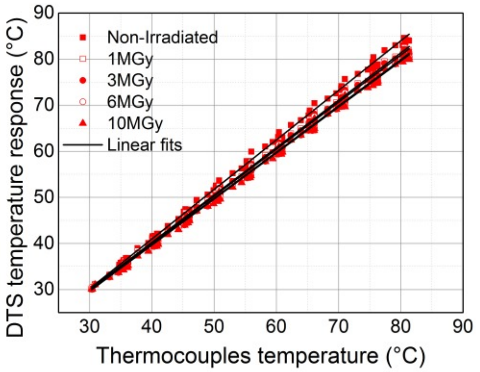

Figure 1. F-doped fiber with acrylate coating measured temperature as a function of detected temperature from thermocouple during the second thermal treatment in non-irradiated (full square) and irradiated at 1MGy (empty square), 3MGy (full circle), 6MGy (empty circle) and 10MGy (full triangle); black straight lines indicate linear fits obtained from experimental data.

Figure 2 reports the evolution of temperature coefficient C_T with thermal treatments. In the case of stripped fiber C_T remains stable in non-irradiated and irradiated samples within an uncertainty of 0.5%, which we can associate to temperature fluctuations in the oven. In coated samples we detect the maximum variation of C_T between the first and the second treatment; this variation is 8% in non-irradiated fiber and it decreases with increasing dose (in 10MGy irradiated sample it is lower than 0.5%). Between the second and the third treatment, and the third and the fourth treatment we have differences lower than 0.5%, as well as in non-coated samples. This effect can be explained by the influence of thermal treatment on the coating which is subjected to a dilatation that releases stress into the fiber, effect that considerably decreases after the first thermal treatment.

The comparison of C_T between coated and non-coated fibers evidences the influence of coating depends on irradiation dose. The highest effect is observed in non-irradiated sample as shown in Figure 2 (a), where difference between coated and non-coated sample is lower during the first treatment (2.4%) and it increases up to 5.0% in the second run to reach the highest value during the last one (6.1%); coefficient evolution of 1MGy irradiated fiber, Figure 2 (b), shows that differences are considerably decreased and they varies from 1.5% in the first treatment to 2.0% in the last one. Figure 2 (c) shows the behavior of C_T in 3MGy irradiated sample: here differences are high in the first point (2.3%) and they decrease up to 0.2% in the successive ones. Finally, Figure 2 (d) and (e) show 6 MGy and 10 MGy irradiated samples, respectively; variations between coated and non-coated parts of the sample remain constant within 1% during all thermal treatments in both samples . Clearly, radiation changes the properties of coating, affecting the calibration of the fiber sensors and then the temperature monitoring. For acrylate coating and no previous thermal treatment, we note a positive effect of radiation that behaves itself as a pre-thermal treatment and stabilizes C_T.

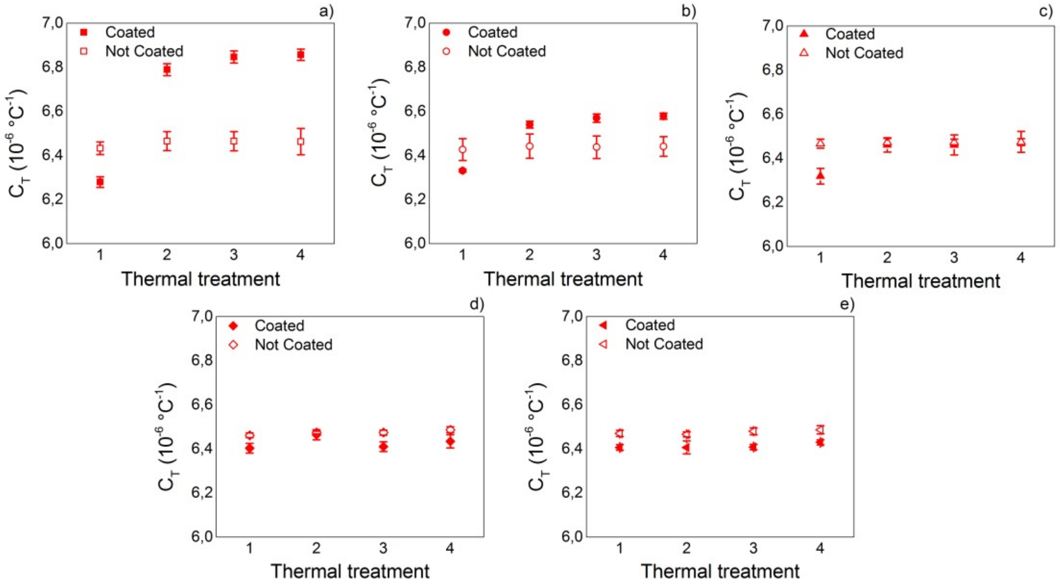

Figure 2. F-doped fiber with acrylate coating temperature coefficients in consecutive thermal treatments for coated (full points) and stripped (empty points) segments of F-doped fiber (a) non-irradiated, irradiated at (b) 1MGy, (c) 3MGy, (d) 6MGy and (e) 10MGy.

Table 1. Temperature coefficients for coated and stripped samples of the F-doped fiber

Dose (MGy)	***C_T (10^{-6}°C^{-1}) II Thermal Treatment***		***C_T (10^{-6}°C^{-1}) III Thermal Treatment***	
	Coated	***Non-coated***	***Coated***	***Non-coated***
0	6.79±0.03	6.46±0.02	6.85±0.03	6.46±0.04
1	6.54±0.02	6.44±0.01	6.57±0.02	6.44±0.05
3	6.46±0.03	6.47±0.01	6.46±0.05	6.47±0.02
6	6.46±0.02	6.473±0.006	6.41±0.02	6.473±0.012
10	6.41±0.03	6.465±0.012	6.408±0.012	6.48±0.02

From this analysis on C_T evolution with thermal treatments we can conclude that the temperature coefficient stabilizes after the first treatment. For this reason, to evaluate sensor performances we use the C_T obtained from the second warming sequence in temperature calculations of the third and the fourth day and that of the third warming in temperature calculations during the fourth day. Values of these coefficients are reported in Table 1 with their comparison with stripped counterparts.

Results on distributed temperature measurements are shown in Figure 3, where we reported fiber temperatures as a function of registered thermocouple values during the third (a) and fourth test (b) for non-irradiated and irradiated fibers using C_T obtained from the second thermal treatment and (c) during the fourth test using C_T obtained from the third thermal treatment. By performing a linear fit on the data we obtain a slope of (1.003±0.004) and a zero intercept, thus leading to a median error on temperature of 0.35%. These graphs clearly show that pre-treated fiber has a better response than the DTS data reported in Figure 1 and they confirm that irradiation, even up to doses of 10MGy does not permanently influence temperature sensitivity of the sensor (this did not exclude other radiation effects such as radiation induced attenuation that will also affect the sensor performances). Indeed, we are able to measure temperature changes, in non-irradiated and irradiated fibers, from 30°C up to 80°C with a precision of 0.05°C (value obtained from variation of data in each step).

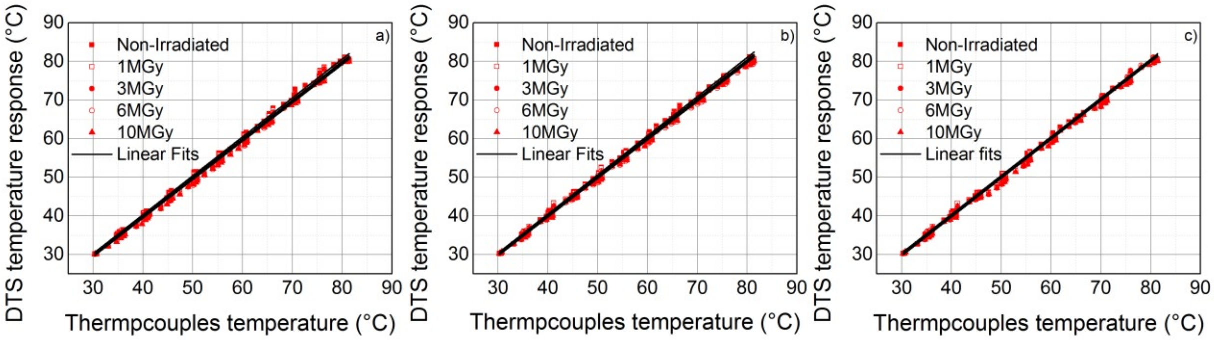

Figure 3. Fiber measured temperature as a function of detected temperature from thermocouple of (a) third test and (b) fourth calculated with coefficient of second day, and (c) fourth test calculated with coefficient of third day in tested fiber non-irradiated (full square) and irradiated at 1MGy (empty square), 3MGy (full circle), 6MGy (empty circle) and 10MGy (full triangle); red straight line indicates linear fit obtained from experimental data.

4. CONCLUSION

In this work we evaluate the response of an F-doped acrylate-coated single mode fiber to be employed as distributed temperature sensor up to high temperature of 80°C and how radiation can affect its temperature coefficient. We find that C_T is influenced by temperature effects on coating; this influence manifests itself with a stronger contribution in non-irradiated sample where variation of C_T reaches 6.1%; the contribution decreases on increasing the dose from 2% to 1%. We note also that C_T stabilizes by performing consecutive thermal treatments, with fluctuations below 0.5%: a pre-thermal treatment on OFDR-based sensor is therefore a good procedure to eliminate coating contribution on distributed temperature measurements. Moreover, we show that irradiating the fibers up to a 10MGy dose does not affect its temperature coefficient; indeed, temperature variation can be measured within an uncertainty of 0.05°C even in irradiated samples. This opens the way to the development of OFDR systems for use in facilities associated with high radiation doses.

A deep study on diverse coatings (e.g. high temperature acrylate, polyimide and metallic ones) will be presented in the full paper to investigate the potentiality of OFRD distributed temperature sensors operating at high temperature from 150°C up to 700°C.

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