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Sensors for Harsh Environment: Radiation Resistant FBG Sensor System

Atasi Pal, Anirban Dhar, Aditi Ghosh, Ranjan Sen, Babita Hooda, Vipul Rastogi, Martin Ams, Matthias Fabian, Tong Sun, and K. T. V. Grattan

Abstract—**This paper presents radiation resistant characteristics of fibre Bragg grating (FBG) sensors written in a photosensitive fiber and connected to a silica core radiation resistant optical fibre, aiming to develop a sensor system suitable for both sensing and data transmission in harsh environment. The silica core fluorine-down-doped clad optical fibre has been specifically designed and fabricated for this study using the modified chemical vapor deposition technique. Key waveguide parameters, including the width of the fluorine doped inner cladding have been optimized to obtain a low loss ($<$0.2 dB/km) at the operating wavelength region of 1550 nm. The fibre fabrication process, mainly the deposition condition, has also been optimized to achieve smooth deposition and sintering of silica core layers, to minimize radiation induced absorption. As a result, radiation induced absorption of $\sim$2.2 dB/km at 1550 nm under accumulated dose of 25 MRad at dose rate of 0.39 MRad/hr has been successfully achieved. To create an effective sensor system for harsh environmental conditions, this specialty fibre is connected to a number of FBGs (sensors) fabricated in photosensitive fibres prior to their extensive evaluations by being exposed to different accumulated dose of gamma radiation. Their corresponding Bragg wavelength shifts (BWS) and peak amplitudes were continuously monitored. It was found that the radiation induced BWS can be greatly reduced by shielding the sensors using stainless steel tubing. The temperature sensitivity and peak amplitude were found to be largely unchanged before and after exposure to Gamma radiation of 25 MRad which shows their potential use for temperature measurements in radiation environments with an uncertainty of around 0.1 °C.**

Index Terms—**Fibre Bragg gratings, Gamma-ray effects, optical fibre, optical sensors, radiation effects, sensor system, silica core fibre.**

I. INTRODUCTION

NARROW wavelength encoding of sensing information through the use of a Fibre Bragg Grating (FBG)-based sensor device has the potential to mitigate the influence of the broadband radiation-induced absorption (RIA) in an optical fibre [1]. FBG-based sensing technique, which is in particular attractive in harsh environment, both in terms of multi-parameter sensing (temperature, strain, pressure, humidity) and of the network topology it offers based on wavelength-division-multiplexing. As the spectral signature of FBGs renders the measurement, the sensor performance is immune to intensity fluctuations, thus ensuring reproducible measurements made, irrespective of any optical losses that might occur, e.g., bending, ageing of connectors or even under high radiation environments (darkening of fibres). Moreover, FBGs can be easily embedded into materials (e.g., composite materials) for local damage detection as well as internal strain field mapping showing high spatial resolution, high sensitivity and wide sensing range for strain and temperature measurement. Radiation influences the refractive index of the glass and therefore the position of the reflection (Bragg) peak. A variety of publications have pointed out that FBGs, written in high Germanium (Ge)-doped fibre using UV exposure, can be quite radiation insensitive, without altering their strain/temperature sensitivity. The influence of fibre composition and manufacturing parameters on the radiation sensitivity of the both UV and femtosecond laser-inscribed FBGs has been studied [2]–[4], showing the potential to be used for monitoring changes in temperature, as well as the structural integrity of reactor containment buildings, nuclear waste repository and for remote safety control of nuclear installations [5].

On the other hand the RIA of the fibre (doped with Ge) transmitting the sensor signals degrades the signal to noise ratio resulting in poor performance of the sensing system. Hence both the transmitting fibre and the FBG probe determine the threshold radiation-acceptance level of a sensor system [6]. The transmitting fibre is required to be compliant with the international standard ITU-T G.652.B which recommends a value of loss less than 0.4 dB/km at 1310 nm and 0.35 dB/km at 1550 nm. The radiation tolerance, of light at 1310 nm should not exceed 7 dB/km for a total ionizing dose of 10 MRad [7].

The radiation resistance of an optical fibre depends on a number of factors, which includes the fibre parameters (waveguide parameters, the core and cladding composition), the characteristics of the radiation exposure (total dose and dose rate) and the system parameters (operational wavelength, light intensity and temperature). Previous investigations have shown that pure-silica (SiO_2) core optical fibre exhibits better radiation resistance compared to germano-silicate or phospho-silicate core optical

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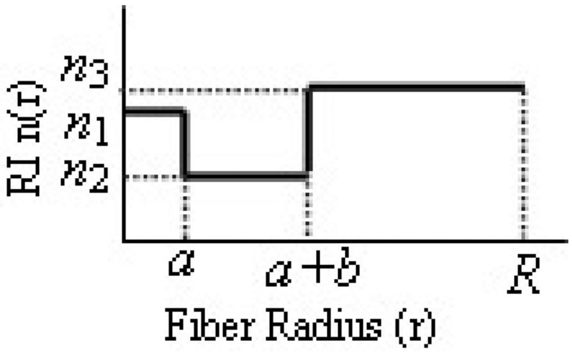

Fig. 1. Representative refractive index profile of SCFC.

fibres [8], [9]. The optimum level of Fluorine (F) doping in the core and O_2-excess during the core fabrication is known to improve the radiation resistance property of silica core optical fibre [10]. Doping with F, used to form the inner cladding of a silica core fibre is also important to enable the development of suitable waveguide designs for the most appropriate operating wavelength region.

In this work, a silica core F-down-doped clad (SCFC) optical fibre has been specifically designed and fabricated using modified chemical vapor deposition (MCVD) process for the harsh radiation conditions. This is achieved through the use of optimized process parameters and deposition conditions. The waveguide and transmission properties of the fibres fabricated in-house are subsequently characterized in order to optimize the fibre design to achieve low loss in the near infrared (NIR) region. This is followed by the exposure of the fabricated specialty fibre to gamma radiation and as a result the RIA of the fibre, both during and post irradiation, can be obtained. The sensor performance is realized by Type I FBG sensors, written into photosensitive fibres using a UV-laser-based phase mask technique and their performance were evaluated in radiation environment using the specialty fibre fabricated for data transmission. The temperature sensitivity of the FBG sensors is characterized before and after radiation exposure.

II. DESIGN OF RADIATION-RESISTANT FIBRE

The SCFC designed, developed and fabricated comprises a silica core with refractive index n_1, an inner cladding (doped with F) with refractive index n_2 and an outer cladding made of silica with refractive index n_3, as shown schematically in Fig. 1. *a* denotes the fibre core radius and *b* as the width of inner cladding, *R* is the overall fibre radius, $\Delta_1 = (n_3^2 - n_1^2)/2n_3^2$ is the relative index difference between the core and the outer cladding and $\Delta_2 = (n_1^2 - n_2^2)/2n_1^2$ is the relative index difference between core and inner cladding.

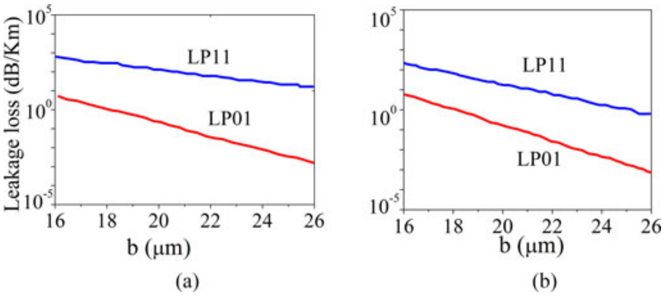

Fig. 2. Variation of leakage loss of LP_{01} and LP_{11} modes of the fibre with *b* for different values of core diameter: (a) a $= 10$ μm and (b) $= 12$ μm.

Silica deposited using MCVD and commercial silica tubing used during fabrication of preform have shown slightly different refractive indices, which then results in different values of n_1 and n_3. For pure silica core fibre, the Rayleigh scattering loss is small while Δ_2 and *a*/*b* are the critical parameters in the SCFC design to reduce the leakage loss of the fundamental mode. Fig. 1 indicates that the fibre structure is "leaky" and all the modes suffer from finite leakage loss. The criterion for single mode operation is a high differential leakage loss between the first two modes (LP_{01} and LP_{11}) with minimal leakage loss to the fundamental mode at the designated operating wavelength region. The leakage loss of the modes has been calculated using the transfer matrix method (TMM) to optimize the refractive index profile of the fibre for single mode operation in the NIR wavelength region. Fig. 2 shows the variation of the leakage loss of first two modes for different values of *b* with $a = 10$ μm and 12 μm, considering that $\Delta_1 = 0.09\%$ and $\Delta_2 = 0.44\%$.

Fig. 2 reveals that leakage loss of the modes decreases and the differential leakage loss of the LP_{01} and LP_{11} modes increases with the increment of the parameter *b*. For large values of *b,* that is $b \geq 25$ μm, the leakage loss of the first higher order mode is four orders of magnitude larger than that of the fundamental mode, which ensures effective single-mode operation of the fibre by discrimination of the higher order modes [11].

It has also been observed that the differential leakage loss decreases with increase in *a,* as the modal field spread of the LP_{11} mode into the cladding decreases. This makes the fibre susceptible to variations in core diameter. Hence the appropriate selection of the parameters *a* and *b* of the fibre for given values of core and cladding refractive indices is an important step, before proceeding to the fabrication of the actual fibre.

III. EXPERIMENTAL DETAILS

A. *Fabrication of Optical Preform and Fibre*

Fabrication of the SCFC fibre designed as discussed requires the initial fabrication of an optical preform through the MCVD process followed by drawing of the resin coated fibre. The process was initiated with the deposition of a number of sintered F-doped silica cladding layers inside the silica tube at a temperature above 1850 °C. At this stage, a gas mixture containing $SiCl_4$, O_2 and SiF_4 reacts to form fluorosilicate glass layers in the forward-pass direction i.e. the burner and gas mixture moving in the same direction.

Subsequently, a number of pure silica core layers were deposited in the presence of an appropriate amount of $SiCl_4$ and O_2 gases at a temperature above 1900 °C to ensure complete sintering of the silica layers. The number of core layers and F-doped inner clad layers to be deposited was pre-determined to match the waveguide design derived through theoretical modeling as mentioned above. Finally, the tube was collapsed in steps at a temperature above 2200 °C to obtain the SCFC preform with an outer diameter of about 10.8 mm. The collapsing condition, especially the temperature used and number of passes has been optimized to minimize the F-diffusion inside the preform core from the inner cladding which results in a reduction of Δn and deviation of the RI profile.

The primary fabrication parameters on which the properties of fibre depend are i) the inner cladding composition which in turn controls the numerical aperture (NA) of the fibre, ii) $SiCl_4$ flow which determines the deposition thickness per pass during inner clad fabrication and iii) the number of core/cladding layers. During the deposition of the flurosilicate layer, the F incorporation efficiency depends on $(p_{SiF4})^{0.25}$ where p_{SiF4} is the partial pressure of SiF_4 [12]. The challenge during deposition of F-doped inner cladding was the optimization of the $SiCl_4$ to SiF_4 ratio in order to achieve the desired RI difference as well as the width required to ensure good single mode propagation. This required several trials and ultimately the NA of the preform was adjusted between 0.09 and 0.14 (this corresponds to a core-cladding index difference of 0.003–0.0078) by controlling the $SiCl_4$ to SiF_4 flow ratio in the range of 1.5 to 2.5. The number of cladding layers was up to 35 to enhance the F-doped layer thickness beyond 25 μm. The deposition temperatures for the inner cladding and pure silica core layers were maintained at 1860 ± 10 and 1920 ± 10 °C, respectively, depending on selected vapor phase composition, i.e., the amount of $SiCl_4$, SiF_4 and partial pressure of O_2. This was important to avoid deposition of unsintered layers and formation of bubbles during collapsing.

At the final stage, UV cured acrylate coated fibres with an overall diameter of 250 ± 2 μm were drawn from the preform at a drawing speed extending up to 40 m/min, maintaining the fibre diameter of 125 ± 0.5 μm by using a drawing tower.

B. Characterization of Preform/Fibre

The RI profile of the fabricated preforms was characterized by using a preform analyzer (PK2600). Following that, the RI and geometric profile of the fabricated fibres were characterized through Optical Fibre Analyzer (NR-9200, EXFO) to determine the RI and the thickness of the various layers. The base loss of the fibre was measured by employing the “cut-back” method in the NIR (900–1700 nm) region, using a white light source, a monochromator and a detector.

The room temperature RIA of the fibres (of length of 40 m) was monitored online at 1550 nm under gamma radiation (during a period of 180 min; which corresponds to a dose of 1.17 MRad at a rate of 0.39 MRad/hr) and in the process of post-irradiation recovery (during a 70 min period). The schematic of the measurement set-up used is shown in Fig. 3 where the laser power at 1550 nm was fixed at the microwatt level and a low power detector was used for monitoring.

C. Fabrication and Characterization of FBG Sensor

Sets of nine type I- FBG sensors with Bragg wavelengths between 1520 and 1590 nm were written into photosensitive fibres (Fibrecore SM1500 and PS1250) using the phase mask technique [13] at CUL, UK, and subsequently annealed at 180 °C for 4 h. Besides the effects of radiation to bare gratings, the influence of protective tubing (glass and stainless steel) was investigated. This is done to compare the performance of the bare FBG sensors and the sensors protected by tubing using materials known to have good radiation protection properties. The influence of Gamma radiation on the RI of those photosensitive fibres has been recorded off-line till the accumulated dose of 25 MRad at a dose rate of 0.39 MRad/hr in different steps. In addition to the direct effects of radiation on the Bragg wavelengths of the FBGs, the temperature sensitivity of a number of FBGs was measured before and after exposure. This was done in an environmental chamber where the Bragg wavelengths for eight different temperatures between 20 and 80 °C were fitted using the least squares method.

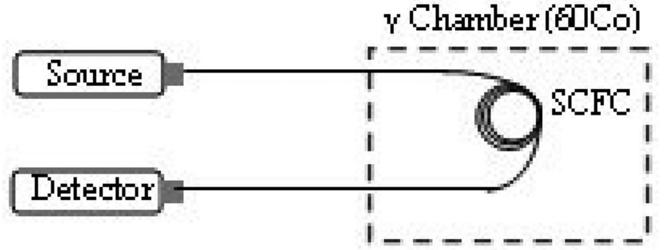

Fig. 3. Schematic of the measurement set up to monitor RIA under gamma radiation and during post irradiation.

TABLE I
SUMMARY OF THE USED PHASE MASKS OF PERIOD Λ AND THE CORRESPONDING BRAGG WAVELENGTHS λ_B IN THE TWO DIFFERENT TYPES OF PHOTOSENSITIVE FIBRE AT AROUND 20 °C

λ_B (nm), SM1500	λ_B (nm), PS1500	Λ (um)
1530.2	1527.1	1054.0
1538.8	1535.6	1061.0
1546.5	1543.3	1066.3
1551.7	1548.5	1069.9
1556.2	1553.0	1073.0
1561.4	1558.2	1076.6
1566.3	1563.1	1080.0
1571.0	1567.8	1083.2
1584.3	1581.1	1092.4

To create a series of optical fibre-based radiation-resistant sensor system, a length of 20 m fabricated radiation resistant fibre has been spliced with a set of FBGs and placed into the Gamma chamber set at a dose rate of 0.39 MRad/hr. A thermocouple, placed adjacent to the FBG sensors was used to monitor the temperature in the Gamma chamber. The Bragg wavelength shift and the amplitude of the FBGs sensors were continuously monitored up to an accumulated dose of 25 MRad using an optical sensing interrogator (Micron Optics: SM130-700). Table I details the phase masks used to manufacture the FBGs and Fig. 4 shows the FBG sensor layout inside the Gamma chamber.

IV. RESULTS AND DISCUSSION

The core diameter and NA of the radiation resistant optical fibre have been set to ~10 μm and ~0.12, respectively, to ensure

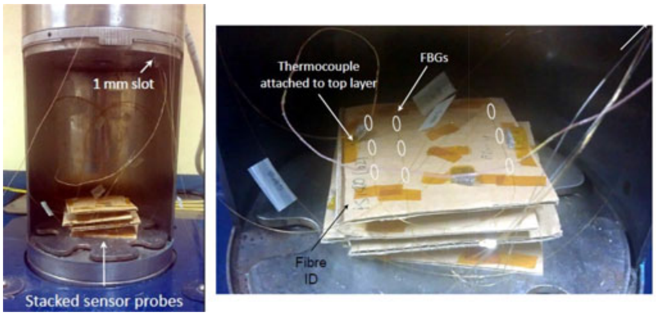

Fig. 4. Sensor layout inside the Gamma chamber.

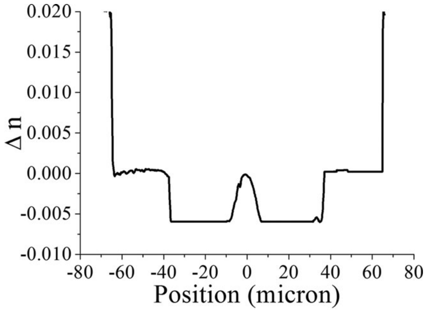

Fig. 5. Refractive index (RI) profile of the fabricated fibre.

its compatibility with the standard telecommunication fibre. A set of SCFCs having different widths of F-doped inner cladding has been fabricated through MCVD, with the process parameters as mentioned above being optimized. The RI profile, shown in Fig. 5, indicates a flat distribution of the F throughout the inner clad region. The RI profile of the fabricated fibre differs to a small extent from the schematic of the idealized design because of the evaporation from the deposited core region and the diffusion of F in the core region during the collapsing stage. This causes a small variation between the RI of deposited pure silica in the core region and the silica cladding (from a commercial silica tube).

It is also observed that the reduction in RI compared to pure silica in the preform core is 0.07% only against F-content of 2.5 mol% (estimated through the EPMA) in the inner cladding ($\Delta n = 0.007$). Such low diffusion of F into the core region from inner clad region is an outcome of the optimization of preform collapsing conditions.

The calculated loss of the propagating mode and the absorption measured in the fabricated fibres (at 1550 nm) having different values of F-doped inner cladding width (b) have been compared and shown in Fig. 6. For the calculation of the leakage loss, the measured RI profile of the fabricated fibre has been included in the use of TMM.

Fig. 6 shows that the calculated leakage loss agrees well with the measured loss when the inner cladding width is larger than 22 μm. The measured loss as it would be expected is somewhat higher as it also includes the scattering loss and the material loss in the actual fibre. The fibre that was finally fabricated had a value of "b" of around 27 μm which is effective to achieve a base attenuation of 0.193 dB/km, at a wavelength of 1550 nm.

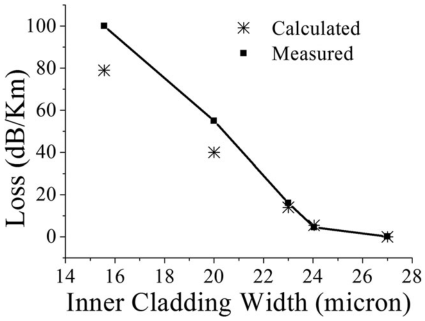

Fig. 6. Calculated leakage loss and measured total loss of the fabricated fibres at 1550 nm.

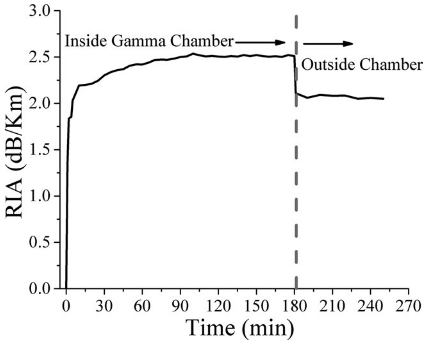

Fig. 7. RIA evolution under gamma irradiation (0–180 min) and post-irradiation (180–250 min) at 1550 nm. The dose rate is 0.39 MRad/hr, the dose at time point 180 min is 1.17 Mrad.

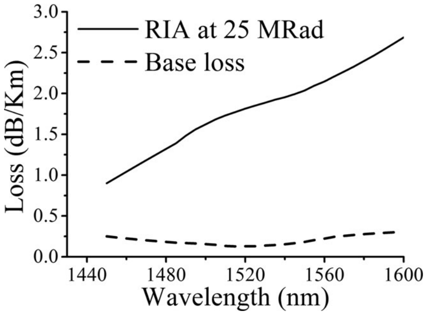

Fig. 8. Base loss of the fibre and RIA under accumulated dose of 25 MRad.

The loss value lies well within the recommended international standard [4].

Fig. 7 shows the variation of the RIA in the fabricated fibre (having core diameter of 9.8 μm, NA of 0.12 and F-doped inner cladding width of 27 μm) at the time of irradiation and the post-irradiation recovery at an operating wavelength of 1550 nm. The RIA increases rapidly at the beginning of the irradiation and then becomes saturated. There is fast post-irradiation recovery and the long-lived RIA lies at a value of around 2.09 dB/km for an accumulated dose of 1.17 MRad.

The base loss and the long-lived RIA under an accumulated dose of 25 MRad for the similar fibre are shown in Fig. 8 in the wavelength range of 1450–1600 nm.

The fibre shows a base attenuation <2 dB/km in this wavelength range and RIA (at 25 MRad dose) of 2.2 dB/km at 1550 nm which lies well within the recommended international standard and is comparable with previously reported data [4],

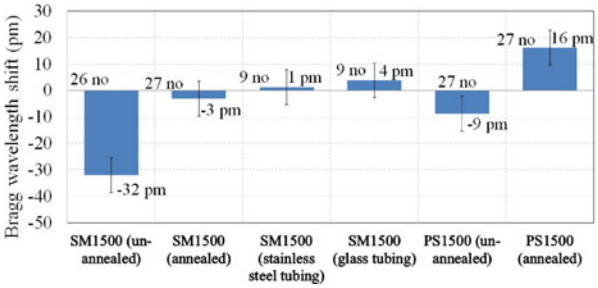

Fig. 9. FBG Bragg wavelength shift at 8 MRad for FBGs written into different fibres. The bars indicate the average shift of the given number of FBGs. The error bars indicate the minimum and maximum shift seen by the FBGs.

[7] for the doped silica core radiation resistant optical fibre. Such low level of RIA, achieved without F doping in core, is an outcome of the optimized silica deposition condition by controlling the deposition rate, O_2 : SiO_2 proportion, deposition temperature and heat flow to the reaction zone which led to smooth deposition and sintering of silica layers with thus a significant reduction in the defect formation in fibre under radiation. Using six oxy-hydrogen burners is a major advantage to achieve greater uniformity of temperature on the tube surface and consequently in the reaction zone. The quantum of heat flow (adjusted by controlling H_2/O_2 flow rates) was important to facilitate the sintering process. The O_2:SiO_2 proportion was maintained above 8 to ensure oxidizing condition.

It has also been observed that the fibre with similar core diameter and NA having single mode operation, RIA decreases with increment of F-doped inner clad layer. For the optimum thickness of the F-doped layer, the tail of the propagation mode stays within the F-doped region resulting in lower RIA.

Under gamma exposure, the RI of the core in the photosensitive fibre SM1500 (bend-insensitive, B/Ge doped) and the PS1500 (B/Ge highly doped) has been observed to increase until the accumulated dose reaches 2 MRad and stabilizes until the accumulated dose exceeds 25 MRad. Such RI increment is due to the formation of radiation induced color center generation in Germanium doped core region which modifies the RI. The mechanism of FBG formation within Germanosilicate fibre involves Ge related color center, which is also created by ionizing radiation. Fig. 9 shows the average Bragg wavelength shifts of all tested FBGs, grouped by the types of host-fibres, at 8 MRad (almost all sensors reached saturation after about 3–4 MRad). In Fig. 9, each bar indicates the number of FBGs tested for the particular fibre type and the error bars indicate the range of Bragg wavelength shifts obtained. It is clear from Fig. 9 that the gratings written into SM1500 and annealed are less affected by the radiation than those written in PS1500. The results also show that stainless steel tubing in particular reduces the radiation effect on FBGs within it.

The temperature sensitivity of the FBG sensors written into both the SM1500 and PS1500 photosensitive fibres remain effectively unchanged after a radiation exposure of 25 MRad. Fig. 10 shows a typical temperature response of a FBG (written in the SM1500 fibre) before and after radiation. No hysteresis was observed.

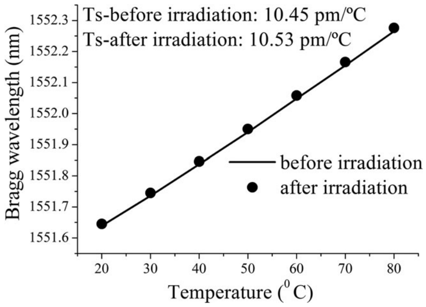

Fig. 10. Graph showing the effectively unchanged temperature sensitivity of the FBGs, written into SM1500 photosensitive fibre, before and after exposure to a radiation level of 25 MRad.

The amplitude (reflectivity) and the spectrum of the FBGs are unchanged throughout the exposure and post radiation.

V. CONCLUSION

The SCFC optical fibre, fabricated through MCVD exhibits a very good transmission properties as well as radiation resistance in the NIR region. Such a low loss, of 0.193 dB/km at a wavelength of 1550 nm, arises from the quality of fibre design and the fabrication of a thick F-doped inner cladding, maintaining low diffusion of F into the core region through the optimization of the collapsing process during fabrication of the optical preform. The F-doped layer supports the propagation of light through the core and prevents the tunneling of light from the core region to the outer clad region.

The low level of the long-lived RIA (2.2 dB/km at 1550 nm) has been achieved through the optimization of the core layer deposition condition to reduce the initial defect precursor. Fibre of such quality and having a low loss, along with a low RIA, has been achieved through an optimized manufacturing process. The fibre design used makes it possible to create an optical fibre-based radiation-resistant sensor system, through constructing arrays of FBGs for use for effective sensing and data transmission in environments of high radiation.

The FBG sensors written in SM1500 and protected with steel tube are quite radiation hardened. The radiation induced Bragg wavelength shift of around 1 pm with unaltered temperature sensitivity under radiation shows potential use for temperature measurements in radiation environments with an uncertainty of around 0.1 °C. The saturation of BWS under exposure of 3–4 MRad leads to the opportunity of pre-annealing of the FBGs before installation to achieve better accuracy.

REFERENCES

[1] H. Henschel, S. K. Hoeffgen, K. Krebber, J. Kuhnhenn, and U. Weinand, "Influence of fibre composition and grating fabrication on the radiation sensitivity of fibre Bragg gratings," *IEEE Trans. Nucl. Sci.*, vol. 55, no. 4, pp. 2235–2242, Aug. 2008.

[2] H. Henschel, S. K. Hoeffgen, J. Kuhnhenn, and U. Weinand, "Influence of manufacturing parameters and temperature on the radiation sensitivity of fibre Bragg gratings," *IEEE Trans. Nucl. Sci.*, vol. 57, no. 4, pt. 1, pp. 2029–2034, Aug. 2010.

[3] D. Grobnic, H. Henschel, S. K. Hoeffgen, J. Kuhnhenn, S. J. Mihailov, and U. Weinand, "Radiation sensitivity of Bragg gratings written with femtosecond IR lasers," *Proc. SPIE*, p. 73160C-1–9, 2009.

[4] A. I. Gusarov *et al.*, "High total dose radiation temperature effects on temperature sensing fibre Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 11, no. 9, pp. 1159–1161, Sep. 1999.

[5] P. Niay *et al.*, "Behaviour of Bragg gratings, written in germanosilicate fibres, against y-ray exposure at low dose rate," *IEEE Photon. Technol. Lett.*, vol. 6, no. 11, pp. 1350–1352, Nov. 1994.

[6] T. Wijnands, K. Aikawa, J. Kuhnhenn, D. Ricci, and U. Weinand, "Radiation tolerant optical fibres: From sample: Testing to large series production," *J. Lightw. Technol.*, vol. 29, no. 22, pp. 3393–3400, Nov. 2011.

[7] T. Kakuta *et al.*, "Radiation resistance characteristics of optical fibres," *J. Lightw. Technol.*, vol. LT-4, no. 8, pp. 1139–1143, Aug. 1986.

[8] T. Kakuta, K. Sakasai, T. Shikama, M. Narui, and T. sagawa, "Absorption and fluorescence phenomena of optical fibres under heavy neutron irradiation," *J. Nucl. Mater.*, vol. 258, pp. 1893–1896, 1998.

[9] L. Jian *et al.*, "Study on pure silica core optical fibres," *Sci. China Ser. E, Technol. Sci.*, vol. 56, no. 1, pp. 58–64, 2008.

[10] A. L. Tomashuk *et al.*, "Enhanced radiation resistance of silica optical fibres fabricated in high O_2 excess conditions," *J. Lightw. Technol.*, vol. 32, no. 2, pp. 213–219, Dec. 2013.

[11] A. Ghatak and K. Thyagarajan, *An Introduction to Fibre Optics*. Cambridge, U.K.: Cambridge Univ. Press, Jun. 28, 1998.

[12] J. Kirchhof, P. Kleinert, S. Unger, and A. Funke, "About the fluorine chemistry in MCVD: The influence of fluorine doping in SiO_2 deposition," *Cryst. Res. Technol.*, vol. 21, pp. 1437–1444, 1986.

[13] K. O. Hill and G. Meltz, "Fibre Bragg grating technology fundamentals and overview," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1263–1276, Aug. 1997.

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