Gamma irradiation effects in photonic crystal fibre Bragg gratings

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In this paper, we demonstrate and report the effects of Cobalt-60 gamma irradiation on Endlessly Single Mode Photonic Crystal Fibre Bragg grating (PCF-FBG) sensors. Optical measurements were performed to determine the shift of the Bragg wavelength as a function of accumulated dose and relaxation time. We were able to obtain a Bragg wavelength shift with PCF-FBGs through each stage and each experiment, with a near full recovery. The performance of the FBGs was identical for subsequent stages of irradiation. This makes them a strong candidate as optical fibre FBG sensors in the area of radiation dosimetry.

1. Introduction

The advantages of optical fibre Bragg grating (FBG) sensors have made them attractive for various industrial sensing applications. Typically, their main attributes compared to electronic, chemical, mechanical and electrical sensors is that they are immune to electromagnetic interference, are light weight and small, resistant to harsh environments, have greater sensitivity, are mass producible and cost effective, and are able to measure remotely in real time [1].

During the past decade, research has shown that FBGs are also affected by ionizing radiation [2]. This relates to radiation environments such as high dose rate nuclear areas and low dose rate space environments. Exposure to gamma radiation in nuclear environments causes optical attenuation of the fibre, due to the change in the refractive index. This is dependent on the fibre composition, including the chemical composition and photosensitization technique used [3,4].

Two important issues in this area are (i) developing radiation resistant FBGs for use in nuclear environments, allowing temperature and strain measurement applications [5,6], and (ii) investigating as possible high dose radiation sensors [7,8]. To improve the radiation tolerance of FBGs and stability whilst under gamma irradiation, one method used is hypersensitisation through pre-irradiation. The best results are obtained using pure silica with light hydrogen doping presumably to seal off colour centres with hydride [9]. Pre-irradiation can reduce the sensitivity of FBGs leading to a reduction in the BWS, but producing a more stable FBG. If FBGs are to be used in radiation environments successfully they should remain stable. For example, in Ge-doped and hydrogen loaded SMF-FBGs, pre-irradiation treatment can reduce the variation of radiation induced BWS by 8-27% at a dose of 50 kGy [10].

Silica-based Photonic Crystal Fibres (PCFs) potentially show lower attenuation loss for conventional fibre such as single mode fibre (SMF) [11]. Irradiated standard (SMF) FBGs have shown a relaxation effect where the Bragg wavelength shift has only partially recovered when the gamma source is removed [8]. Results to date indicate that silica PCF have superior recovery time compared to conventional fibres [12] principally because there is no dopant such as Ge involved. To help quantify and establish the effect of gamma irradiation on FBG sensors, we have examined the effect on the Bragg wavelength during three irradiation periods and three relaxation periods in FBGs written in solid core PCF. Of particular interest is the effect of pre-irradiation and relaxation performance.

2. Fibre Bragg Gratings

A FBG is a periodic perturbation of the refractive index along the fibre length. The formation of permanent gratings in optical fibre was first demonstrated by Hill and Metz [13], who exposed Germania-doped fibre to intense Argon-ion laser radiation and observed an increase in the reflected light intensity until almost all the light was reflected from the fibre. It is in a sense a type of Bragg reflector written into the optical fibre. The fibre reflects certain wavelengths of light and transmits all others [1]. When a section of fibre is exposed to axial strain, temperature or pressure changes from an external source (e.g. those arising from colour centre or bond absorption during gamma irradiation) it will change either or both the refractive index and grating period of the FBG [1]. This enables changes to the FBG to be detected from the shift in the Bragg wavelength (λ_B):

$$\lambda_B = 2n\Lambda \tag{1}$$

where (n) is the average refractive index of the grating and (Λ) is the grating period.

3. Method

Optical fibres: The optical fibre was endlessly single mode PCF (ESM12-01) manufactured by BlazePhotonics (NKT). These fibres have a hexagonal distribution of 54 holes within a ϕ = 125 μm diameter silica fibre, inside a holey region diameter of ϕ = 57.4 μm. Additional characteristics include a pitch between holes of Λ = 8.0 μm; a core diameter of ϕ = 12.0 μm, hole diameter relative to pitch of Λ/ϕ = 0.46, and a coating diameter of ϕ = 220 μm (single layer acrylate).

FBG inscription: The FBGs were inscribed into the PCF using 193nm pulsed UV radiation of an ArF laser [14]. The inscription parameters were: fluence per pulse, f_{pulse} = 248 mJ/cm^2; cumulative fluence, f_{cum} = 8.9 kJ/cm^2; repetition rate, RR = 30 Hz; pulse duration, τ_w = 15 ns. Prior to FBG inscription: short (L = 10-15 cm) sections of PCF were pigtailed at each end with standard SMF-28 fibre using a tailored fusion splicing technique (Fittel s175 model Arc fusion splicer). After splicing, hydrogen (H_2) loading commenced at pressure P = 180 atm and temperature T = 80°C for t = 7 days. The FBG inscription commenced immediately after the unloading of fibre samples from the hydrogen vessel. Two PCF-FBGs with central wavelengths of 1532.860 nm (PCF1) and 1541.020 nm (PCF2) were fabricated.

FBG characterisation: During irradiation, optical measurements were performed at ANSTO to determine the BWS as a function of accumulated dose and relaxation time, compared to the base non–irradiated Bragg wavelength. The experimental setup is shown in figure 1. A superluminescent light emitting diode (SLD) (Dense Light DL-BZ1-SC5403A) was used as the light source with a centre wavelength of 1550nm, bandwidth of 100nm, and 25mW optical power. The FBG reflective spectrum was measured as a function of wavelength via a 50-50 circulator and an Agilent86142A Optical Spectrum Analyser (OSA) connected by a GPIB/USB Agilent interface to a PC. The OSA had a wavelength resolution of 10 pm. A Matlab data acquisition program allowed us to record the results automatically.

Optical characterisation measurements were performed at ECU before and after the irradiation studies using a similar setup to that shown in figure 1, except that the OSA was a Thorlabs OSA202.

Gamma irradiation: Irradiation studies were performed at the Australian Nuclear Science and Technology Organisation (ANSTO) using the Gamma Technology Research Irradiator (GATRI). A Cobalt-60 radiation source was used for all of the exposure stages, and the dose rate was 2.35 kGy/ hr. The two PCF-FBGs were multiplexed into one optical fibre cable, and were mounted inside a polystyrene box for support. During the irradiation process, measurements were taken and recorded at 30 minute intervals. Each exposure period amounted to exactly 49.35 kGy for a time period of 21 hrs, followed by 3 hrs of relaxation (no irradiation). A total accumulated dose of 148.05 kGy was reached.

Dosimetry was performed by placing cerie cerous type dosimeters [15] in cylindrical polyethylene holders (for electron equilibrium) at the sample position in the GATRI chamber. This established the average dose rate, which determined the dose absorbed by the FBGs throughout the exposure stages. The overall uncertainty associated with an individual dosimeter reading includes both the uncertainty of calibration of the batch of dosimeters and the uncertainty due to variation within the batch, and was calculated to be 3%, with a level of confidence of approximately 95%. The uncertainty evaluation was carried out in accordance with the ISO Guide on the Expression of Uncertainty in Measurement [16].

4. Results and Discussion

The Bragg wavelength shifts (BWS, $\Delta\lambda_B$) observed for PCF1 during the multi-stage irradiation procedure, are shown in figure 2. Almost identical results were obtained for PCF2 in terms of wavelength shift values. Each irradiation period reached an exact dose of 49.35 kGy over 21 hours, which equated to a dose rate of 2.35 kGy/hour. A 3.0 hour relaxation period with no irradiation followed each irradiation period. The actual FBG reflection peaks for PCF1 are shown in figure 3 for the first irradiation cycle.

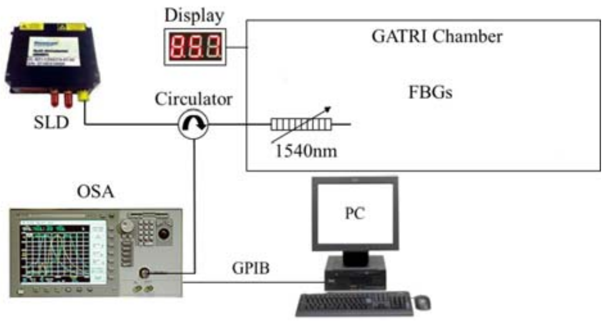

Fig. 1. Experimental set-up for measuring reflective spectra.

During the first irradiation period, the Bragg wavelength shift (BWS) of both PCF1 and PCF2 was $\Delta\lambda_B$ = 50 pm, followed by a relaxation in the BWS of $\Delta\lambda_B$ = 30 pm. During the second irradiation period, the BWS was $\Delta\lambda_B$ = 30 pm, and the relation shift was $\Delta\lambda_B$ = 30 pm. The response of the FBG reached the previous total BWS of the first irradiation stage. A similar result was obtained during the third irradiation period, with a BWS shift of $\Delta\lambda_B$ = 30 pm and an identical relaxation of $\Delta\lambda_B$ = 30 pm. Hence, it appears that there is an initial radiation hardening period for the pre-irradiated FBG that corresponds to a BWS of $\Delta\lambda_B$ = 20 pm. After this pre-irradiation hardening, the FBGs both behaved identically, both in comparison to each other, and for repeated identical irradiations. It can be seen after the initial irradiation shift, the second and third irradiation periods are identical. This result again highlights a solid BWS ($\Delta\lambda_B$ = 50, 30, and 30pm) which is still compatible with standard SMF28+H results with a similar accumulated dose of 50 kGy which produced a 46pm shift in their first stage and 35pm shift in their second stage [8].

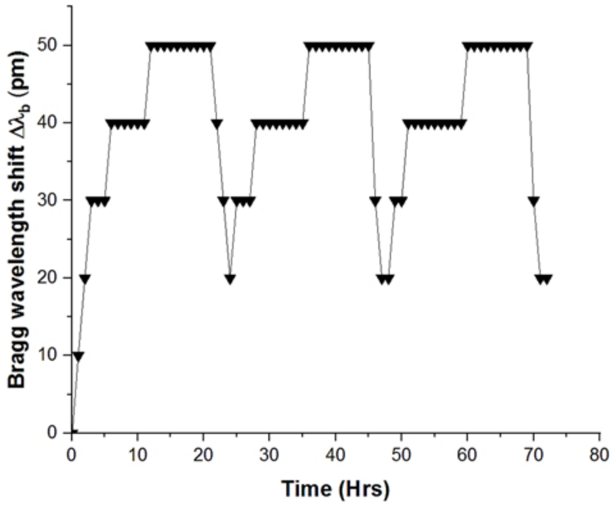

Fig. 2. Graph showing accumulated BWS of PCF1 (λ_B = 1532.860nm) for the three irradiation and relaxation periods. Numbers 1 to 3 indicate where the relaxation ceased. Total BWS $\Delta\lambda_B$ = 20pm. After initial radiation hardening of 20 pm, almost full recovery is achieved on subsequent irradiation stages.

All relaxation periods were conducted over a 3.0 hr. period. During each relaxation period there was a shift back towards the original wavelength. It shows there is a slight reduction after the first dose however there is still a positive shift ($\Delta\lambda_B$ = 50pm, 30pm, and 30pm) during each phase of the irradiation study. Interestingly, both PCF-FBGs had identical shifts. During the relaxation periods, the PCF-FBGs consistently showed a strong significant recover, especially after the second and third irradiation periods which indicated a full recovery. This is definitely larger than that of conventional fibres under similar regimes and is in keeping with research that pure silica PCF-FBGs has a superior recovery time [12]. After the first irradiation period, the FBGs showed consistent results in terms of BWS versus gamma dose, and recovery during relaxation.

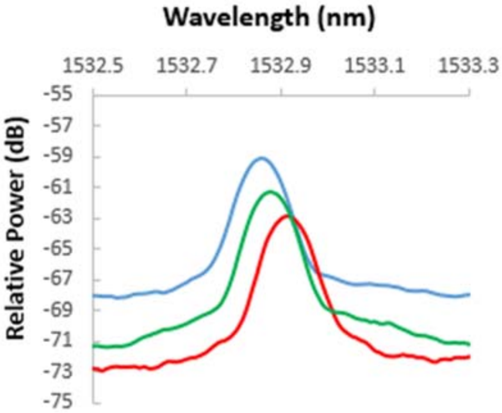

Fig. 3. Individual FBG reflection peaks for PCF1, (a) before irradiation (blue peak), (b) at the end of the first irradiation period (after 49.35 kGy of gamma irradiation) showing a BSW of $\Delta\lambda_B$ = 50 pm (red peak), and (c) at the end of the first 3 hour relaxation period, showing a BWS relaxation of $\Delta\lambda_B$ = 30 pm (green peak).

5. Conclusions

A BWS is observed in all three initial irradiation periods. After the second irradiation dose, the BWS reduced in all FBGs. This could be due to pre-irradiation effects and radiation hardening. Such radiation-based solarisation appears analogous to that observed with both optical and thermal pre-exposure of hydrogen loaded optical fibre prior to grating writing using heat, laser and broadband sources [9,17,18]. Particular interest is focused on the relaxation effects. For the first and second relaxation periods there is a reduction of wavelength back towards the original. On average there is a 30 pm drop in the Bragg wavelength for about 50 kGy irradiation dose.

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