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Desmond Baccini

Steven Hinckley
Edith Cowan University

Graham Wild
Edith Cowan University

Connie BANOS

Justin B DAVIES

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Gamma Irradiation in Fibre Bragg Gratings

Desmond Baccini [1], Steven Hinckley[1], Graham Wild [1,2], Connie Banos [3], and Justin B. Davies [3,4]
[1]Centre for Communications Engineering Research, Edith Cowan University, Joondalup WA 6027, Australia.
[2]School of Aerospace, Mechanical, and Manufacturing Engineering, RMIT University, Melbourne VIC 3000, Australia.
[3]Australian Nuclear Science and Technology Organisation, Lucas Heights NSW 2234, Australia.
[4]Institute of Medical Physics, School of Physics, University of Sydney, NSW 2006, Australia.

Abstract Summary

We report a preliminary study of gamma radiation effects on the current generation of optical fibre Bragg grating sensors, and the effects of relaxation after gamma irradiation, as a function of dose.

Keywords- fibre Bragg gratings (FBGs), gamma irradiation, sensors.

I. INTRODUCTION

Optical fibre sensing systems have been used as sensors for temperature, strain, pressure and other important measurement systems. In the past decade, there has been increased interest in extending the application of these sensors to ionizing radiation environments, including their use in monitoring various parameters in space environments (low dose rate and level) and hazardous nuclear areas (high dose rate and levels) [1]. There has even been some development in the area of using these types of sensing systems (and in particular, the damage caused to the fibres) for ionizing radiation dosimetry [2].

Results obtained to-date indicate that gamma irradiation causes attenuation degradation in various optical fibre types, through the generation of defects such as color centers [1-3], causing refractive index changes in the fibre. Studies so far have limited the determination of the effects of gamma radiation on the optical properties of fibres to the visible wavelength range of 400 nm to 700 nm. It has also been found that the specific type of fibre (for example, fibres made with different dopant types) have different responses to ionizing radiation [3].

The FBG is a fundamental building block of any optical fibre-based sensing system [4]. Recently, a number of studies have examined the changes in the Bragg wavelength of FBGs under gamma irradiation [4,5,6]. These studies have reported conflicting results, and the mechanism responsible for the proposed shift in the Bragg wavelength is still unknown.

Previous work [3] examined the influence of fibre composition and the effect this has on the Bragg wavelength under irradiation. Irradiation dose rates of 0.90Gy/s up to a dose of 100kGy were used, which is compatible to our accumulated dose of about 86kGy. The highest Bragg wavelength shift (BWS) recorded was 160pm for Ge-doped fibres, and the lowest BWS was 50pm with Ge-free fibre. Gamma-induced attenuation loss was also examined [6] in Ge-doped fibres and pure silca core fibres, when exposed at a dose rate of 720Gy/hr up to a total dose of 100kGy. The optical loss of all fibres was in the range 0.04-0.06dB/m at 100kGy.

In this study, we performed a preliminary study of gamma radiation effects on a selection of optical fibres and FBGs. This study was needed to examine the feasibility of performing these types of measurements on different samples using the facilities at ANSTO, and to determine the most appropriate procedures to complete our proposed study. The three day project generated some interesting data, which demonstrated some interesting, although not totally conclusive, results on the effects of gamma radiation on our sample set. Our eventual aim is to investigate the use of FBG sensors as gamma dosimeters for high dose applications.

II. FIBRE BRAGG GRATINGS

A. General Theory of FBGs

Fibre Bragg gratings (FBGs) are passive devices utilized extensively in optical fiber communications and sensing. A FBG is a short section of optical fibre that is manufactured to reflect a particular wavelength of light and to transmit all other wavelengths. This is achieved by having a periodic variation to the refractive index in the core of the optical fibre, as shown in Fig. 1. Since some light will be reflected at a change in refractive index, a specific wavelength will be reflected, while all others will be transmitted. Hence, the FBG acts as an optical filter, reflecting a narrow wavelength range, centred about a peak wavelength. This wavelength, known as the Bragg wavelength (λ_B), is given by [7]

$$\lambda_B = 2n\Lambda, \qquad (1)$$

where n is the average refractive index of the grating (average of n_2 and n_3 in Fig. 1), and Λ is the grating period (as shown in Fig. 1).

Any measurand that has the ability to affect either the refractive index or the grating period will result in a change in the Bragg wavelength. This allows FBGs to be used in sensing applications. For example, if there is a change in the length of the FBG due to strain, the spacing between the dielectric mirrors changes, so the wavelength that the FBG reflects changes. In this instance, the change in length will decrease the optical density of the fibre, which would decrease the refractive index.

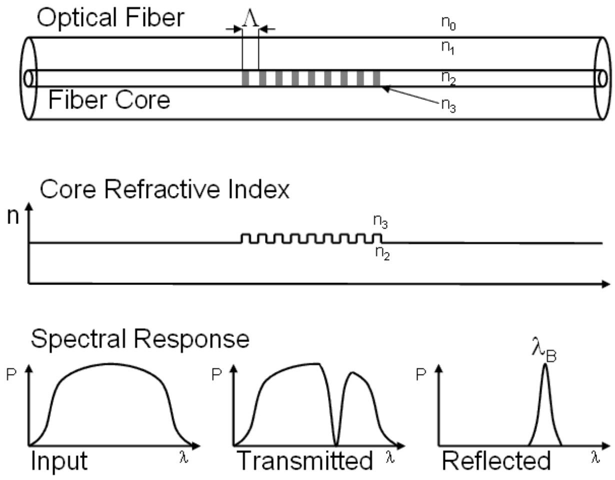

Figure 1. FBG structure and operation.

B. Gamma Irradiation of FBGs

When FBGs have been exposed to gamma irradiation, a Bragg wavelength shift (BWS) occurs. A recent study examined the relationship between the total dose and BWS up to a dose of 100kGy [8]. Results indicate that the BWS and FBGs sensitivity increase as the radiation dose increases with FBGs of varying Bragg wavelengths (820nm, 1285nm and 1516nm). The BWS was about 40-50pm for a total dose of 100kGy for all FBG wavelengths.

The effect of the variation in fabricating methods of FBGs has shown that fibres with medium to high germanium (Ge) content (10-21mol%) and loaded with hydrogen result in a high BWS (approximately 160pm after a dose of 100kGy) [3]. Fibres without Ge resulted in a 50pm BWS.

Further study has revealed the influence of hydrogen loading pressure on the radiation sensitivity of FBGs. The Bragg wavelength as a function of dose rate was measured, with FBGs that were made after loading the fibre at various pressures of 100, 200 and 300bar [9]. When increased to 300bar, the radiation sensitivity increased by 14% compared to the 100 and 200bar. The BWS for a dose of 100kGy was in the range 130-150pm for 100-300bar hydrogen.

Hence, there is a range of structural, compositional and manufacturing parameters that influence the FBGs sensitivity and wavelength shift. There is a need to study the properties of FBG sensors, and their manufacturing methods and fibre types, under the influence of ionising radiation.

III. Experimental Method

In this study, we measured the transmission characteristics of optical fibres and incorporated FBGs as a function of the accumulated gamma dose over a three day period. All measurements were performed at approximately 22^{o}C.

A. Gamma Irradiation

Gamma irradiation was performed using a wet storage cobalt-60 irradiation facility at ANSTO. FBGs were irradiated for various times at dose rates of 50-64 Gy/minute to accumulated doses of between 1 and 100 kGy. For example, for Sample 3 was subjected to consecutive irradiation times of 1, 5, 30, 30, 240, 600 and 600 minutes. After each irradiation period, the samples were removed from the gamma irradiation facility, and optical measurements performed. The samples were then returned for further irradiation. Unfortunately, the time between when the sample was removed and then subsequently returned to the irradiator was random due to the short and rushed timetable involved.

Dose rates were determined using Fricke [10] and Ceric Cerous [11] dosimeters. These dosimeters were calibrated in a cobalt-60 radiation field, in which the dose rate was determined from reference dosimeter measurements made under similar conditions. The overall expanded uncertainty (k=2) [12] associated with an individual dosimeter reading included both the uncertainty of calibration of the batch of dosimeters and the uncertainty due to variation within the batch, and was calculated to be 2.0% (Fricke) and 3.5% (Ceric Cerous).

B. FBG Samples

The FBG samples were purchased from Photronix Technologies (Malaysia). FBGs were manufactured in standard SMF-28 and SMF-28e optical fibres, with no H2 loading. They have a reflectivity of 80-98% and a 3dB spectral width of 0.2 to 1.0nm. All gratings were used without coatings.

C. Optical Measurements

Optical measurements were performed in the wavelength range from 1520 nm to 1600 nm using a superluminescent laser diode (DenseLight DL-BZ1-SC5403A) and an optical spectrum analyzer (Agilent 86142A). The transmittance spectrum was measured, and used to determine the shift in the Bragg wavelength as a function of absorbed dose, and as a function of relaxation time post-irradiation.

D. Relaxation Effects

At the completion of the irradiation studies, a relaxation experiment was performed. After final removal from the gamma irradiation cell, the Bragg wavelength of the FBG was determined as a function of relaxation time, and compared to the initial (base) Bragg wavelength.

IV. Results and Discussion

The results of two basic experiments are reported in this section: the transmittance of an FBG (Sample 3) as a function of accumulated gamma dose, and relaxation of Sample 1 post-irradiation.

A. FBG Bragg Wavelength Shift vs Dose

In general, our results show an increase in the Bragg wavelength with dose, although this effect did not saturate as observed in previous work, as the accumulated dose of < 86kGy was too low. Fig. 2 shows the transmittance curves versus light wavelength as a function of gamma dose. The data has been normalized to a baseline of 0 dB for comparison.

Fig. 3 shows the Bragg wavelength shift (BWS) as a function of accumulated gamma dose (in kGy) obtained from the data shown in Fig. 2 for sample 3. To obtain the BWS, we need to determine the transmittance minimum of reach curve in Fig. 2. This was obtained by first smoothing the data using a 4-point smoothing algorithm, normalizing each curve to 0 dB, and then implementing a search algorithm to find the minimum transmitted optical power. The uncertainty in each Bragg wavelength was estimated to be 5 pm based on a combination of the resolution of the OSA and the uncertainty in determining position of the minimum for each curve.

The results for low dose (< 3 kGy) seem inconsistent, and there are negative shifts in the Bragg wavelength compared to the pre-irradiation value. This small negative BWS could be due to two possible sources: temperature sensitivity during the optical measurements, and the limited resolution and repeatability of the OSA. Since these values are of the same magnitude as the resolution and repeatability of the OSA, then these will be affected by "noise" related issues.

Temperature cross-sensitivity is a major issue in the application of FBGs to the measurement of parameters other than temperature. Typical temperature sensitivity coefficients for FBGs are of the order of 10pm/^{o}C at 1300nm [13], depending on fibre type. Therefore, there may be an expectation that, after removal from the irradiation apparatus, the fibre may not cool down to room temperature in the time before the optical measurements were performed, if the gamma irradiation caused the temperature of the fibre to increase. Previous work indicates that a maximum temperature rise of 0.5^{o}C occurs in FBGs subjected to 100kGy gamma irradiation [6], so the uncertainty in the BWS due to temperature would be 6pm at most for a 1550nm FBG if the fibre temperature remained 0.5^{o}C above room temperature. The wavelength resolution of the OSA was 10pm, so the total BWS uncertainty was about 12pm, which allows for any uncertainty in the BWS measurement.

The remaining data points (for dose > 3kGy) are reasonably consistent, except for the data point at 51.6kGy, where the BWS appears to have decreased compared to the other data points. This occurred since, after removal from the gamma irradiator, the optical measurements were not performed for at least 12 hours, so that this data point is affected by the relaxation of the Bragg wavelength post-irradiation. Hence, we have re-plotted a restricted data set showing the BWS versus Accumulated Dose in Fig. 4. This data set indicates a logarithmic dependence of the BWS on gamma dose for accumulated dose in the range of about 3 to 87 kGy. This behaviour is consistent with previously observed results [3,9].

B. FBG Relaxation After Removal of Gamma Source

Fig. 5 shows the effect of post-irradiation relaxation for sample 1 after a total irradiated dose of 100.8kGy (accumulated 30 hours at 56Gy/minute). That is, the effect of removal of the radiation source and the subsequent relaxation of the shifted Bragg wavelength back towards the pre-irradiation (base) value. The initial Bragg wavelength was 1540.787nm. Post-irradiation, the Bragg wavelength relaxed to 1540.866nm after 9 hours and 1540.840nm after 13 hours.

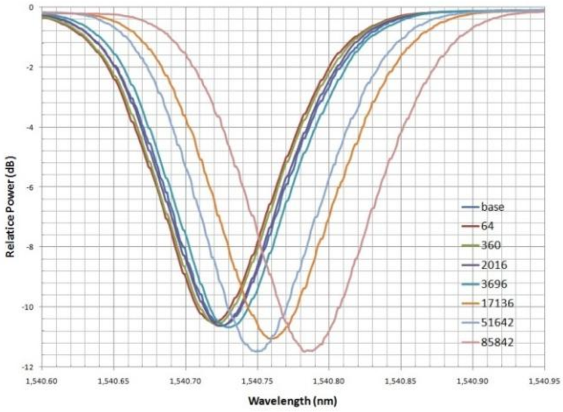

Figure 2. Transmittance spectra versus wavelength of FBG Sample 3, as a function of accumulated gamma dose (in Gy). All curves are normalised to a transmitted optical power of 0 dB.

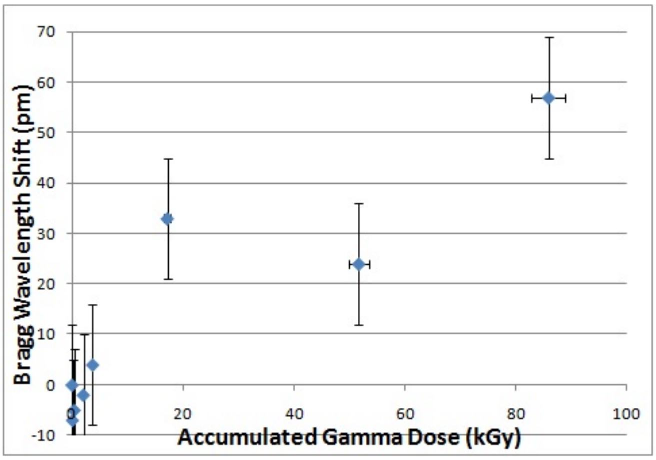

Figure 3. Plot of complete data set of the Bragg wavelength shift as a function of accumulated dose (in kGy) for FBG Sample 3.

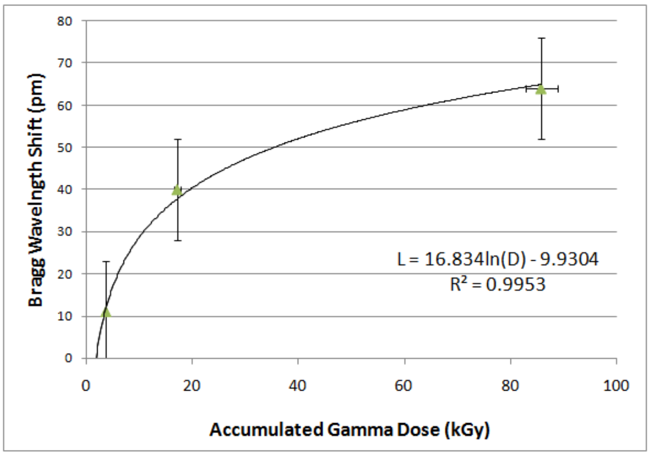

Figure 4. Plot of modified data set of the Bragg wavelength shift as a function of accumulated dose (in kGy) for FBG Sample 3.

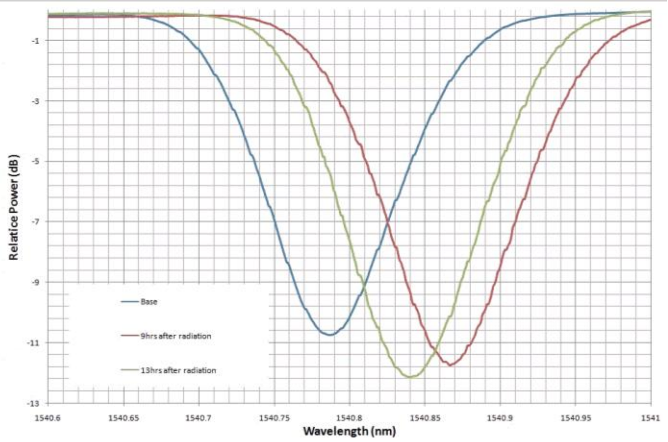

Figure 5. Bragg wavelength shift after removal from irradiation source, for Sample 1. The base curve corresponds to the pre-irradiation FBG properties.

V. FUTURE WORK

Unfortunately, the limited nature of the previous study does not allow us to report a definitive quantitative behavior and subsequent explanation of gamma radiation-optical fibre-FBG interaction. Future measurements are planned that will eliminate some of the uncertainty occurring in the current results. This will involve (i) performing optical measurements in-situ (which will increase the uncertainty in the dose measurements, but considerably reduce any uncertainty in the optical measurements), (ii) quantification of the relaxation phenomenon, (iii) explicit quantification of the BWS for different types of fibre-FBG combinations, and (iv) examination of the affect of temperature cross-sensitivity (which will be an issue for in-situ optical measurements) on the performance of FBGs as potential gamma dosimeters. We also intend to automate the optical measurements, to allow us to obtain continuous measurements of the BWS as a function of accumulated dose.

VI. CONCLUSION

We have made some interesting observations in this preliminary study of gamma irradiation effects in SMF FBG sensors, especially the relaxation behaviour in Fig. 5, which needs further examination and quantification. However, the results do show important trends that indicate that FBGs may be useful as gamma dosimeters, especially for high accumulated doses (of the order of 100's of kGy). The Bragg wavelength shift followed a logarithmic dependence on gamma absolute dose, and a significant relaxation in the Bragg shift was observed post-irradiation. This experiment has also given us the opportunity to explore the capabilities of the ANSTO irradiation facility, and we intend to use this information to modify future experiments to obtain greater efficiency and reduced experimental time.

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