Fibre Bragg gratings of type I in SMF-28 and B/Ge fibre and type IIA B/Ge fibre under gamma radiation up to 0.54 MGy

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ABSTRACT

The sensitivities of type I and IIA fibre Bragg gratings written to different reflectivities in SMF-28 and B/Ge fibres to ionizing radiation up to 0.54MGy are investigated. The Bragg wavelength shows a small and rapid increase at the start of irradiation followed by either a plateau (type I) or a decrease (type IIA).

Keywords: Fibre Bragg grating, photo sensitive fibre, ionizing radiation, type I, type IIA, fibre optics sensor

1. INTRODUCTION

The nuclear industry requires sophisticated and reliable sensor technology for use in radiation environments, where the use of electrical sensors is severely limited through ionizing radiation damage. Electrical wiring is prone to pickup of electromagnetic [EM] interference and electrically powered devices require extensive protection and safety features for use in hazardous environments. Optical fibres have long been used as communication links in these environments[1]. Although radiation induced attenuation is observed, this can be counteracted by increasing power levels[2]. Wavelength encoded sensor technology i.e. based on fibre Bragg gratings [FBGs] immunises a sensor system against radiation induced attenuation in interconnecting fibres. Optical sensors are inherently safe and fused silica is a chemically inert and stable material. However, the wavelength stability of FBGs to ionising radiation exposure requires investigation.

1.1. Photosensitivity of fibres for FBGs manufacturing

FBGs are predominantly generated by exposure of a photo sensitive fibre core by a spatially modulated UV intensity to produce the required periodic refractive index modulations in the core. Photosensitivity in fibres is achieved either by boron co-doping or by hydrogenation of *germanosilicate* fibres (e.g. SMF-28)[3]. Alternative techniques for generating refractive index modifications based on densification of the fibre material exist, although densification and stress centres have also been observed following conventional UV irradiation[4].

Detailed photochemical and structural changes underlying the complex process of photoinduced refractive index changes in fibres materials and sensitisation techniques are still under active investigation. In summary, in the case of germanosilicate fibre without H_2 present, photosensitivity has been ascribed to the formation of oxygen deficiency centres [GODC] in the germanium matrix, however the presence of H_2 significantly alters the chemistry which according to Grubsky et.al.[5] is a two stage process ending in Si-OH, GeE' (electron hole) and atomic H via excitation of a Ge-O bond. The enhancement of photosensitivity in germanosilicate fibres by boron co-doping is reported to be due to a increased probability of the formation of GODCs in the presence of boron[6]. Processes leading to UV induced refractive index modulations which underlie a FBG are very complex and dependent on many variables.

Although specific analytical techniques to study these processes are complex, it is fairly straightforward to follow the effect of these dynamics by monitoring the Bragg wavelength of a FBG as it is formed. For the simplest case of Type I FBGs formed in H_2 loaded SMF-28 and non H_2 loaded B co-doped fibre, the Bragg wavelength is red shifted (towards longer wavelength) with increasing UV irradiation and saturates at the maximum reflectivity. Continuing UV irradiation beyond this point leads to two different FBG sub types the so-called regenerated FBGs of type IA[7,8] and type IIA[9]. Type IA FBGs show a strong continued red shift of up to 16nm whereas regenerated FBGs in non-hydrogenated B co-doped fibres show a completely different behaviour on over exposure. Before formation of the regenerated FBG (type IIA) at a slightly shorter wavelengths, the reflectivity of the original type I FBG is gradually eliminated, while the new FBG continues to grow and at the same time continues to shift to the blue. The change in shift direction is indicative of different processes becoming dominant upon irradiation.

1.2. Ionizing radiation interaction with fibres and FBGs

Ionizing radiation effects on bulk samples of fused silica, namely radiation-induced attenuation [10] and refractive index

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change[11], have been studied extensively but less so in optical fibres [12,13]. Typical refractive index modulations (Δn) in a FBG are in the order of 10^{-4} to 10^{-3}. The Bragg wavelength λ of a FBG is calculated from $\lambda = 2\, n_{eff}\, \Lambda$, thus a change of n_{eff} in the order of 9×10^{-7} results in a Bragg shift of ~1pm for a 1550nm FBG.

Published values and limits for refractive index changes induced by γ radiation are in the order of 6×10^{-3} for an irradiation dose of 13MGy [12]. The underlying physical processes which lead to the refractive index change is in one model described by the formation of colour centres, where the induced absorption which leads to a change of the refractive index via Kramers-Kronig relations [14]. Irradiation studies on FBGs written into different types of fibre material, including nitrogen-doped fibres which have been shown to be radiation hard with respect to attenuation losses, have been carried out previously [15, 16]. These studies report that FBGs generally show a small but rapid increase of the Bragg wavelength at the beginning of the irradiation in the order of 20 to 100pm depending on the fibre and photosensitisation, with the shift saturating after a dose of typically 80 kGy [17,18].

2. EXPERIMENTAL

2.1. Fibre Bragg gratings under investigation

In order to study fundamental aspects of radiation induced changes in FBGs as a function of the underlying mechanism of refractive index changes in different fibres and FBG types, 3 batches of 4 FBGs each were manufactured at Aston University using a phase mask and 244nm UV illumination. Each FBG in a batch was written with increasing UV flux, resulting in FBGs with increasing reflectivities for batch 1 and 2 and in a set of 4 regenerated type IIA FBGs with near constant reflectivities (Table 1). Fibres used were SMF-28™ for batch 1 and Fibercore 1250/1500 for batches 2 & 3. FBGs were annealed at 80^0C for 24h following manufacture. Selecting FBGs with increasing reflectivities will reveal potential links between UV flux and ionizing radiation sensitivity, especially for the type I to IIA transition in the photosensitive fibre. Any change in radiation sensitivity should show up prominently in an otherwise homogeneous self-consistent dataset. Type IIA, regenerated blue shifting, FBGs are formed by a different photochemical process which can form the basis of different radiochemical behaviour. The irradiation was carried out at SCK-CEN, Mol in the R*ita* ^{60}Co irradiation facility at a dose rate of 1.63±0.1 kGy/h. FBGs were installed in a temperature stabilised oven assembly containing an aluminium sample holder which also provides conditions for secondary electron equilibrium [SEE] across the fibre cross section. Each fibre was located in a tight fitting channel (270µm wide) behind a 3mm thick aluminium cover plate. The overall assembly was placed in a sealed and N_2 purged container which can be lowered into the radiation zone inside a cooling water pool. The sample holder containing the FBGs was actively temperature stabilised at 55 $^{\circ}$C in order to compensate for ambient temperature changes and gamma radiation heating of the FBG holder[17]. Temperature stabilisation of the sample mount was better than $\pm0.2^0$C over the whole irradiation period with a 0.6^0C rise during the first 3 hours due to radiation heating. Total irradiation period was 13.8 days resulting in a total dose of 0.54MGy. FBGs were monitored for 1 day prior to the irradiation,, during irradiation and for 4 days after removal at SCK•CEN, followed by continued monitoring at Heriot Watt for 44 further days

	Batch 1	**Batch 2**	**Batch 3**
Fibre	H_2 loaded SMF 28	B/Ge	Be/ Ge
FBG type	I	I	IIA
Reflectivity [%]	12, 30, 58, 89	9, 29, 60, 91	91, 97, 98, 71
Exposure time [s]	NA	10, 50, 100, 180	330, 420, 510, 900

Table 1) FBG properties in batch 1 to 3

2.2. Interrogation of FBGs

In order to ensure that all FBGs were as nearly identical as possible, except for their reflectivities, FBGs within a batch were written to the same Bragg wavelength. FBGs were interrogated in reflection using a broadband source, circulator, and 1x16 fibre optic switch, addressing FBGs sequentially. Reflected power was analysed after the circulator using an OSA (Ando AQ6315A). A 'dummy' fibre loop without FBG was used to compensate for radiation induced losses in down leads. Spectra were acquired over two spectral ranges, one for batch 1 and 2 and a second range for batch 3. After each cycle HCN gas cell spectra for wavelength calibration in the two ranges used were acquired. A complete acquisition cycle was completed in ~20minutes resulting in 920 measurements over a 19 day period.

3. RESULTS

Figure 1 shows detailed results from recorded Bragg wavelength shifts of batch 1, containing 4 type IA FBGs in H_2 loaded SMF-28 written to 4 different levels of reflectivity. Irradiation starts at time 0 and ends after 13.8 days with a total dose of 540kGy after which the sample tank was removed from the *hotzone* but remained in the pool for a further 4 days with continuous online monitoring before shipping to Heriot Watt. Fluctuations in recorded Bragg wavelength were due to limitations of the OSA, showing fluctuations in start wavelength and span after each range switching. Although HCN spectra were used to correct for an initially much larger error the remaining errors cannot be fully eliminated because HCN spectra were recorded after range switching which introduced random fluctuations. The similarity of deviations observed throughout all spectra allow the assertion that linear fits as shown in Figure 1 and Figure 2 to define radiation induced drift of the Bragg wavelength can be used. Data sets are divided into *pre* (day-1 to 0), *irradiation* (day 0 to 13.8) *post I* (day 13.8 to 18) and *post II.* (day 21 to 64). Slopes (normalised to 1kGy/h) are for the period day +1 to day 13.8 (excluding rapid change at start) and post irradiation period I.

3.1. Analysis Batch 1: Type I FBGs in hydrogenated germanosilicate fibres

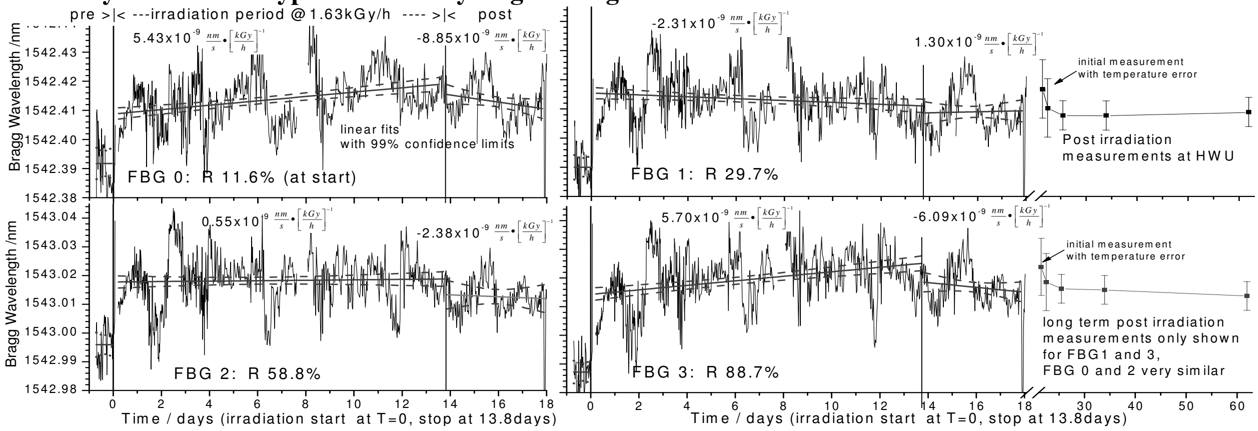

Figure 1) Bragg wavelength shift of type 1 FBGs in H_2 loaded germanosilicate fibre before, during and after irradiation.

FBGs in H_2 loaded SMF-28 (Figure 1) show a 'rapid' increase in Bragg wavelength of 17 to 26pm over 1 day at the start of the irradiation, after which the change gradually plateaus off. Over the remaining irradiation period a total change between -5pm (FBG1) and 12pm (FBG3) is observed, although the slope of FBG1 can be zero within the 99.9% confidence limits. For FBG1 and FBG3 data of the long term recovery measurements at HWUI are also shown, which indicate no further change within the error limits of the measurement technique. Long term data for FBG0 and 2 (not shown) are very similar. All gratings show an insignificant recovery over the initial 4 day post irradiation period with no further recovery over the extended 40 day period.

3.2. Analysis Batch 2 and 3, Type I and IIA FBGs in B/Ge co-doped photosensitive fibres

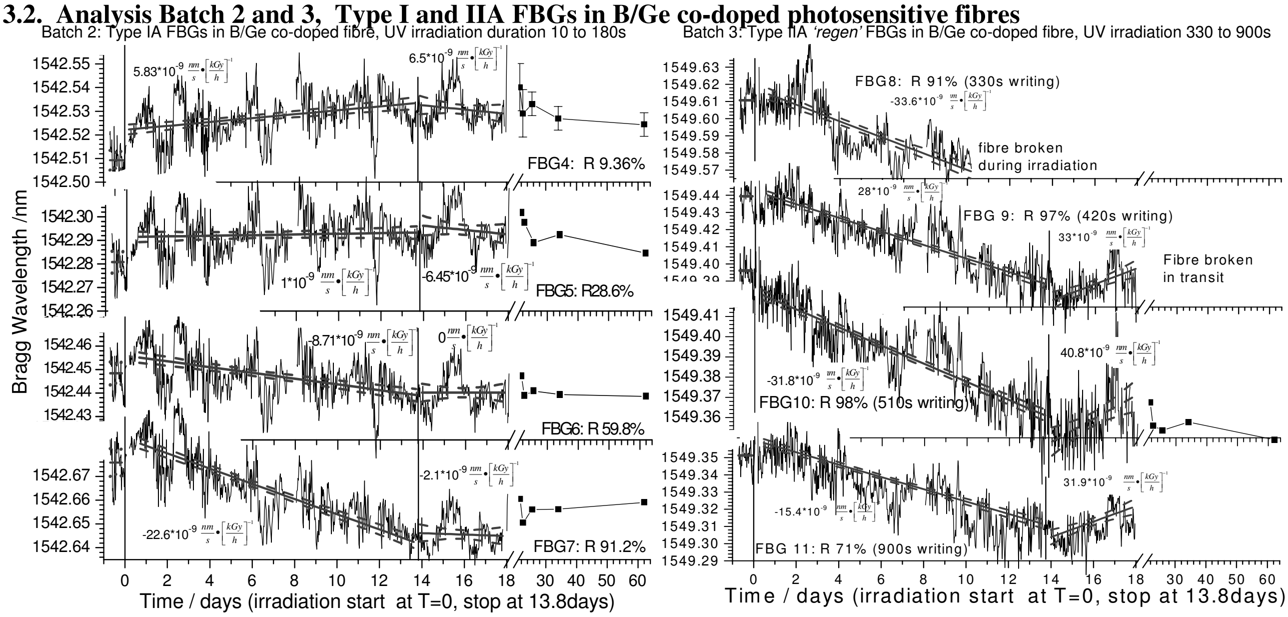

Figure 2) Bragg wavelength shift in photosensitive fibre *left:* Batch 2: Type IA FBG; *right*: Batch 3: Type IIA FBG

FBGs in batch 2 are of type I formed in photosensitive fibre using UV exposure times of 10 to 180s. FBGs in batch 3 have been generated using exposure times between 330 and 900s (identical flux as in batch 2) which leads to regenerated blue shifting type IIA FBGs[9]. Figure 2 clearly shows the difference in radiation sensitivity in these fibres as a function of UV irradiation. While low UV dose FBGs (4 and 5) show similar behaviour to batch 1 with 10 to 15pm rapid change at the start of irradiation followed by a slow gradual increase between 0 and 12pm, higher UV dose FBGs show a lower initial increase followed by a marked decrease in Bragg wavelength which becomes especially clear in the long UV exposure FBGs 7 through 11. Although FBG 7 is nominally still a type I FBG, it appears that the characteristics of a type IIA are already becoming dominant and should therefore be reclassified as type IIA. The transition from type I to

IIA is gradual as shown in [9]. All surviving type IIA FBGs show a short term recovery with FBG7 showing indication of a more gradual recovery process. The observed changes clearly indicate that the original UV induced reduction of the average refractive index leading to a blue shifting FBG is continued by the high energetic γ radiation.

3.3. Radiation induced changes in Reflectivities

Reflectivity information for FBGs has been extracted from data sets. Although R is best monitored in transmission, the integrated reference fibre loop permitted power normalisation of reflection spectra. Figure 3 shows the changes in reflectivity relative to their start value, normalised for radiation induced losses in the down leads.

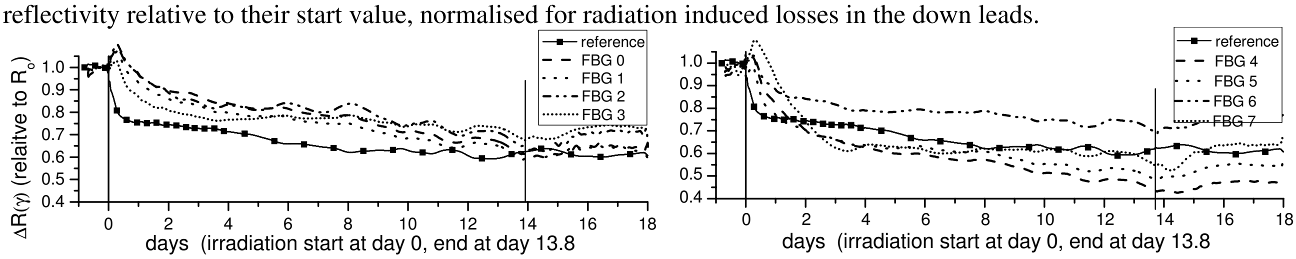

Figure 3) Reflectivity of FBGs 0 to 7, shown together with radiation induced losses in reference fibre used for power normalization.

Batch 1 shows a general reduction in reflectivity of up to 30% at the end of the irradiation period fairly independent of the original starting reflectivity, whereas in batch 2 the *strongest* gratings (FBGs 6 and 7) show a lower loss in reflectivity. Reflectivity data show for both batches an *unexplained* increase in reflectivity at the start of the irradiation. There is a clear discrepancy between the rapid increase in attenuation at the start of the irradiation in the reference fibre and the observed speed of the reduction in reflectivity of the FBGs. It is currently not possible for us to state if this increase in R at the start is real or an experimental artefact.

4. CONCLUSIONS

Fibre Bragg gratings of type I formed in H_2 loaded germanosilicate and B/Ge co-doped photo sensitive fibre (FBGs 0 to 6) under γ radiation at a dose rate of 1.63kGy/h show a small and rapid increase in Bragg wavelength in the order of 10 to 20pm over 1 day, followed by a plateau or very slow further increase in Bragg wavelength in the order of 0 to 12pm over a period of 14 days. Total radiation induced shift of the Bragg wavelength for type I FBGs is between 10 and 34pm for a total dose of 0.54MGy. Type IIA 'regenerated' FBGs (FBGs 7 to 11) show a lower or zero increase at irradiation onset compared to type I, followed by a decrease in Bragg wavelength during the following 14 day period in the order of -30 to -60pm. Neither type show a significant recovery from radiation induced Bragg shifts although recovery is stronger in type IIA. FBGs of both types show a marked decrease in reflectivity of up to 30% from their start value for type I FBGs in SMF-28 and up to 50% for type I in B/Ge co-doped fibre. The observed low levels of radiation induced shift in Bragg wavelength indicate that FBGs, especially of type I in germanosilicate fibres, are compatible with a radiation environment of up to 0.54MGy. Radiation hardening by pre-irradiation appears to be a possibility.

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