Radiation sensitivity of Bragg gratings written with femtosecond IR lasers

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ABSTRACT

The radiation sensitivity of Bragg gratings written with a femtosecond IR laser was measured for the first time. Type I-IR and type II-IR gratings were written into hydrogen loaded as well as unloaded fibers of distinctly different radiation sensitivity with the intention to find extremely radiation resistant gratings for temperature or stress measurements in radiation environments, as well as very radiation sensitive ones for radiation dose measurements. With a highly radiation-hard F-doped fiber we found a radiation-induced wavelength shift between about 3 and 7 pm after a dose of 100 kGy. These are the lowest shifts observed so far. In such fibers it is very difficult to write gratings with an UV laser. However, gratings made of the highly radiation-sensitive fibers only showed shifts of about the same size as those made of the quite radiation-insensitive Corning SMF-28e fiber. This was already observed with UV laser gratings written in such fibers.

Keywords: Annealing, femtosecond laser, fiber Bragg gratings, gamma radiation, hydrogen loading, optical fiber sensors, radiation effects, type I and type II gratings.

1. INTRODUCTION

By now fiber Bragg gratings (FBGs) are a widely accepted sensor type for temperature and stress measurements especially in regions where conventional electronic sensors are too bulky or disturbed by electromagnetic interference. Another advantage is that several gratings can be multiplexed, i.e. a greater number of FBGs with slightly different wavelength can be interrogated simultaneously. A variety of publications point out that FBGs can be quite radiation insensitive so that they also can be used in nuclear facilities [1] - [10] or space environments [11]. But it was also mentioned that some types might be radiation sensitive enough so that they can be used for radiation dosimetry at least at higher dose values [12],[13]. As pointed out in the latest FBG paper of Fraunhofer-INT [14], we aim at two goals: the development of especially radiation sensitive FBGs that can also be used for the measurement of lower radiation doses, and of very radiation insensitive ones for temperature and stress measurement in radiation environments. Both goals seem to be unreachable with FBGs written with ultra-violet (UV) lasers. Most of them seem to be quite radiation insensitive because the UV light already eliminated the precursors of color centers [7]. Therefore even the use of fibers with very high radiation-induced attenuation (RIA) will not lead to highly radiation sensitive FBGs, as demonstrated in [14]. On the other hand radiation hard FBGs should be obtained from fibers with the lowest RIA, i.e. fibers with pure or F-doped silica core [15],[16] . Writing of FBGs in pure silica fibers is in principle possible[17], but very difficult. Therefore we investigated gratings written with femtosecond (fs) infra-red (IR) lasers[18]. With this laser type it is possible to write FBGs even in the radiation-hard fibers with a pure or F-doped silica core, with as well as without hydrogen loading. But the influence of fs-IR lasers on the radiation sensitivity of pristine fibers is unknown so far. Therefore we investigated FBGs written with an fs-IR laser in five fibers with distinctly different radiation sensitivity to find out if fibers with high RIA would lead to very radiation-sensitive FBGs with that laser type. In order to see the influence of grating manufacturing parameters, we investigated type I-IR and type II-IR gratings made of unloaded as well as of hydrogen loaded fibers.

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2. EXPERIMENTAL

2.1 Selected fibers for grating fabrication

For grating fabrication we selected five fibers with distinctly different radiation hardness, i.e. different RIA. Table 1 gives an overview of manufacturers, dimensions, and doping concentrations in core as well as cladding. Four of the fibers were already used in [14] (no. 2-5). No. 1 is the extremely radiation-hard F-doped fiber made by Fujikura [15], [16]. Some manufacturers told us the dopants as well as their concentrations. From fibers that were known to be only or predominantly doped with Ge, we calculated the Ge-content from the known numerical aperture under the assumption of an un-doped cladding material. To improve our knowledge about fiber composition, we asked the Fraunhofer-IST in Braunschweig, Germany for an "Electron Probe Microanalysis (EPMA)". The EPMA detection limit was given as 0.01 mol% (or at%), and the uncertainty as ± 20 %. The F-concentration is given in wt% (no.1) or at% (no. 4) since the manufacturers argue that they are not sure about the placement of F within the SiO_2 grid.

Table 1: Single mode fibers for the fabrication of Bragg gratings.

No.	Fiber Type		Manuf. Year	Core Diameter [µm]	Core Dopants [mol %]			Cladding Dopants [mol %]	
	Manufacturer	Designation			Manufacturer	Calculated	Measured	Manufacturer	Measured
1	Fujikura	RR-C	2007	8.7	F (0.8 wt %)	—	0.7 (wt %)	F (2.2 wt %)	F (2.1 wt %)
2	Corning*	SMF-28e	2006	8.2	—	GeO_2 (4.7)	GeO_2 (4.2)	None	None
3	FiberLogix	FL-HNA-01	2006	5.7	—	GeO_2 (10.5)	GeO_2 (7.8) F (0.1 at %)	None	P_2O_5 (0.3) F (<0.1 at %)
4	FORC	No. 141-2	2003	4.9	Al_2O_3 (7.0) P_2O_5 (1.0) F (0.3 at %)	—	Al_2O_3 (1.8) P_2O_5 (0.2) GeO_2 (< 0.1) F (< 0.1 at %)	P_2O_5 (1.0) F (0.3 at %)	P_2O_5 (0.5) F (0.2 at %)
5	IPHT Jena	Ce 2s		5.0	GeO_2 (10.0) CeO_2 (0.1)	—	GeO_2 (7.0) CeO_2 (0.2)	P_2O_5 (0.5)	P_2O_5 (0.3)

* Calculated and measured dopant concentrations not confirmed by the manufacturer.

Fiber no. 1 is the radiation-hardest with a RIA of only about 2 dB/km at 1310 nm after a dose of 10 kGy (dose rate 0.2 Gy/s), compared with about 30 dB/km of fiber no. 2 and about 30000 dB/km of fiber no. 4. The RIA of fiber no. 3 should be only less than 10 times higher than that of fiber no. 2, whereas that of fiber no. 5 should be about 10 times lower than that of fiber no. 4. It is well known that doping with Ce reduces the RIA of technical glasses, e.g. lead glass in windows of hot cells. However, in silica fibers Ce-doping causes a considerable increase of their radiation sensitivity.

2.2 Production of Bragg gratings

An ultrafast (120 fs) Ti:sapphire laser (Spectra Physics-Spitfire) operating at 800 nm wavelength and a pulse repetition rate of 100 Hz was used to write third-order retro-reflective FBGs in each of the fibers listed in Table 1. The 6.4 mm diameter laser beam was focused through a cylindrical lens with a focal length of 30 mm and zero-order-nulled silica phase mask with ~ 3.18 µm pitch into the core of the fibers. Phase masks with slightly different pitches were used in the grating inscription process in order to be able to simultaneously interrogate multiple gratings. The difference in the effective refractive index of the different fibers also helped to spread the distribution of the Bragg wavelength over the range 1525 nm – 1552 nm. In samples of each type of optical fiber listed in Table 1, there were written two gratings each of the four grating types: type I-IR and type II-IR gratings [19] in both hydrogen loaded and un-loaded fibers. The conditions for fiber exposure with the laser pulses were chosen depending upon the type of the fiber, loading condition and desired grating type (I-IR or II-IR). The fibers were placed behind the phase mask either 3 mm or 500 µm for the type I-IR and type II-IR gratings, respectively [19]. The Bragg wavelength of most of the gratings still showed the small drift to shorter wavelengths observed with nearly all FBG types shortly after their production. They became smaller or even zero after a stabilization treatment (four days at 100 °C) before irradiation at Fraunhofer-INT.

2.3 Measurement procedure

The irradiation tests were made with the experimental arrangement shown in Fig. 1. The Bragg peaks were measured in reflection with the interrogator FOS&S FBG-Scan 608 (wavelength repeatability < 1 pm, wavelength resolution 1 pm). The device has eight independent channels. Usually we irradiated four FBGs at the same time (Fig. 1). A fifth FBG was placed near the interrogator in the temperature-stabilized measurement booth (stability ± 0.2 °C) in order to check the interrogator stability. The spectra were read out with a PC to apply our own problem–orientated peak detection routine.

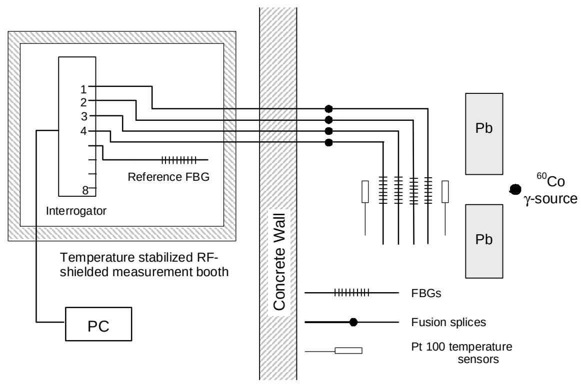

Fig. 1. Experimental set-up

The FBGs were mounted stress-free on an aluminum plate and covered with an appropriate dose build up layer. At both sides we fixed small Pt-100 temperature sensors (Fig. 1). Placement of all sensors (FBGs as well as Pt-100) on an aluminum plate guaranteed that they show the same temperature changes during and after irradiation. The dose rate can be changed by varying the distance between ^{60}Co-source and FBGs. Because of the extremely high RIA of some of the fibers, the FBG leads were shielded with lead (Pb). For measuring the temperature sensitivity of the FBGs the aluminum plate was placed in a climate chamber.

3. RESULTS

3.1 Temperature dependence of the Bragg wavelength

With some FBGs made of the different fibers we determined their temperature sensitivity. The temperature was varied between about 25 °C and 65 °C. From linear fits to the measured Bragg wavelength shift (BWS) with temperature we obtained values around 10 pm/°C, i.e. the same as with the different UV laser FBGs investigated in [14] (see there for more details). For correcting our measured radiation-induced BWS for the temperature changes during and after irradiation we therefore used the same mean value of 10.45 pm/°C.

3.2 Radiation-induced Bragg wavelength shift

Irradiation was performed at room temperature with a dose rate of 0.94 Gy/s up to the dose 100 kGy. Here Gy always means Gy(SiO_2). During these irradiations we observed a temperature increase of 0.5 °C – 0.7 °C that remained nearly constant during the whole irradiation time of about 30 h and decreased to about the initial value after the end of irradiation. The shown BWS is corrected for this influence. For about 15 h – 60 h before irradiation we performed a stability test. During these tests some of the FBGs still showed the small wavelength drifts to lower values often observed with newly fabricated FBGs, even after our stabilization treatment. From these drifts we estimated an additional error component (see section 3.3).

Fig. 2 shows the typical BWS ($\Delta\lambda_B$) observed with most of our fs-IR laser FBGs (and also most of the UV laser FBGs) during and after irradiation: a more or less pronounced increase during irradiation is followed by an annealing after the end of irradiation. To facilitate the comparison of results obtained with the different fiber and FBG types, we show the BWS increase (as a function of radiation dose) and the annealing (as a function of time after irradiation) for most of the fibers separately. The results for the five fiber types of Table 1 are shown in figures 3 - 7. The left part shows the BWS increase during irradiation, whereas the right part shows the BWS annealing after the end of irradiation. With fibers 2 - 5 the BWS increase of the different FBG types is distinctly different. To be able to compare their annealing behavior quantitatively, we divided the BWS *after* the end of irradiation by the value *at* the end of irradiation (= normalization to 1). However, the four FBG types made of the Fujikura fiber show nearly the same BWS at the dose of 100 kGy, and after the end of irradiation the Bragg wavelength is lower than before irradiation (Fig. 3). Therefore we show here absolute BWS values.

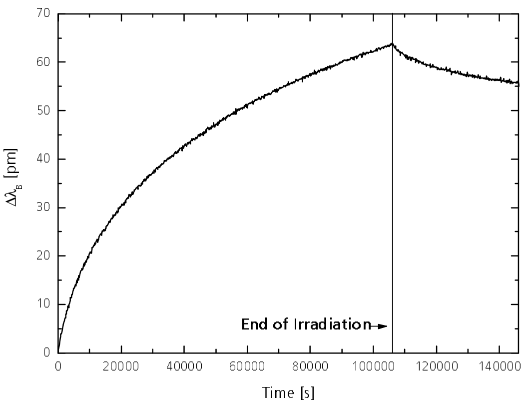

Fig. 2. Radiation-induced BWS as a function of irradiation time. Left side: irradiation phase, right side: annealing phase. Measured with a type I FBG made in a hydrogen loaded Corning SMF-28e fiber.

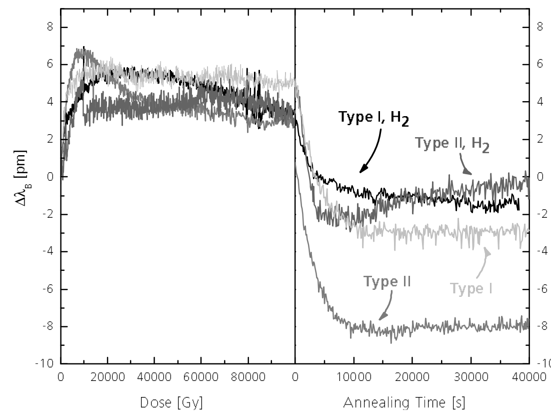

Fig. 3. Radiation-induced BWS measured with type I and type II FBGs made in a hydrogen loaded and unloaded Fujikura fiber.

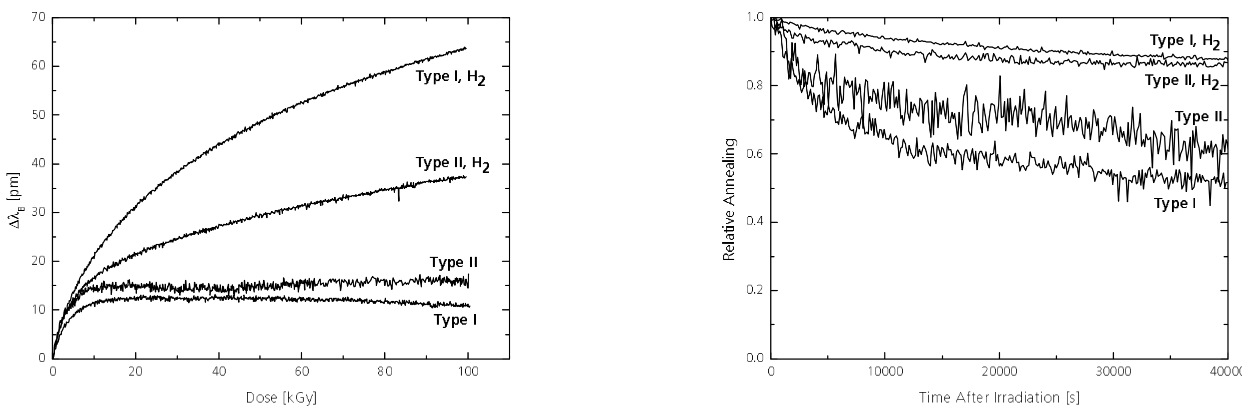

Fig. 4. Radiation-induced BWS measured with type I and type II FBGs in a hydrogen loaded and unloaded Corning SMF-28e fiber. Left side: irradiation phase, right side: annealing phase.

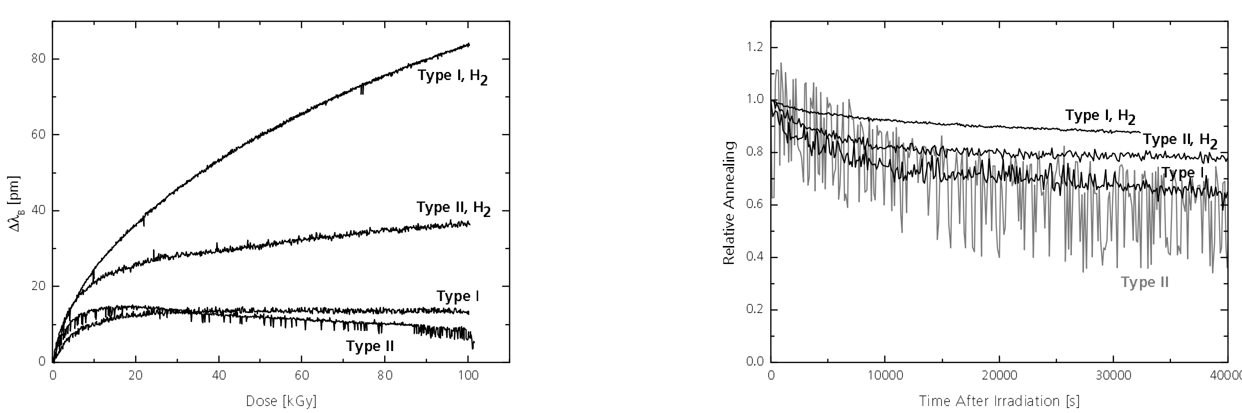

Fig. 5. Radiation-induced BWS measured with type I and type II FBGs in a hydrogen loaded and unloaded FiberLogix HNA-01 fiber. Left side: irradiation phase, right side: annealing phase.

Despite of the huge RIA differences between the five fibers (more than four orders of magnitude), we only have moderate BWS differences, as also observed with the UV laser gratings made of the same fibers [14]. FBGs made of the extremely radiation-sensitive fibers no. 4 and 5 show a BWS comparable with that of the quite radiation-hard Corning-SMF-28e (no. 2). With the FBGs made of fibers 2-5 we see the result already known from UV laser FBGs [14]: gratings made of hydrogen-loaded fibers have higher radiation sensitivity than those made of unloaded fibers, especially with type I FBGs. The BWS of the type I and type II FBGs made of the unloaded fibers shows a pronounced saturation behavior above dose values of about 10 kGy (fibers 1 - 3) or about 20 kGy (fibers 4, 5), respectively. Within both fiber groups the saturation BWS of the type I and type II gratings is about the same. With some FBGs made of the radiation-hard fibers (1-3) the BWS even seems to decrease beyond about 20 kGy. This behavior should be proven by an irradiation up to higher dose values. With the hydrogen-loaded fibers nearly all type II FBGs have a lower BWS than the type I gratings.

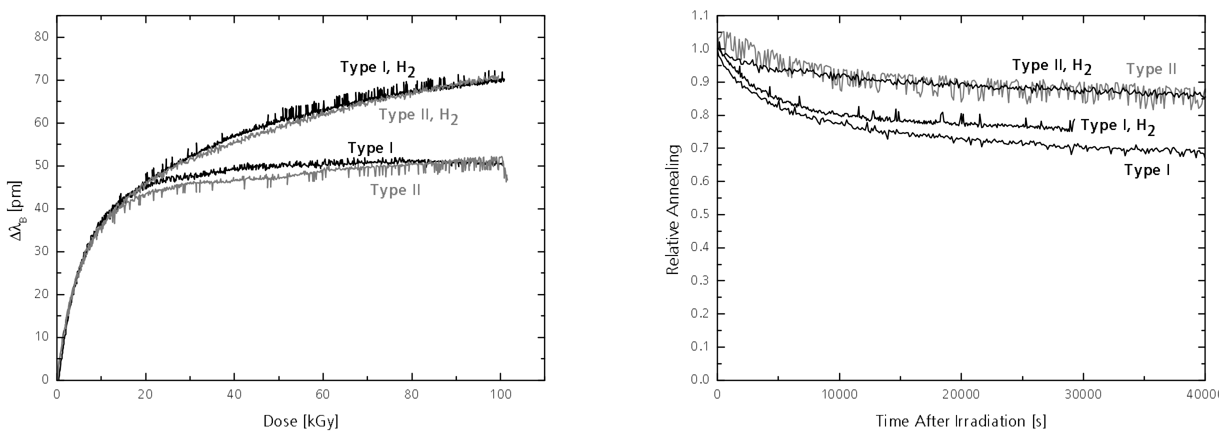

Fig. 6. Radiation-induced BWS measured with type I and type II FBGs in a hydrogen loaded and unloaded FORC No. 141-2 fiber. Left side: irradiation phase, right side: annealing phase.

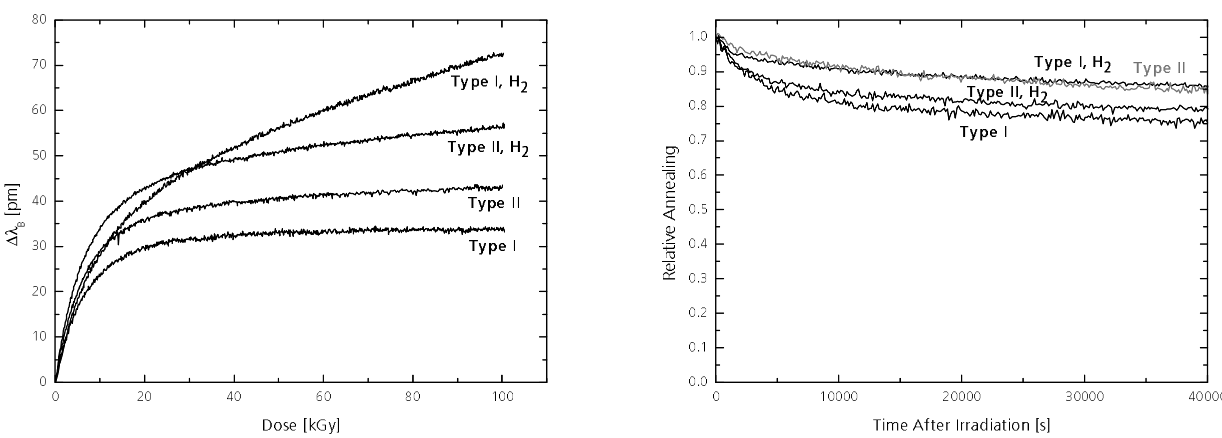

Fig. 7. Radiation-induced BWS measured with type I and type II FBGs in a hydrogen loaded and unloaded IPHT Ce2s fiber. Left side: irradiation phase, right side: annealing phase.

In figures 8 - 11 we demonstrate the influence of fiber composition on the radiation-induced BWS of the four FBG types separately. If the fibers are unloaded (Fig. 8, 9), the radiation harder fibers (no. 1 - 3) result in distinctly radiation harder FBGs, especially with the type I FBGs. But the BWS differences are only about a factor of five. With the hydrogen-loaded fibers (Fig. 10, 11) the BWS differences between FBGs of the different fibers are less than a factor of two, apart from the Fujikura fiber.

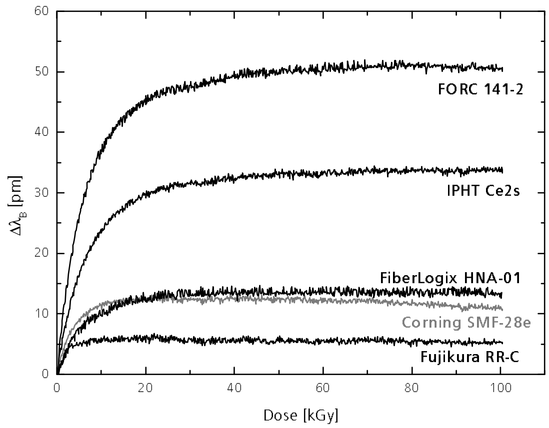

Fig. 8. Radiation-induced BWS measured with type I FBGs made in the unloaded fibers no.1 - 5 (see Table 1).

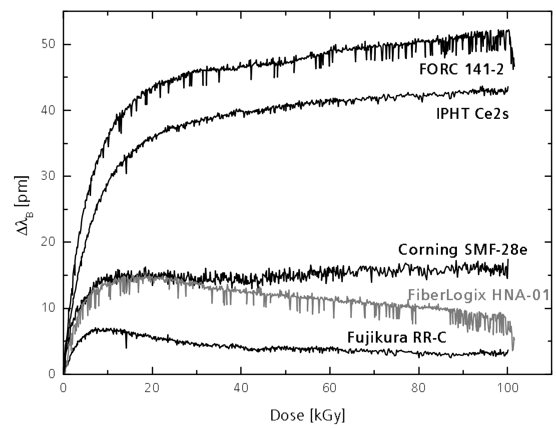

Fig. 9. Radiation-induced BWS measured with type II FBGs made in the unloaded fibers no. 1 - 5 (see Table 1).

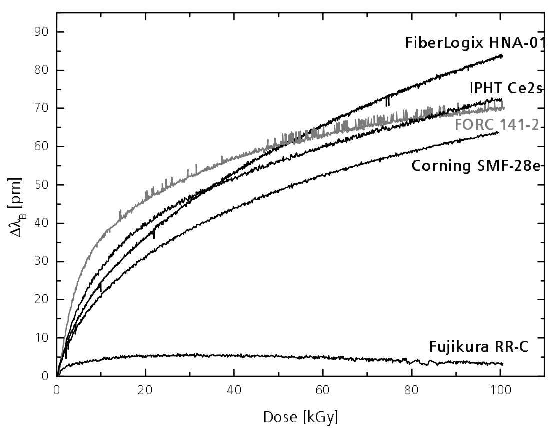

Fig. 10. Radiation-induced BWS measured with type I FBGs made in the hydrogen loaded fibers no. 1 - 5 (see Table 1).

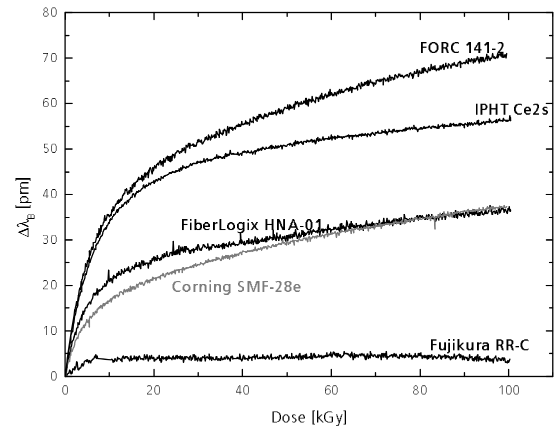

Fig. 11. Radiation-induced BWS measured with type II FBGs made in the hydrogen loaded fibers no.1 - 5 (see Table 1).

The BWS of all FBG types shows a relatively strong annealing already within about 11 h after irradiation. Strong and fast annealing is observed with the type I FBGs made of unloaded fibers. However, an even stronger and faster annealing is observed with all FBG types made of the Fujikura fiber. The Bragg wavelength always decreased to values below that before irradiation within less than one or two hours. That this is true can be seen from a comparison of the fast BWS increase at the beginning of irradiation with the even faster decrease at the end of irradiation: with all four FBG types the increase is smaller than the decrease. These values can not be explained by the slow drifts observed during our stability tests. It seems that the gamma radiation, in addition to directly increasing the refractive index, also erases some of the original refractive index increase that was induced by the fs-IR laser. The Fujikura fiber also showed a deviating behavior during the RIA measurements [15],[16]: at the beginning of irradiation the RIA increased within seconds to nearly the final value, and the annealing after the end of irradiation was very fast.

The FBGs made of the radiation hardest fiber (Fujikura, no. 1) show an extremely low radiation-induced BWS of only 3 pm – 7 pm. If such a grating would be used as temperature sensor in a nuclear power plant or space vehicle, radiation dose values up to at least 100 kGy only would lead to a temperature error of ≤ 0.7 °C. This is to our knowledge the lowest FBG radiation sensitivity ever reported. In future tests it should be examined if this also holds for distinctly higher dose values. The four different FBGs made of that fiber do not show the systematic behavior observed with the four FBGs types made of the other fibers. The reason should be that their BWS is so low that the small errors, mainly due to the FBG instability, are bigger than possible differences between the different grating types.

3.3 Reproducibility, uncertainties

We have to distinguish between the reproducibility of our measurements of the radiation-induced BWS and that of the grating manufacturing process. We only had two FBGs of each type of each fiber and could not make at least two measurements with each grating type since we also changed some irradiation parameters and some gratings were broken during their installation. Therefore we can at the moment make no statement concerning the reproducibility of the radiation sensitivity of the different grating types which could, e.g., even differ between a set of FBGs with exactly the same temperature or stress sensitivity.

One possible measurement uncertainty is the slightly different FBG positioning below the ^{60}Co (point) source. With most of the FBGs we could locate the FBG position accurately by the scattering of red laser light injected into the fiber. Where this was not possible, the error in the FBG position was up to 7 mm leading to a dose error of up to 4.5 %. This dose error can cause BWS errors between 0 pm (saturating curves) and 2 pm (steepest curves) of the final BWS.

During our stability tests before irradiation we saw with most of the FBGs small drifts of the Bragg wavelength to lower values, even after the stabilization treatment (four days at 100 °C). The mean value during about 30 h (our irradiation time up to 100 kGy) was about 2 pm., i.e. our BWS values after 100 kGy could be about 2 pm higher, on the average.

4. DISCUSSION

UV laser FBGs can be quite radiation-insensitive. One explanation is that the high energetic UV radiation promotes the grating stability (against ionizing radiation) by eliminating the precursors of color centers [7]. The interference UV field generated by the phase mask is sinusoidal so that there is a considerable UV exposure also along the whole FBG. In addition to the sinusoidal exposure resulting from the ± 1st order interference, there is a supplementary exposure of the fiber from the zero order and the higher orders generated by the phase mask. For a phase mask with good zero order suppression, only ~ 70 % of the UV beam energy is coupled into the +/- 1 orders. The remaining 30 % will create an almost blanket exposure along the grating length. Because of the high nonlinearity of grating writing with fs-IR lasers, the interference field generated by the phase mask results in a non-sinusoidal index change, with little or no index change in the interstitial regions. Therefore one could expect a higher sensitivity of these regions against ionizing radiation, resulting in a higher radiation-induced BWS. However, a comparison of our present results with fs-IR laser FBGs with those obtained with UV laser FBGs [14] shows that both methods lead to FBGs of approximately the same radiation sensitivity.

The measurements of [14] were predominantly made with type I FBGs made of hydrogen-loaded fibers. Our present results with that FBG type are shown in Fig. 10. The values obtained with fibers no. 2 - 5 are lower (apart from fiber 4) than those obtained with the same fibers in [14]. But these FBGs were usually "annealed" at 240 °C immediately after grating inscription. When such FBGs were only annealed at 100 °C, their radiation-induced BWS decreased to values only slightly above those obtained with type I fs laser FBGs. I.e.: FBGs made with fs-IR lasers seem to have about the same radiation sensitivity as comparable types made with UV lasers. One reason could be that the interstitial regions in fs-IR FBGs were exposed to the shortwave light generated during grating inscription, leading to about the same passivation as the UV light [7].

In Figs. 8, 9 we see the pronounced BWS saturation above dose values of about 10 kGy. It is often stated that such FBGs would be completely radiation hard after a pre-irradiation up to that dose. But the distinct BWS annealing after the end of irradiation observed with UV laser as well as fs-IR laser FBGs suggests that after irradiation interruptions of several hours or days such FBGs will show nearly the same BWS increase as at the beginning. Such interruptions as well as changes to distinctly different dose rates are usual in nearly all radiation environments, e.g. high energy physics accelerators.

5. SUMMARY

We performed for the first time irradiation tests with FBGs made with an fs-IR laser. Type I-IR and type II-IR gratings were written into hydrogen-loaded and unloaded fibers of distinctly different radiation sensitivity. The aim was to find extremely radiation-insensitive FBGs for e.g. temperature and stress measurements in radiation environments, as well as very radiation-sensitive versions for the measurement of medium or even lower radiation doses.

For producing radiation insensitive FBGs we used a highly radiation hard F-doped Fujikura fiber [15],[16] , no. 1 of Table 1. All grating types showed a radiation-induced BWS between only 3 pm – 7 pm after a dose of 100 kGy. These are the lowest values ever reported. This behavior should be confirmed for higher dose values, at least up to 1 MGy.

The FBGs made of the very radiation-sensitive fibers (no. 4, 5) did not show a distinctly higher BWS than those made of the quite radiation-insensitive fibers no. 2, 3. The same result was obtained with type I UV laser FBGs written in hydrogenated samples of these fibers [14]. With UV as well as fs-IR lasers it is possible to produce FBGs for the measurement of higher radiation dose values (above several 100 Gy), but not very sensitive ones for the measurement of medium or even low dose values (several Gy to several 100 Gy).

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