Influence of Manufacturing Parameters and Temperature on the Radiation Sensitivity of Fiber Bragg Gratings

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***Abstract*—For the first time the radiation sensitivity of Bragg gratings was investigated as a function of hydrogen loading pressure before and fiber tension during grating inscription, of the recoating procedure, and of the grating temperature. At −50 °C the radiation-induced Bragg wavelength shift was about two times higher than at room temperature. This should be considered when selecting Bragg gratings e.g., for certain space applications.**

***Index Terms*—Fiber Bragg grating, fiber tension, gamma radiation, grating temperature dependence, hydrogen loading, optical fiber sensor, radiation effects, recoating, type I grating.**

I. Introduction

RECENTLY we investigated the influence of fiber composition and some manufacturing parameters on the radiation sensitivity of fiber Bragg gratings (FBGs) written with an ultra violet (UV) laser. The results are published in [1] where we also discuss FBG irradiation test results of a variety of other laboratories. We therefore do not repeat citation of all previous work. In [1] it was shown that fiber composition only has a moderate influence (factor of three) on the radiation-induced Bragg wavelength shift (BWS), despite the fact that the radiation-induced attenuation (RIA) of the fibers differed by several orders of magnitude. Variation of the hydrogen (H_2) loading of the fibers before grating inscription and of the annealing temperature of the gratings led to BWS changes of up to a factor of 10. The lowest BWS was observed with unloaded fibers and annealing with only 100 °C, and the highest with fibers loaded with "180 bar" H_2 and annealing at 240 °C plus 100 °C (see [1]). "180 bar" means that the fibers usually were loaded with 180 bar but then stored for several days or even weeks at low temperatures until the gratings were written. So the H_2 content during grating inscription could have been distinctly lower. In order to find out a possible influence of the H_2 content during grating inscription on the FBG radiation sensitivity, the gratings for our present study were made from two of the fibers used in [1] without H_2 loading and immediately after loading with 100, 200, and 300 bar. Therefore, the saturation concentration at 200 and 300 bar actually was a factor of 2 or 3 higher than at 100 bar.

Two other parameters not considered so far are the fiber tension during and the recoating of the fibers after grating inscription. The tension is varied to obtain gratings with slightly different Bragg wavelength. But in [2] it is reported that increasing the fiber stress during grating inscription might lead to a higher increase of the refractive index. We therefore investigated whether FBGs made with the standard (lowest) and the highest applicable tension will show different radiation sensitivity. Our FBGs are written in two different fibers after removal of their acrylate coating. They can be supplied with and without coating. The recoating procedure might influence their radiation sensitivity. We only investigated the influence of the acrylate coatings made with the recoater of our present grating supplier and were not interested in the influence of other recoater types or coating materials. The authors of [3] compared the influence of different coating materials (acrylate, polyimide, ormocer). Their FBGs are written during fiber drawing (draw tower FBGs) before application of the respective coating. From some of the ormocer-coated FBGs the coating was stripped off before irradiation. Ormocer coatings led to a distinctly higher radiation-induced BWS. The lowest BWS was obtained when that material was removed. The authors conclude that the effect of the coating must be taken into account for correctly interpreting the radiation sensitivity of FBGs.

Finally we investigated for the first time the influence of the FBG temperature during irradiation. This could be of great interest when FBGs are used as temperature or stress sensors e.g., in space vehicles. Therefore, we irradiated FBGs not only at room temperature but also at about −50 °C and +80 °C.

II. Experimental

The FBGs were made of the fibers Corning SMF-28e and FiberLogix HNA-01, i.e., fibers no. 2 and 8 of [1]. Their properties are shown in Table I. Because of the low Ge-content of the Corning fiber it was hardly possible to write FBGs into that fiber without H_2-loading, as can be seen from the low values of transmission loss and reflectivity in Table II. The FiberLogix fiber was drawn from a new preform that was made as identical as possible with the previous one. Comparing standard irradiation tests with FBGs made of fibers from the new and the previous preform would give valuable information about the reproducibility of FBG production with respect to their radiation sensitivity.

All FBGs are of type I and were made by AOS GmbH, Dresden, Germany as described in [1]. They used a KrF laser (248 nm), and the grating length was 11–12 mm for our 1550 nm FBGs. Before grating inscription the fibers are loaded with H_2 for about one week at 50 °C, and immediately after inscription the FBGs are annealed two times at 240 °C

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TABLE I
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	Corning*	SMF28-e	2006	8.2	—	GeO_2 (4.7)	GeO_2 (4.2)	None	None
2	FiberLogix	FL-HNA-01	2008	—	—	GeO_2 (10.5)	GeO_2 (7.8) F (0.1 at %)	None	P_2O_5 (0.3) F (<0.1 at %)

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

TABLE II
PROPERTIES OF THE INVESTIGATED FBGS

Fiber	H_2-Pressure [bar]	Number of Gratings	Mean value of		
			FWHM [nm]	Transmission Loss [dB]	Reflectivity [%]
Corning SMF-28e	0	1	0.120	0.03	0.7
	100	2	0.168	6.0	74.2
	200	9	0.174	6.4	76.5
	300	6	0.195	8.3	84.0
FiberLogix HNA-01	0	3	0.123	0.24	5.4
	100	2	0.478	31.1	99.9
	200	9	0.455	27.0	99.6
	300	6	0.772	33.5	100.0

for 3 minutes each for stabilization and then 72 h at 100 °C to accelerate out-diffusion of H_2. The irradiation tests were performed about three months later. Already the exposure to 100 °C for three days reduces the H_2 saturation concentration in the order of $10^{20}/\mathrm{cm}^3$ (for all three pressures) to about $10^{11}/\mathrm{cm}^3$, i.e., far below the detection limit of about $10^{15}/\mathrm{cm}^3$ [4]. In order to have stable writing conditions, the fibers are pre-stressed by about "0.2–1 nm", i.e., after writing under that stress and releasing it after inscription, the Bragg wavelength is shifted to lower values by about 0.2–1 nm. These details, together with H_2 loading at 200 bar, we call our standard manufacturing conditions. For our present work gratings were also made without H_2 loading as well as after loading with 100 and 300 bar. At the standard conditions AOS also made two gratings of each fiber type with a tension of "8 nm", the highest value that can be applied. For [1] all gratings were delivered without coating. This time we ordered all gratings with coating to increase their stability. Recoating was made with the recoater Vytran PTR-200 before the 72 h annealing at 100 °C. Curing of the injected acrylate is done there by two rows of UV LEDs. In order to see the influence of the recoating procedure, some gratings made of the two fiber types were also delivered without coating.

Table II shows the properties of the gratings made of the two fibers after loading with different H_2 pressure. The greater the reflectivity, the greater is the grating width (FWHM). The higher Ge concentration in the core of the FiberLogix fiber leads to a higher photosensitivity and thus to a higher FBG reflectivity and a greater width. Since also the H_2 loading increases the photosensitivity, reflectivity and width increase with increasing H_2 pressure. So FBG writing under different H_2 pressure leads to different gratings and will also lead to different material changes, e.g., formation of OH-groups in different concentration. It is to be expected that these differences might influence the radiation sensitivity of FBGs, but not perhaps a different concentration of residual H_2 from loading with different H_2 pressure.

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–oriented peak detection routine. This became necessary when we investigated a variety of FBGs mostly made of fibers that are not well suited for FBG fabrication [1]. The resulting Bragg peaks often were asymmetric, with a shoulder of differing height in one or both flanks. We fitted short straight lines to both flanks in a height that depended on the peak shape,

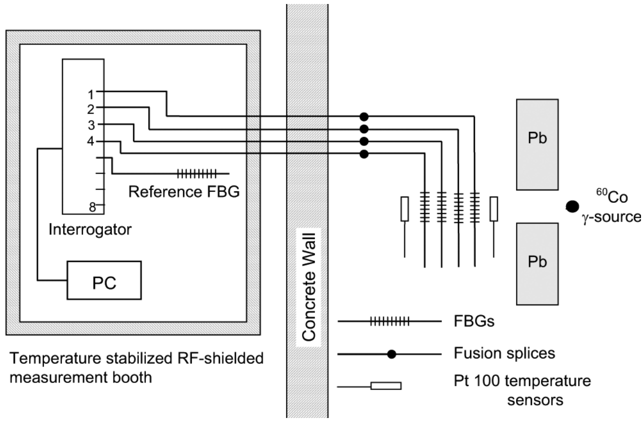

Fig. 1. Experimental set-up.

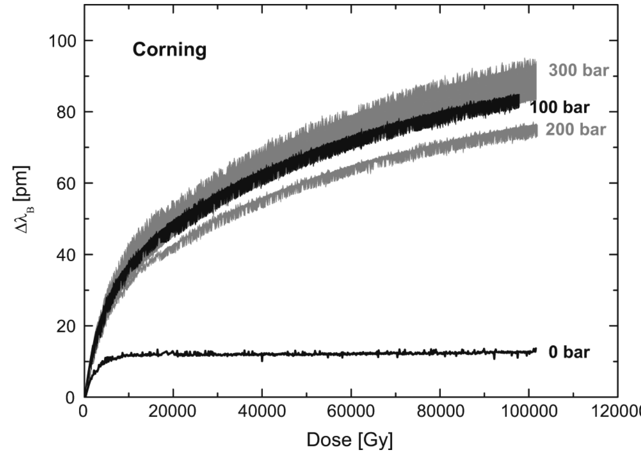

Fig. 2. Radiation-induced BWS of FBGs made of the Corning SMF-28e fiber after hydrogen loading at different pressures.

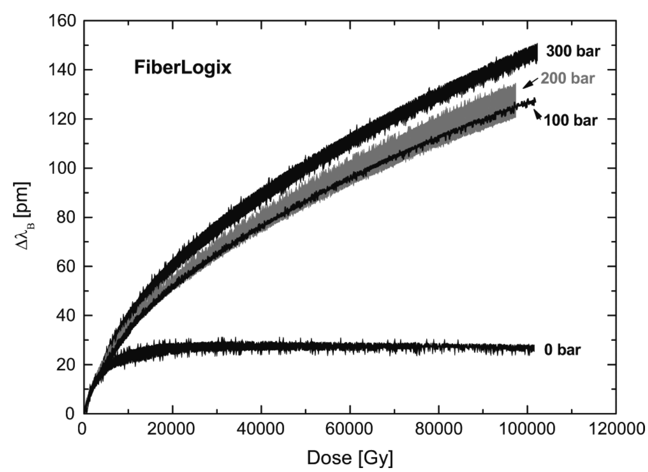

Fig. 3. Radiation-induced BWS of FBGs made of the FiberLogix HNA-01 fiber after hydrogen loading at different pressures.

mostly above the shoulders, preferentially 3 dB below the peak. The middle of the intersection of e.g., the 3 dB line with the fitted lines is the peak position.

For the measurements at room temperature 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 FBG leads were shielded with lead (Pb). All irradiations were made with a dose rate of 0.92 Gy/s up to a dose of 100 kGy. Here, Gy always means $\mathrm{Gy(SiO_2)}$. For investigating the temperature influence, one recoated FBG of each fiber type that was made under standard conditions (200 bar, low tension) was placed on a thick aluminum disc that was during irradiation cooled down to about -50 °C or heated up to about $+80$ °C. During the long measuring time ($>$ 30 h) the cooled FBGs would be covered by a thick ice layer that would induce stress on the FBGs and thus falsify the results. We therefore inserted each FBG into a thin quartz capillary of about 55 cm length (inner diameter about 450 μm) so that at least 15 cm of the capillary on each side remained free of ice. To get comparable conditions, the same arrangement was used at room temperature and $+80$ °C. Again the temperature was measured with two Pt 100 sensors placed near the FBGs.

III. Results

A. Influence of the Hydrogen Pressure

Figs. 2 and 3 show the radiation-induced BWS ($\Delta\lambda_B$) as a function of dose measured with FBGs that were made after fiber loading at different hydrogen pressures. All measurements were made with two gratings each for all pressures and both fibers, apart of "0 bar" with the Corning fiber were we only had one grating (see Table II). We show all 7 (Corning) or 8 (FiberLogix) curves, respectively, in order to see the scattering of our measurements. The range between the two curves for each pressure is shaded to facilitate distinguishing between the results for the different pressures. We show both curves instead of the respective mean values to get a feeling for the measurement uncertainties. These are already discussed in detail in Section III-B-4) of [1]. For dose error, temperature compensation, and residual drifts we estimated a maximum measurement error for the BWS at 100 kGy of 6 pm. So far we did not discuss the error of the peak position determination. But with the present gratings the Bragg peaks are very high (a signal-to-noise ratio of about 25 dB) and the radiation-induced attenuation after 100 kGy is of the order of only 0.5 dB with both fibers so that the peak shape remains nearly unchanged and possible errors of the peak position determination are $<$ 2 pm, leading to a possible total error of $<$ 8 pm. However, some of the curves in Figs. 2 and 3 are separated by up to about 12 pm. This might be due to still existent sensitivity deviations even within FBGs of one production series.

As already observed with FBGs written with UV lasers (see [1] and the literature cited therein) as well as with femtosecond (fs) infra-red (IR) lasers [5], FBGs made of unloaded fibers show a distinctly lower BWS. With the FBGs of both fibers loading with 100 or 200 bar does not lead to a clear tendency, i.e., leads to about the same BWS, within the limits of uncertainty. However, FBGs made of the fibers loaded with 300 bar seem to show a slightly (Corning) or distinctly (FiberLogix) higher BWS than loading with 100 and 200 bar.

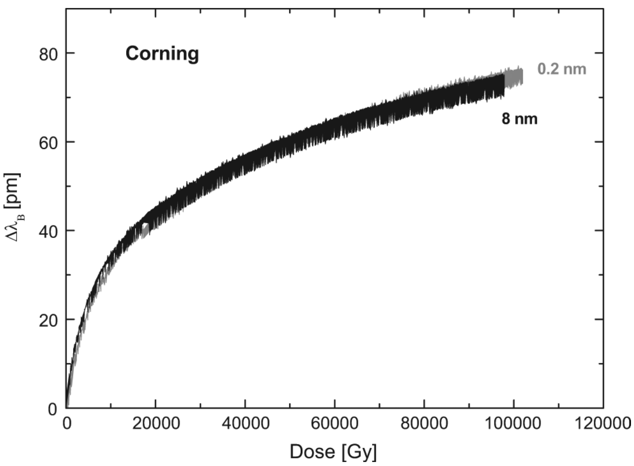

Fig. 4. Radiation-induced BWS of FBGs made of the Corning SMF-28e fiber with different fiber tension (0.2 nm and 8 nm, see Section II).

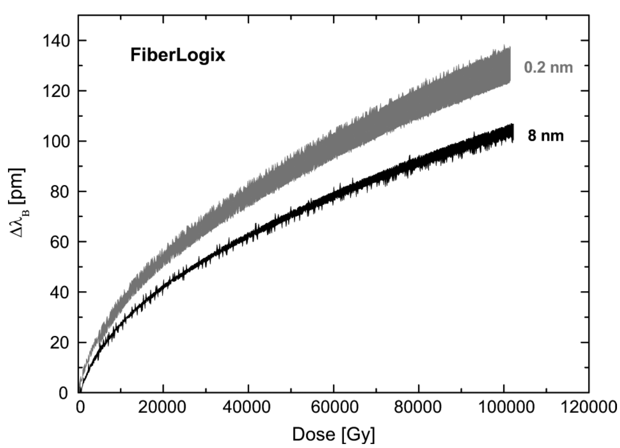

Fig. 5. Radiation-induced BWS of FBGs made of the FiberLogix HNA-01 fiber with different fiber tension (0.2 nm and 8 nm, see Section II).

B. *Influence of Fiber Tension During Grating Inscription*

The influence of fiber tension during grating inscription was also measured with two gratings each for the two tensions and each fiber. The results are shown in Figs. 4 and 5. As already observed with the hydrogen pressure of 300 bar, we only see a noticeable influence of the tension on FBGs made of the FiberLogix fiber. The higher tension leads to an about 24% lower BWS increase.

C. *Influence of the FBG Recoating*

Three influences of recoating on the radiation sensitivity of FBGs are imaginable:

1) shielding of the radiation;
2) change of the mechanical properties;
3) influence of the UV light used for curing the recoating material (mostly acrylate).

Radiation shielding only has to be considered with UV light or X-rays of very low energy, but can be neglected for ^{60}Co gamma rays with an energy of about 1 MeV. From our FBG manufacturer we heard that they observe a shift to lower wavelengths during the acrylate curing. They explain this by a shrinking of the acrylate. It is known that ionizing radiation can change the mechanical properties of plastic materials, can e.g., lead to a swelling and thus slightly change the FBG wavelength, too. In [6] we irradiated one recoated FBG and one from which the acrylate coating was removed. Therefore, only a mechanical degradation could have an influence since both FBGs were exposed to the UV curing light. However, in Fig. 8 of [6] it can be seen that both FBGs showed the same BWS. Therefore, the most probable influence on the radiation sensitivity of FBGs would be that of the UV curing light. In [7], it was shown that post-fabrication irradiation of FBGs with UV light did not change their radiation sensitivity. The main reason might be that the authors only considered FBGs of quite high radiation hardness, e.g., type IIa gratings written in fibers that were not loaded with H_2. We, however, investigated for the present paper FBGs that according to [1] show the highest radiation sensitivity, i.e., type I gratings written in highly H_2 loaded fibers. Therefore, UV illumination after the high temperature annealing procedure possibly can slightly change their radiation sensitivity.

TABLE III
INFLUENCE OF FBG RECOATING ON THE RADIATION-INDUCED BWS

Fiber	H_2-Pressure [bar]	$\Delta\lambda_B$ [pm] when FBGs are	
		un-recoated	Recoated
Corning SMF-28e	200	83.5	83.0
	300	85.5	84.0
FiberLogix HNA-01	200	135.0	133.0
	300	155.5	147.5

Table III shows the influence of the recoating procedure on FBGs made of both fiber types after H_2 loading with 200 and 300 bar, respectively. All results are mean values of BWS measurements with two gratings. Each of the measured differences is within the limits of error, but together they seem to suggest that recoating slightly decreases the radiation-induced BWS, the more the higher the radiation sensitivity, i.e., $\Delta\lambda_B$. FBGs made after loading with the same pressure (recoated and un-recoated) were made on the same day, in one working cycle. From [1] we know that such gratings show exactly the same radiation sensitivity, so that the observed tendency (lower BWS values of recoated FBGs with increasing radiation sensitivity) seems to be reliable. It is possible that the observed BWS reduction would be even higher with recoaters that apply a higher UV curing light intensity. On the other hand the influence of the recoating should be distinctly lower with radiation insensitive FBGs, e.g., those made without H_2 loading.

The results of [3] are not comparable with our present ones. Gusarov *et al.* investigated first of all the influence of three different coating materials. One of them (ormocer) led to a distinctly higher BWS than polyimide and acrylate. Removing the ormocer layer led to a BWS lower than that with acrylate and polyimide. They explain this by a radiation-induced swelling of ormocer. They found no difference between acrylate and polyimide, despite of the different curing, i.e., UV with acrylate and heating with polyimide. The reason might be that they used the most radiation insensitive FBGs, made without H_2-loading, whereas we used the most sensitive ones, made after loading with high H_2 pressure.

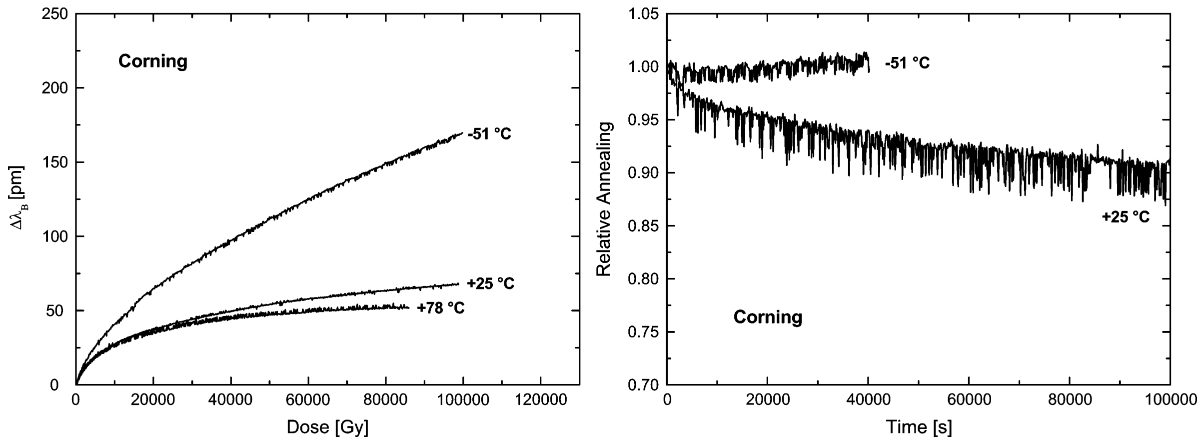

Fig. 6. Radiation-induced BWS at room temperature as well as at −51 °C and +78 °C of FBGs made of the Corning SMF-28e fiber. Left side: irradiation; right side: annealing after irradiation.

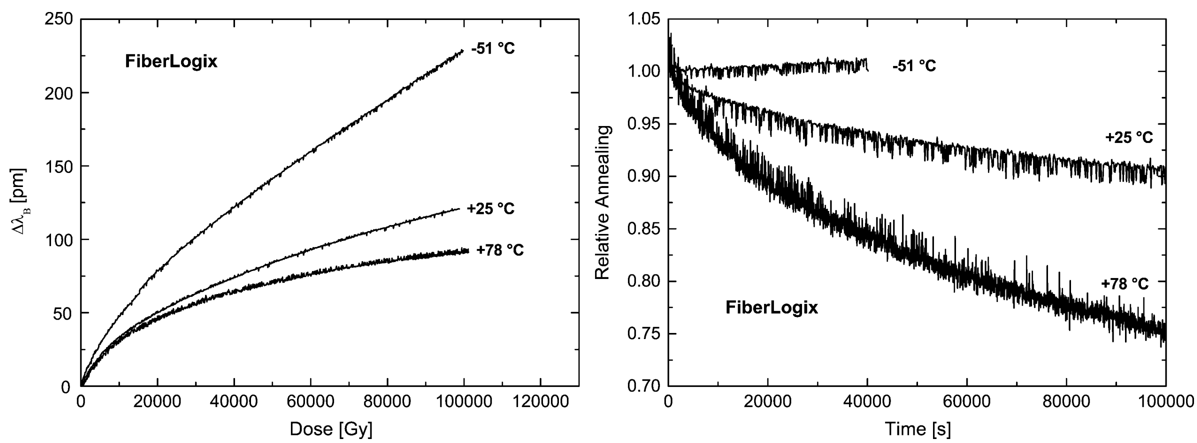

Fig. 7. Radiation-induced BWS at room temperature as well as at −51 °C and +78 °C of FBGs made of the FiberLogix HNA-01 fiber. Left side: irradiation; right side: annealing after irradiation.

D. Influence of the Fiber Perform

At the beginning of Section II Experimental it is mentioned that the present FiberLogix HNA-01 fiber was drawn from another preform that was made as identical as possible with that our fiber no. 8 of [1] was drawn from. FBGs made of that old fiber showed the highest radiation-induced BWS (about 160 pm after a dose of 100 kGy) so that such gratings can be used for coarse radiation dose measurements. Therefore, it would be important to get FBGs of at least the same sensitivity when the same fiber type has to be drawn from a new preform.

Our present measurements with FBGs made of that new fiber under standard conditions (see Section II) only yielded a BWS of about 130 pm instead of about 160 pm obtained in [1], i.e., nearly 20% less. However, also the BWS now measured with FBGs made of the fiber Corning SMF-28e showed a BWS of only about 80 pm instead of about 130 pm in [1], i.e., nearly 40% less. So it seems to be obvious that both grating types made two years later under supposed identical conditions had a distinctly lower radiation sensitivity. That the FBGs made of the new FiberLogix fiber only showed an about 20% lower BWS instead of 40% observed with FBGs made of an identical fiber (Corning SMF-28e) suggests that the new FiberLogix fiber two years ago would have led to FBGs of at least the same or an even higher radiation sensitivity than the FBGs made of the old FiberLogix fiber.

E. Influence of the Grating Temperature During Irradiation

The measurements at high and low temperature were only made with one grating of each fiber type written under standard conditions. Figs. 6 and 7 show on the left side the BWS during irradiation at room temperature as well as at +78 °C and −51 °C. On the right side we see the relative annealing, i.e., the BWS *after* the end of irradiation devided by the respective value *at* the end of irradiation. At −51 °C the BWS is about a factor of 2 higher than at room temperature, whereas the BWS at +78 °C is only about 30% lower than at room temperature. The annealing curves show the behavior already known from the RIA of optical fibers, i.e., nearly no changes at low temperatures and faster annealing at elevated temperatures. Our measurements show that FBGs with quite low radiation sensitivity at room temperature might show an unacceptable high radiation sensitivity when they are used for temperature or stress measurements at extremely low temperatures as observed in space. For the selection of FBGs for such space applications it is therefore necessary to also perform irradiation tests especially at low temperatures.

IV. Discussion

The variation of the hydrogen loading pressure has shown that with both fiber types loading with 100 bar or 200 bar has no significant influence on the FBG radiation sensitivity. Therefore, in this pressure range no special care has to be taken to meet exactly a certain loading pressure to guaranty a certain radiation sensitivity. However, with the FiberLogix FBGs increasing the pressure from 200 bar to 300 bar led in the mean to an about 14% higher radiation sensitivity.

Variation of the fiber tension during grating writing has shown that FBGs made of the FiberLogix HNA-01 fiber have a distinctly higher radiation sensitivity at low fiber tensions. This, together with 300 bar loading pressure, can be used to increase the suitability of such FBGs for radiation dosimetry. This suitability was already stated in [1]. The result confirms our suspicion discussed there that variation of the fiber tension in order to vary the FBG wavelength might influence the radiation-induced BWS and thus spoils the reproducibility of results obtained with otherwise identical FBGs.

With nearly all FBG inscription processes it is necessary to remove the fiber coating. However, for many applications the customers order recoated gratings to increase their stability. At least with the most radiation sensitive FBGs the recoating process can lead to a reduction of the radiation-induced BWS. When ordering gratings for radiation sensing purposes one therefore has to examine whether recoating leads to an unwanted sensitivity reduction.

The influences of H_2 loading pressure, fiber tension, and recoating are relatively small and can only be measured when using a greater number of identical FBGs, from the same lot. Unfortunately we only could use two gratings for most of our measurements. However, these influences are small compared with the BWS differences between our present FBGs and those made of the same fibers by the same manufacturer about two years ago (see Section III-D). There seems to exist a so far unidentified process parameter that sometimes leads to FBGs of distinctly different radiation sensitivity. In order to find this error source one should perhaps make FBGs of the same fiber several times a year and measure their radiation-induced BWS.

It was shown that the radiation-induced BWS is at least two times higher at temperatures below $-50\ ^\circ$C than at room temperature. This has to be considered when FBGs are intended as temperature or stress sensors e.g., in space vehicles. The FBGs used for our present test (type I, hydrogen loaded fibers) do not belong to the radiation hardest that would be selected for such applications. Nevertheless it became evident that selection of FBGs for certain space applications also has to include at least irradiation tests at low temperatures.

V. Summary

We have investigated for the first time the influence of hydrogen loading pressure and fiber tension before or during grating inscription, respectively, as well as of the recoating procedure and the FBG temperature during irradiation on the radiation sensitivity of FBGs. In the usual pressure range of 100–200 bar, the loading pressure had no distinct influence on the FBG's radiation sensitivity. An increase to 300 bar slightly increased the radiation-induced BWS with fibers that anyhow yield the most sensitive gratings.

It could be shown that a higher fiber tension during grating inscription will lead to a lower radiation sensitivity of those FBGs that are made of the fibers leading to FBGs with high radiation sensitivity.

Recoating leads to a slightly lower radiation sensitivity of those FBGs that show the highest radiation-induced BWS. It is concluded that this is due to the UV light used for curing of the acrylate layer so that this effect should depend on the intensity of the UV light source of the respective recoating device.

FBG cooling to $-51\ ^\circ$C or heating to $+78\ ^\circ$C, respectively, leads to an about two times higher or an about 30% lower radiation- induced BWS than at room temperature. This should be considered when qualifying FBGs for e.g., temperature or stress measurements in space or nuclear facilities.

For getting further FBGs with the highest radiation sensitivity, we had to order a new sample of the fiber FiberLogix HNH-01. We asked for a preform that is made as identical as possible to that used for the old fiber sample. The FBGs made of that new fiber showed at least the same sensitivity than those made of the old fiber. This is encouraging for their application as sensors for higher radiation doses.

The H_2 loading pressure variation between 100 and 300 bar, the fiber tension during grating inscription, and the recoating had only relatively low influences on the radiation-induced BWS. They became detectable since we used FBGs of very high radiation sensitivity and a measurement set-up of high stability and reproducibility. They can be used to optimize the production of radiation sensitive FBGs for radiation dose measurements. They can, however, be neglected with the production of radiation insensitive FBGs, e.g., type II or IIa FBGs written in H_2-free fibers. Temperature and stress measurements with such FBGs should not be falsified by radiation-induced shifts of their Bragg wavelength. The lowest radiation sensitivity, i.e., a radiation-induced BWS of only about 5 pm after a dose of 100 kGy, was found so far with some FBGs written with femtosecond IR lasers in Ge-free fibers [5].

Acknowledgment

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