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Citation: Journal of Applied Physics **118**, 074502 (2015); doi: 10.1063/1.4928966
View online: http://dx.doi.org/10.1063/1.4928966
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Fiber Bragg gratings in the radiation environment: Change under the influence of radiolytic hydrogen

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(Received 6 May 2015; accepted 9 August 2015; published online 20 August 2015)

The change of the transmission spectra of fiber Bragg gratings written in the optical fibers, whose silica cores are doped with either germanium or nitrogen, is studied experimentally under the influence of gamma-radiation. The transmission spectra in the neighborhood of the resonance (Bragg) wavelengths were regularly recorded "*in-situ*" in the course of irradiation during 24 days. For this purpose, uncoated gratings were placed in a pool near the spent fuel rods of a nuclear reactor. The fibers with the gratings written in them were in immediate contact with water. The estimated total absorbed radiation dose of the fibers is approximately 5 MGy. Molecular hydrogen, which is produced by radiolysis of water and penetrates into the core of silica fiber, is found to interact with the defects of Ge-doped silica induced by gamma-radiation, thereby causing a strong impact on the parameters of the spectrum of the Bragg gratings. On the contrary, in the case of gratings inscribed in N-doped silica fibers, the hydrogen molecules interact with defects induced in the course of laser UV exposure during the grating writing only. The possible subsequent formation of additional defects in N-doped silica under the influence of gamma-radiation has no substantial impact on the transmission spectra of Bragg gratings, which remained stable. The obtained results suggest that a small amount of molecular hydrogen resided in the fiber core is the main source of radiation instability of Ge-doped fiber Bragg grating sensors in radiation environments. These hydrogen molecules can remain in the Bragg gratings, in particular, after the inscription process in the hydrogen-loaded fibers. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4928966]

I. INTRODUCTION

Fiber Bragg gratings (FBGs) are widely used in fiber-optic devices, such as optical filters, fiber lasers, and sensors of physical quantities.[1,2] A separate and significant area of FBGs is fiber-optic systems designed for operation in high radiation environments (e.g., space applications and nuclear installations). In this case, it is frequently necessary to understand the impact of ionizing radiation on the key parameters of the FBG used (resonant wavelength and reflectance).

FBGs are usually fabricated by means of photo-induced inscription of a periodic refractive index structure in a special photosensitive fiber by UV laser radiation. As a rule, silica fibers with high Ge concentration are used.[3] A greater photosensitivity occurs for fibers with a Ge-doped and boron-co-doped silica core.[4] In addition to enhancing the photosensitivity, the addition of boron reduces the refractive index of silica in the core, which makes such fibers better matched with standard telecom optical fiber.

Often to increase the photosensitivity of Ge-doped silica fibers, especially with low Ge content, a preliminary fiber saturation with molecular hydrogen in the chamber at a pressure of 100–150 bar is applied.[5] At the same time, the parameters of FBG written in the hydrogen loaded fiber are recognized to possibly change over time. This feature is especially noticeable at elevated temperatures, as well as under exposure to ionizing radiation.[6,7] Note that fibers with a high Ge content are not radiation resistant and demonstrate a high level of excess losses, even when exposed to low doses of ionizing radiation [see, e.g., Ref. 8]. Fibers with an undoped silica core exhibit the highest radiation resistance,[9] but FBGs fabrication in pure-silica-core fiber is difficult because of the lack of photosensitivity and they can be inscribed by special femtosecond technique only [see, e.g., Ref. 10].

An alternative to Ge-doped silica-core is a radiation-resistant, photosensitive optical fiber in which the fiber core is made of fused silica doped with nitrogen.[11,12] FBGs inscribed in nitrogen doped fibers withstand much higher temperatures than standard Ge-doped ones.[13] However, the writing of FBGs in the N-doped-silica-core fibers is only possible with the use of a deep UV (193 nm) laser. Note that preliminary saturation of this type of fiber by molecular hydrogen negatively affects the photosensitivity.[14] The radiation resistance of the N-doped silica-core fibers and the tolerance of the FBGs using such fiber to high temperatures make sensors based on such FBGs promising for application in the nuclear industry. An example of such an application is the differential sensor for monitoring the deformation of graphite stack channel-type nuclear reactors described in Ref. 15.

One often does not take into account and does not consider the peculiarities of the manufacturing technology of FBG when examining and discussing the experimental data

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on the impact of ionizing radiation on their parameters. This lack of consideration of the manufacturing differences is normal because, in most of the experiments, commercially available FBGs are used; as a result, information regarding the features of their manufacturing technologies is confidential. The lack of details of the fabrication technology of FBGs makes it difficult to adequately interpret the experimental data, which, according to the relevant publications, are somewhat conflicting. For example, Refs. 16–18 stress that changing the parameters of FBGs written in Ge-doped silica-core fibers under the action of ionizing radiation is not significant, which implies high radiation tolerance of such FBGs. Hydrogen unloaded fiber was used for the fabrication of the FBGs for this experiment. On the contrary, FBGs written in hydrogen-loaded fibers show significantly greater Bragg wavelength change under the influence of ionizing radiation. However, the nature of such behavior was not discussed. Reference 19 reported the strong dependence of the resonant wavelength of FBGs with the absorbed dose of gamma-radiation; as a result, they proposed to use them as dosimeters. Although some of the conditions of the photo-induced FBGs writing process are noted in Ref. 19, no indication is provided regarding whether the writing procedure was performed with fibers that used the hydrogen loading process. The use of the hydrogen loading process, as we shall show, is a significant factor in determining the sensitivity of the parameters of FBGs to ionizing radiation.

The information on the FBGs written in N-doped silica fibers is also quite conflicting. Reference 16 claims rather poor radiation resistance of such gratings indicating a steady shift of the resonant wavelength with increasing dose of gamma-radiation. In Ref. 20, no explicit dependence of the resonant wavelength with increasing dose was observed; in contrast, in Ref. 21, no changes of the resonant wavelength with increasing radiation dose are observed, indicating higher stability of the FBGs with N-doped silica core fibers in comparison with their Ge-doped silica core counterparts. This conflict drew the attention of the authors of Ref. 22.

In this paper, we present and discuss the results of our systematic experiments on gamma-irradiation of different types of specially fabricated FBGs to study the effects of ionizing radiation on the parameters of the FBGs in the presence of the radiolytic hydrogen. The experiment consists of "*in-situ*" monitoring of the transmittance and reflectance spectra of FBGs placed in a pool of water nearby the rods of the spent nuclear fuel. The experimental results clearly demonstrate the changing resonant wavelength of FBGs under the influence of gamma-radiation associated with the presence of even a small amount of hydrogen in the core of the fiber. The possible causes of the formation and diffusion of residual and/or radiolytic hydrogen molecules in the core of an optical fiber, which are often not taken into account in the preparation and conducting radiation tests of FBGs, are discussed. In Ge-doped FBGs, molecular hydrogen is found to primarily interacts with gamma-radiation-induced defects and has a significant effect on the spectrum of the fiber Bragg gratings. In the case of N-doped FBGs, significant is interaction of hydrogen with the active centers photo-induced in the course of UV-irradiation during the inscription of the FBGs. In contrast, gamma rays do not significantly affect the behavior of the parameters of these FBGs, even in the presence of molecular hydrogen.

II. EXPERIMENTAL

Photosensitive single mode optical fibers with three different types of silica in the core were specially fabricated for the experiments. All fibers have an outer diameter of 125 μm and are drawn from the preforms that were synthesized via the SPCVD process.[23] Some of the parameters of the optical fibers are presented in Table I.

Sample #3 contains 1 at. % of fluorine in the material adjacent to the core glass layer of the reflective cladding as well. FBGs of types I and IIa with resonance (Bragg) wavelengths at approximately 1530–1550 nm were imprinted into the fibers for the experiments. The gratings writing was conducted using an ArF excimer laser (193 nm wavelength) and a phase mask. The mean energy density of the laser pulses during grating imprinting was approximately 200 mJ/cm^2. Inscription occurred in the fibers without hydrogen loading, which is important for the interpretation of the results of our experiment. The fiber sections with the imprinted gratings remain uncoated during our gamma-irradiation experiment. The parameters of the Bragg gratings used in the experiment and their writing conditions are summarized in Table II.

Fibers with imprinted Bragg gratings were freely turned around the frames of aluminum coils with a diameter of 90 mm, which are then placed in a capsule for the subsequent gamma-irradiation. The irradiation was performed using spent fuel rods of RBMK-1000 reactor, which acted as gamma-ray sources. This irradiation was performed by placing a capsule containing the samples into a spent fuel pool between the fuel rods at a depth of 11 m. An approximate distance to the nearest three rods was approximately 100 mm. The estimated exposure dose rate was 8.64 kGy/h. During the experiment, the Bragg wavelengths of the gratings and the transmission spectra of the fibers in the wavelength range of 1200–1700 nm were recorded.

All of the samples were in direct contact with the water, the latter being an important feature of the experiment. As is known, the gamma-radiation causes intense water radiolysis, with the formation, in particular, of hydrogen molecules.[24] These hydrogen molecules can penetrate into the glass network of the fiber and interact with radiation-induced defects. The infiltration of hydrogen molecules into the glass and the possible formation of hydroxyl groups as a result of the reaction of H_2 with radiation-induced defects can be monitored by the changes in the loss spectra of the fibers.

Fig. 1 shows a block diagram of the experimental setup. The spectral features of the Bragg gratings were recorded

TABLE I. The fibers used in the experiment.

Sample	Additives to silica in the fiber core	Coating
#1	GeO_2 (14 mol. %) B_2O_3 (2 mol. %)	Acrylate
#2	N (3 at. %)	Acrylate
#3	N (3 at. %) F (1 at. %)	Bronze-like alloy

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TABLE II. Bragg gratings and their parameters.

Fiber	Grating	Grating "type"	193-nm UV laser exposure dose (J/cm^2)	Phase mask pitch, nm	Bragg wavelength, nm	Grating's strength, dB
#1 (Ge, B-doped)	G1	IIa	900	1051	1529.68	2.0
	G2	I	120	1056	1535.28	3.0
	G3	IIa	837	1060	1541.38	9.0
	G4	I	24	1063	1546.04	2.0
#2 (N-doped)	G5	IIa	3450	1051	1534.09	6.5
	G6	I	899	1056	1539.64	2.0
#3 (N, F-doped)	G7	I	725	1051	1528.33	5.0
	G8	IIa	2790	1056	1534.65	5.0
	G9	I	210	1060	1539.77	1.5

using a Luna OBR 4400 optical frequency domain reflectometer (OFDR). In addition, the transmission spectra of the fibers and FBGs were measured at the same time using an Agilent 86140B optical spectrum analyzer. Superluminescent diodes with emission wavelengths between 1300 and 1550 nm and half-maximum spectral widths of 80 nm were used as light sources. Switching between fibers with imprinted FBGs was performed via Agilent 86060 C and Agilent 86061 S optical switches connected to the inlet and outlet of the fibers, respectively.

The samples were continuously exposed to gamma-irradiation during 24 days at an ambient average temperature (the temperature of the ambient water) of 27 °C. The change in the temperature during experiment does not exceed 3–4 °C. The estimated total absorbed dose is 4.96 MGy. Fibers and FBGs transmission spectra were periodically recorded '*in situ*' during the course of irradiation.

III. RESULTS AND DISCUSSION

A. FBGs in Ge-doped-silica-core fiber

Fig. 2 shows the dependence of the Bragg wavelength shift on the absorbed dose of gamma-radiation for gratings G1–G4 inscribed Ge-doped-silica-core fibers (#1, Table I). The variation of this parameter in the initial stage up to the dose of 360 Gy (2 days of irradiation) does not exceed 60 pm. Note that the total error of the Bragg peak spectral position measurement is approximately 20 pm. The graph shows a trend towards a slight decrease in the Bragg wavelength with the accumulation of the dose. Note that the dynamic pattern of this parameter does not depend on the type of gratings. Therefore, such a change can be assumed to be associated with the integral change of the effective refractive index of the light-guiding core under irradiation rather than with an evolution of the Bragg grating structure itself. This change can also be partly associated with the insignificant change in water temperature during the experiment. Note that the temperature change does not exceed 3–4 °C and, hence, cannot cause a Bragg wavelength shift greater than 33–50 pm.

Substantial increase in the Bragg wavelengths was observed for all gratings with increasing doses of gamma-radiation, which indicates an increment in the mean effective refractive index of the light-guiding fiber core. The significant increase in the Bragg wavelengths begins 10 days after the start of gamma-irradiation (2.2 MGy of the accumulated dose). This delay coincides with a diffusion time scale necessary for outer hydrogen molecules penetration through the fiber cladding to reach the fiber core at room temperature.[25]

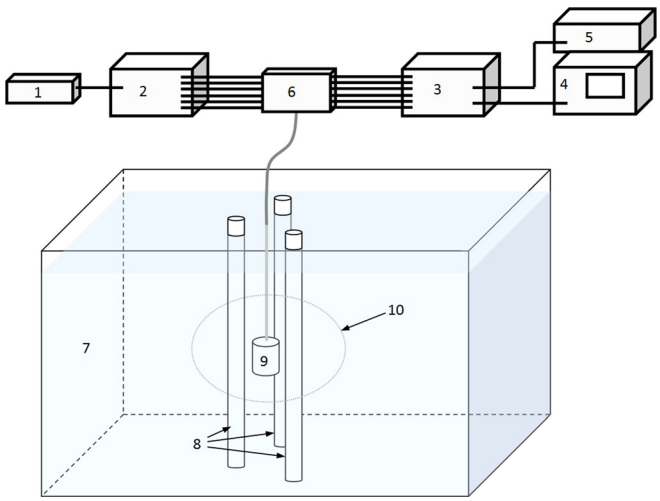

FIG. 1. Block diagram of the experimental setup. 1—light sources, 2, 3—fiber switches 2 × 6, 4—optical spectrum analyzer, 5—OFDR, 6—optical cable connector, 7—spent fuel pool, 8—spent fuel rods (gamma-ray sources), 9—capsule with the Bragg gratings, 10—gamma-irradiation area.

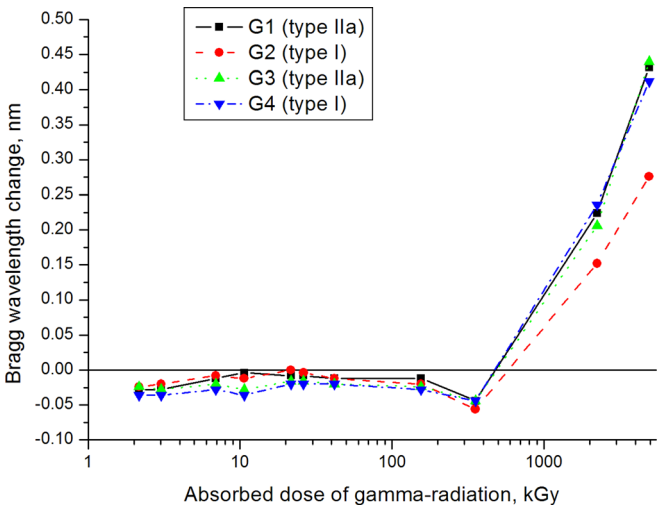

FIG. 2. Changes of the Bragg wavelengths of FBGs G1–G4 as a function of the absorbed dose of gamma-radiation.

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Obviously, the radiolysis of water is the sole source of the "external" molecular hydrogen in this experiment.

A smaller gamma-induced change in Bragg wavelength for sample G2 does not associate with the FBG writing technology but likely is due to a smaller gamma-radiation exposure dose rate for this particular sample. The latter can be caused by a stronger partial absorption of gamma-radiation by the metal core construction of the capsule in the region where the G2 was located.

Consider an estimate of the amount of radiolytic hydrogen that can enter the silica fibers in our experiment. The steady state concentration of hydrogen molecules in water permanently irradiated by gamma-quanta weakly depends on the radiation intensity and is approximately 1 μM/l (Ref. 26) or 6×10^{14} cm^{-3}. This concentration of the dissolved molecular hydrogen corresponds to equilibrium in the system fiber – ambient gas at a hydrogen partial pressure in a gaseous environment of approximately 1.4×10^{2} Pa.[27] Under these conditions, the equilibrium concentration of hydrogen in the silica would be approximately 4×10^{15} cm^{-3}.[28] The above-mentioned estimates of the radiolytic hydrogen amount penetrating into the fiber may slightly vary due to non-equilibrium processes occurring at the interface water/glass. To estimate the possible uncertainty in the evaluation of hydrogen concentration, we introduce the so-called G-factor, which reflects the rate of the molecular hydrogen formation in water during ionizing radiation exposure. The G-factor for the radiolytic hydrogen in water is approximately 0.45 molecules/100 eV for the gamma-irradiation.[26,29] This value of the G-factor implies that the rate of radiolytic hydrogen generation amounts to $\sim 6.8 \times 10^{13}$ s^{-1} cm^{-3} at the gamma-radiation dose rate of 8.64 kGy/h (or 2.4 Gy/s $\approx 1.5 \times 10^{16}$ eV/cm^3/s), which obviously, cannot significantly contribute to the evaluation of the equilibrium concentration of hydrogen molecules in the fiber, even taking into account the non-equilibrium process at the water/glass interface.

Molecular hydrogen within the silica glass network is known to interact with radiation-induced defects, even at room temperature; this interaction contributes to the formation of hydroxyl groups. The characteristic peaks of Si-OH absorption bands correspond to 1.39 μm and 1.24 μm wavelengths, the ratio of intensities of these bands being 1:23.[30] In addition to OH-groups, the absorption coefficient in the spectral band centered at the 1.24 μm also reflects the presence of hydrogen molecules in the glass. However, at the concentration of 4×10^{15} cm^{-3}, the contribution of H_2 to the absorption coefficient at the wavelength of 1.24 μm is only 0.013 dB/km.[28] In addition, the ratio of the band intensities at 1.24 and 1.39 μm in our experiment during gamma-irradiation remained unchanged within the measurement errors. The latter result indicates that the measured evolution of peak absorption at 1.24 μm wavelength in our case is unambiguously associated with an increase in concentration of OH-groups in the glass.

Considering the trends of the absorption coefficient at the characteristic wavelengths against the background of the general level of radiation-induced loss in the fiber, one can determine not only the appearance of hydrogen molecules in the fiber core but also the dynamics in the growth of hydroxyl groups. Fig. 3 shows the dependence of the absorption coefficient in the peak centered at the wavelength of 1.24 μm versus time for fiber #1 since the beginning of the gamma-irradiation. The extinction coefficient for the OH-groups at this specific wavelength amounts to 2.7 dB/km/(OH) wt. ppm.[30] The observed absorption at this wavelength in the end of our experiment was approximately 34 dB/km, which corresponds to 13 (OH) wt. ppm, or approximately 10^{18} hydrogen bonded atoms per 1 cm^3. An inexhaustible source of free radiolytic hydrogen in our experiment is water, which provides a permanent in-diffusion flow to the glass fiber in the process of gamma-irradiation. The concentration of radiation-induced defects that can react with interstitial hydrogen molecules at similar doses of gamma-irradiation is estimated as 2×10^{19} cm^{-3}.[25,31] Such a high concentration of the active defects ensures a high probability of the transformation of an interstitial hydrogen into a hydroxyl group.

Fig. 3 shows the dose dependence of the Bragg wavelength shift for grating G3 inscribed in fiber #1 as well. A comparison of the plots shows that the Bragg wavelength increase during the course of gamma-irradiation is uniquely associated with the penetration of hydrogen molecules into the fiber core and, as a consequence, with the formation of hydroxyl groups due to their interaction with radiation defects. Note that in metal coated fiber #3 (Table I), protected against the penetration of outer hydrogen molecules, the absorption peaks at both 1.24 μm and 1.39 μm wavelengths remain unchanged during gamma-irradiation. This result is additional confirmation of the "external" origin of hydrogen in the glass of the fiber core, in this particular case generated by water radiolysis.

Fig. 4 shows the three normalized transmission spectra of the FBG written in the Ge-doped-silica-core fiber #1 at the start of the experiment and at different accumulated doses of gamma-irradiation (0, 363, and 4490 kGy). The graph indicates that at large doses (prolonged irradiation), a reduction of the Bragg grating reflection coefficient occurs. At first glance, such a reduction is associated with the penetration of the radiolytic hydrogen molecules into the core of the fiber and does not immediately depend on the dose of

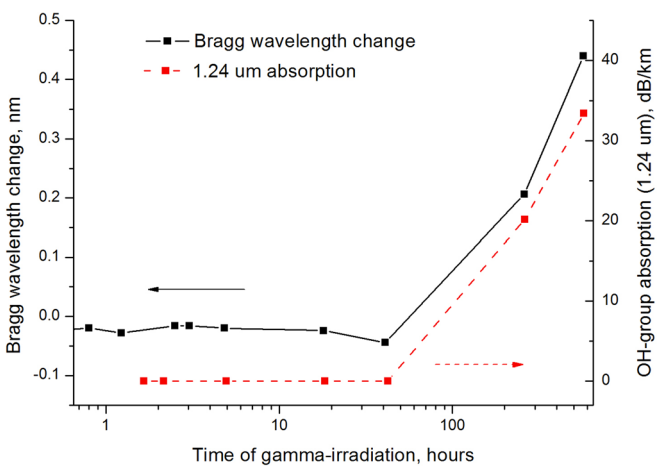

FIG. 3. The evolution of the 1.24-μm peak absorption and the shift of the Bragg wavelength during gamma-irradiation.

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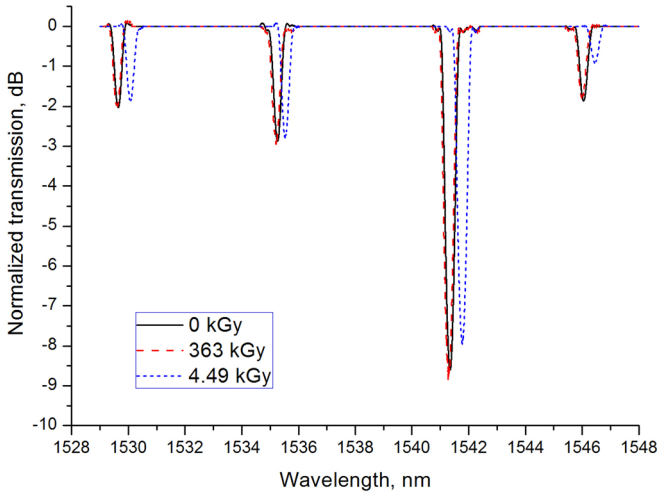

FIG. 4. The transmission spectra of FBGs G1–G4 written in fiber sample #1 at different doses of gamma-radiation.

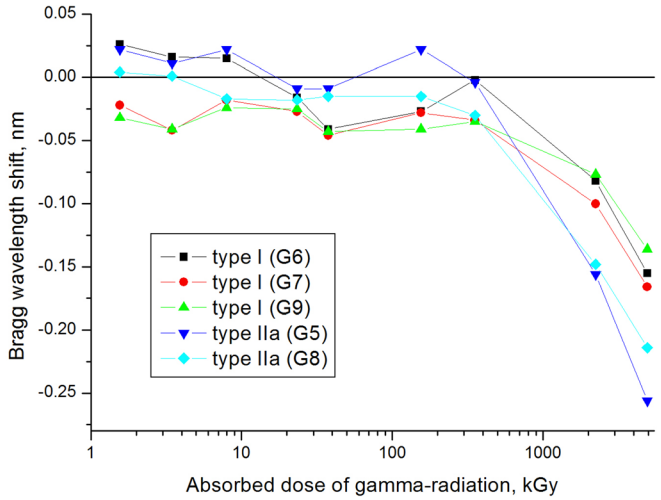

FIG. 5. Bragg wavelength changes as a function of the absorbed dose of gamma-radiation in the nitrogen-doped-silica-core fibers.

gamma-radiation directly accumulated by the grating. A similar behavior of the Bragg grating spectrum is observed in the case of hydrogen loading in a high-pressure chamber at room temperature in the absence of ionizing radiation;[32] note that in our experiments, the concentration of radiolytic hydrogen is smaller by four orders of magnitude. Therefore, in our case, the ionizing radiation is found to be responsible for this effect by stimulating the breakdown of photo-induced refractive index pattern, thereby reducing the contrast of the Bragg gratings. Another possible cause of the reduced contrast of the grating is the modification of the glass network as a result of reactions of H_2 molecules with defects induced by gamma-radiation [see, e.g., Ref. 33 and reference in it].

The above data show that the enhanced sensitivity of Bragg gratings to gamma-irradiation reported, which consists in an increase in a Bragg wavelength as the result of gamma-irradiation, may be first attributed to the presence of even a small amount of hydrogen molecules in the glass network. This effect is most peculiar for the gratings written in hydrogen-loaded fibers. In such gratings, the extra hydroxyl groups may be formed in the process of gamma-irradiation by the reaction of radiation-induced defects in the Ge-doped-silica-core with a small amount of residual hydrogen that was not fully removed from the grating before the start of the experiment. This effect, most likely, has been observed, for example, in Ref. 19. A different amount of residual hydrogen can be one reason for the different sensitivities of the FBGs to gamma-radiation. Based on the data, in the course of the irradiation, the following mechanism cannot be excluded: the reallocation of existing hydroxyl bonds at the expense of their secondary formation in the glass network due to radiolysis, which in turn may also affect the parameters change of the FBGs written in hydrogen-loaded fibers.

B. FBGs in nitrogen-doped-silica-core fibers

Consider the behavior of Bragg gratings written in fibers, in which the refractive index profile is determined by the incorporation of N in the silica network.[11] Fig. 5 shows the dependence of the Bragg wavelengths on the gamma-radiation absorbed dose. Due to the damage of some fiber pigtails while installing samples in the capsule, measurement of the transmittance spectra was not possible. As a result, the spectra of Bragg gratings were extracted from the traces of OFDR LUNA OBR 4400. The uncertainty in the detection of Bragg wavelength in these measurements is approximately 30 pm.

The graph shows data for the five samples of fiber Bragg gratings. One can see that on the first stage of the experiment, prior to penetration of hydrogen in the core of optical fiber, there is no change in the Bragg wavelengths within the errors of measurements for all types of gratings, which is in good agreement with the results of earlier studies reported in Ref. 21. As in the case of Ge-doped-silica-core fiber, 10 days after the start of the experiment, hydrogen, which is the product of the surrounding water radiolysis, penetrates into the core of the fiber, which leads to the formation of the new hydroxyl groups in the glass network. Note that the evolutions of the OH-groups absorption growth with dose of gamma-radiation in the N-doped and Ge-doped silica-core fibers exhibit a similar pattern. However, in the case of the N-doped fibers, a "blue" shift of Bragg wavelength is observed. For "type IIa" gratings, this shift is greater than for the "type I" ones. According to Ref. 32, a similar shift occurs during hydrogen loading of similar FBGs in a high pressure chamber. At the initial stage of the experiment, as described in Ref. 32, a small amount of hydrogen in the core of the fiber lead to an irreversible "blue" shift of Bragg wavelength.

The magnitude of changes of a Bragg wavelength in N-doped fibers caused by molecular hydrogen is assumed to depend not so much on grating type, but rather on the total exposure dose of UV radiation accumulated by the fiber during inscription of the Bragg structures. Hydrogen entering the fiber interacts with the defects of the glass network formed during UV exposure that determines the spectral shift of a Bragg wavelength. The formation of the UV induced defects in the process of Bragg grating inscription increases the average core refractive index. That explains why annihilation of the UV induced defects leads to the opposite result,

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which manifests itself by a decrease in the type I FBGs reflection during the hydrogen entering.[32] That is why we observe a "red" shift of the Bragg wavelength in nitrogen-doped samples in contrast to germanosilicate ones. More information about defects in nitrogen-doped silica can be found in Ref. 34.

Fig. 6 shows the observed shift of Bragg wavelengths of different gratings, inscribed at various values of the UV radiation exposure dose in N-doped fibers #2 and #3. Because fibers # 1 and # 2 have the similar content of nitrogen in the core, we embodied information on different gratings on the same plot. We associate the shift of the Bragg wavelengths with the radiolytic hydrogen formed in water during gamma-irradiation penetrating into the glass. The magnitude of the shift is found to be directly proportional to the dose of UV radiation accumulated by a fiber grating when writing. This result allows one conclude that hydrogen in the N-doped silica reacts mainly with the defects that have been already formed during the UV laser exposure. Note that regardless of the presence of molecular hydrogen, as has been shown previously in Ref. 21 and confirmed in this study, the influence of gamma-irradiation on the parameters of Bragg gratings written in N-doped-silica-core fibers is negligible.

In contrast, in the case of Ge-doped-silica-core fibers, our experiments on gamma-irradiation in the presence of radiolytic hydrogen did not reveal any significant differences in the magnitude of the Bragg wavelength changes on the type of the grating or the UV laser fluence during grating inscribing. This fact additionally confirms the predominant role of the interaction of interstitial hydrogen molecules with defects caused by gamma-radiation rather than by UV laser exposure during grating inscribing in the case of Ge-doped-silica-core fibers.

C. The influence of the weak concentration of hydrogen molecules on the parameters of the FBGs

To verify the above-described mechanism of the influence of interstitial hydrogen molecules on various FBGs, we conducted an experiment to monitor the changes of the Bragg grating spectra in ambient atmospheres with low hydrogen partial pressure in the absence of gamma-radiation. To perform the measurement, a high-pressure chamber was used, which allows for recording of the Bragg grating spectra "*in situ*." The chamber design description can be found in Ref. 32. "Type IIa" gratings written in fibers #1 and #2 (Table I) were used in the experiment. The chamber was filled with a gas mixture containing nitrogen and hydrogen at a ratio of 1000:1, and the total pressure in the chamber was 1 MPa. Therefore, the partial pressure of the molecular hydrogen was 1 kPa or 0.01 bar. To speed up the in-diffusion process and to ensure a higher saturation uniformity, the experiment was performed at a temperature of ~70 °C. At this temperature, the hydrogen molecules do not react with the pure silica network, neither do they react with the germanium- or nitrogen-doped regular silica network.[35] We monitored the change in Bragg wavelengths of the gratings during the saturation process.

Fig. 7 shows the dependence of the Bragg wavelengths on time during the molecular hydrogen loading of various FBGs at the low partial pressure. Illustratively, the calculated growth of the concentration of hydrogen molecules in the fiber core due to in-diffusion is added as a separate plot in Fig. 7.[25,28,36] As one can see from Fig. 7, the change of Bragg wavelength in the FBGs imprinted in the N-doped-silica-core fiber is similar to that one observed in the experiment on gamma-irradiation. The spectrum of an FBG continues to change, even after reaching equilibrium in the system ambient gas-fiber. This change continues because a definite temperature-dependent time is necessary for an interstitial hydrogen molecule migrating in the silica to encounter an active photo-induced defect for subsequent contact interaction. The amount of time depends on both the concentration of hydrogen molecules migrating in the glass and the concentration of active centers, induced during UV exposure during the FBG inscribing process. Similar patterns in the changes of a Bragg wavelength have been observed in the case of gratings written in the Ge-doped-silica-core fibers; however, these changes are nearly an order of magnitude

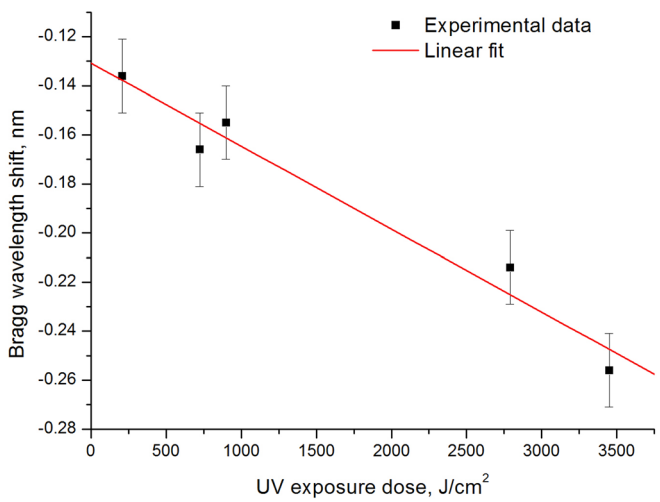

FIG. 6. The dependence of a Bragg wavelength shift caused by hydrogen loading on the exposure dose of UV radiation during grating inscribing in the N-doped-silica-core fiber.

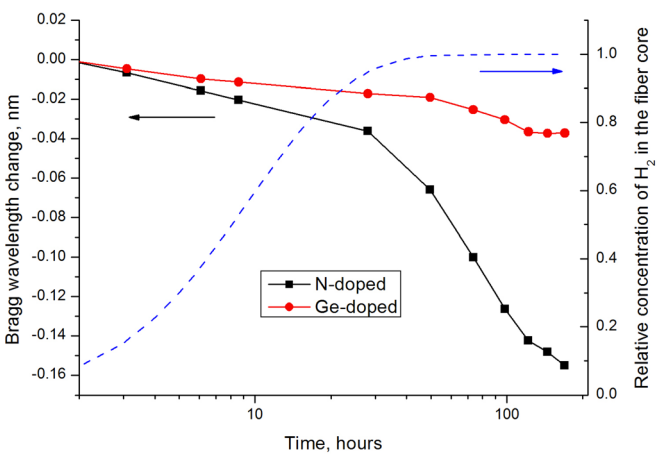

FIG. 7. Dependence of the Bragg wavelength spectral shift for different FBGs on time during their saturation with molecular hydrogen at a low partial pressure.

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less compared to changes in the N-doped FBGs. This experiment fully confirms the preferable interaction of the hydrogen molecules with the UV-induced defects in N-doped silica. In contrast, in the Ge-doped-silica-core FBGs, most of reactions, leading to a change of the Bragg wavelength in hydrogen atmosphere, are associated primarily with the interaction of H_2 molecules with the defects formed under the influence of gamma-radiation.

IV. CONCLUSION

The presented results of the spectral monitoring of various fiber Bragg gratings under the influence of gamma-irradiation indicated that the presence of hydrogen molecules in the glass and the formation of secondary hydroxyl groups play crucial roles in the spectral response of FBGs to gamma-radiation. The radiation sensitivities of the spectrum of the FBGs written in Ge-doped-silica-core fibers are primarily determined by the interaction of residual or radiolytic hydrogen molecules with radiation-induced defects. A number of previous studies ignored this radiation sensitivity, which has led to the ambiguity of the results. A similar study of FBGs written in N-doped-silica-core fibers found that hydrogen molecules entering the glass network mainly interact with the defects formed in the process of UV exposure during the FBG inscribing process. Gamma-radiation alone has no significant impact on this type of FBGs, which confirms their high radiation tolerance.

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