High Radiation Sensitivity of Chiral Long Period Gratings

Henning Henschel, Stefan K. Hoeffgen, Member, IEEE, Jochen Kuhnhenn, and Udo Weinand

Abstract—The radiation sensitivity of chiral long period gratings was investigated for the first time. After a Co-60 gamma dose of 100 kGy they show radiation-induced changes of their transmission dip wavelength of up to 10 nm, which is 100 to 1000 times higher than the radiation-induced wavelength shift of different fiber Bragg grating types. They can therefore be used as radiation sensors down to doses of 10 Gy or even below, but not for accurate dose measurements since the size of the wavelength shift after a certain dose still depends on the radiation dose rate. Chiral gratings made of eight single mode fiber types with differences of their radiation-induced attenuation of several orders of magnitude were investigated in order to look for a correlation between dip wavelength shift and fiber attenuation. However, the dip wavelength curves do not show exactly the same order as the fiber attenuation curves. A theory that can exactly predict all properties of the chiral gratings might enable us to specify from our results an optimized fiber for the production of gratings that can also be used for radiation dosimetry.

Index Terms—Annealing, chiral long period grating, cladding modes, fiber Bragg grating, gamma radiation, optical fiber sensors, radiation effects, radiation dosimetry, radiation sensors, transmission dip wavelength shift.

I. INTRODUCTION

SINCE more than 15 years a variety of papers have been published about the radiation sensitivity of fiber Bragg gratings (FBGs) [11]–[16]. The main purpose was to demonstrate that FBGs are quite insensitive to ionizing radiation so that they can be used as temperature or stress sensors in radiation environments such as nuclear power plants or space. In [2] it was mentioned for the first time that certain FBGs might also be used for radiation dose sensing. In [12] it was shown that radiation dose measurement with FBGs is actually possible, and in [13] it was investigated how the radiation sensitivity of FBGs can be optimized by selecting suitable fibers and manufacturing parameters. The most sensitive FBG type found in [13] was then used for coarse radiation dose measurements at an electron linear accelerator of DESY Hamburg [14]. With such sensors radiation dose values only above about several 100 Gy – 1000 Gy can be roughly determined, i.e., they are quite insensitive. In [7] it was assumed that the relatively high radiation insensitivity of FBGs written in Ge-doped fibers with UV lasers is due to the effect that the UV light already eliminates the precursors of radiation-induced color centers. In [15] we have shown that FBGs written with femtosecond IR lasers in the same Ge-doped fibers show about the same insensitivity against ionizing radiation as FBGs written with UV lasers, i.e., the high IR laser energy seems to cause about the same passivation of the fiber material as the UV light.

In order to obtain fiber gratings with distinctly higher radiation sensitivity that might be used for more sensitive radiation detection, we decided to examine gratings that are produced without changing the refractive index of the fiber material. This is possible with some long period grating (LPG) types as shown in [17]. However, we identified another type, so-called chiral gratings produced by Chiral Photonics Inc., USA. Here a periodic modulation of the optical properties of the fiber is achieved by twisting the fiber as it passes through a miniature oven. The period greatly exceeds the optical wavelength so that core and cladding modes can be coupled to produce several narrow dips in the transmission spectrum [18]–[20]. In order to investigate the influence of the radiation-induced attenuation (RIA) of the fibers on a possibly observable radiation-induced dip wavelength shift (DWS) we selected five of the fibers already used for [13] and [15] and three new fibers with high RIA.

There exist only very few publications about irradiation tests of LPGs. The authors of [7] found no clear spectral shift with LPGs written by UV or CO lasers in Ge and in N doped fibers after dose values up to about 70 kGy. In [21] and [22], no radiation-induced spectral changes up to a dose of 0.5 MGy were found in LPGs written by the arc discharge technique in pure silica core fibers. Chaubey et al. [23] investigated LPGs written by a CO laser in a Corning SMF-28 fiber. No effect on the transmission spectrum was observed after a gamma dose of 5 kGy.

II. EXPERIMENTAL

A. Selected Fibers for Grating Fabrication

We selected eight single mode (SM) fibers with distinctly different radiation hardness, i.e., different RIA, for grating fabrication. Table I gives an overview of manufacturers, dimensions, and core and cladding dopant concentrations. The first four fibers were already used for [13] and [15]. Fiber no. 5 was only used for [15], whereas fibers 6–8 are used for the first time. The core of fiber Nufern 1 is highly doped with P, whereas the cores of the Nufern fibers 2 and 3 are doped among others with Rare Earth elements. The cladding of Nufern 2 is undoped, whereas those of Nufern 1 and 3 are doped, e.g., also with P. They are experimental sensor fibers and were chosen for their high RIA. Some manufacturers provided us with the
TABLE I
SINGLE MODE FIBERS FOR THE FABRICATION OF CHIRAL GRATINGS

<table>
<thead>
<tr>
<th>No.</th>
<th>Manufacturer</th>
<th>Designation</th>
<th>Core Diameter [μm]</th>
<th>Core Dopants [mol %]</th>
<th>Cladding Dopants [mol %]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Manufacturer</td>
<td>Calculated</td>
</tr>
<tr>
<td>1</td>
<td>ALCATEL</td>
<td>6901 MSO 1003623</td>
<td>8.8</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Corning</td>
<td>SMF28-e</td>
<td>8.2</td>
<td>—</td>
<td>GeO₂ (4.7)</td>
</tr>
<tr>
<td>3</td>
<td>FiberLogix</td>
<td>FL-HNA-01</td>
<td>2006</td>
<td>—</td>
<td>GeO₂ (10.5)</td>
</tr>
<tr>
<td>4</td>
<td>FORC</td>
<td>No. 141-2</td>
<td>2003</td>
<td>4.9</td>
<td>Al₂O₃ (7.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P₂O₅ (1.0)</td>
</tr>
<tr>
<td>5</td>
<td>Fujikura</td>
<td>RR-C</td>
<td>2007</td>
<td>8.7</td>
<td>F (0.8 wt%)</td>
</tr>
<tr>
<td>6</td>
<td>Nufern</td>
<td>Nufern 1</td>
<td>2008</td>
<td>7.5</td>
<td>confidential</td>
</tr>
<tr>
<td>7</td>
<td>Nufern</td>
<td>Nufern 2</td>
<td>2008</td>
<td>5.25</td>
<td>confidential</td>
</tr>
<tr>
<td>8</td>
<td>Nufern</td>
<td>Nufern 3</td>
<td>2008</td>
<td>4.5</td>
<td>confidential</td>
</tr>
</tbody>
</table>

dopants as well as their concentration. From fibers that were known to be only or predominantly doped with Ge, we calculated the Ge-content from the known numerical aperture (NA) under the assumption that the cladding material was not doped.

To improve our knowledge about the composition of some of the fibers, the Fraunhofer-IST in Braunschweig, Germany provided 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 at% (no. 4) or wt% (no. 5) since the manufacturers argue that they are not sure about the placement of F within the SiO₂ grid. The cladding diameter of all fibers is 125 μm, apart from fiber 6 with a diameter of 150 μm. That larger diameter could be the reason for difficulties with the chiral grating fabrication and therefore resulting instabilities of the produced gratings. The results of our RIA measurements with all fibers are given in Section III.B.

B. Chiral Long Period Gratings (CLPGs)

All CLPGs were made by Chiral Photonics Inc., Pine Brook, NJ USA in un-coated fiber pieces of about 4 cm length. In order to match the ordered dip position of about 1550 nm and a depth of about 10 dB, the grating parameters had to be chosen as listed in Table II. It is assumed that either the second, third or fourth cladding mode is coupled with the core mode. Corning SMF-28 fiber pieces with lengths of approximately 50 cm are spliced to both ends of the 4 cm long sensor fiber. We ordered two gratings each of fibers 2–8 and four gratings of fiber 1, two of which were recoated. The grating periods show a substantial variation. According to the CLPG’s manufacturer this was necessary because the fibers were non-standard, specialty fibers in which the propagation constant difference between coupled core and cladding modes could vary significantly. Furthermore they suspect that some fibers were spun in the drawing process which may result in large additional uncertainty in the necessary amount of twisting.

The dip wavelength \( \lambda_D \) of the CLPGs is given by the relation [24]

\[
\lambda_D = \frac{(n_{\text{core,eff}} - n_{\text{clad,eff}})\Lambda}{N}
\]

where \( n_{\text{core,eff}} \) and \( n_{\text{clad,eff}} \) are the effective refractive indices of core and cladding, respectively, \( \Lambda \) indicates the order of the respective cladding mode, and \( N \) is the grating period. The denominator \( N \) is an integer that can be \( >1 \) (i.e., \( 2, 3, \ldots \)) and gives the order of refraction. This factor is not considered in most LPG publications, e.g., [17], [23]. So far we are not able to calculate the dip wavelength from \( \Lambda \) and the refractive index difference because \( N \), as well as \( n_{\text{clad,eff}} \), are not known at present, but extensive evaluations of all relevant grating parameters are in progress, e.g., [25].

TABLE II
PROPERTIES OF THE CHIRAL GRATINGS

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Coating</th>
<th>Period [μm]</th>
<th>Diameter [μm]</th>
<th>Length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALCATEL</td>
<td>No</td>
<td>844</td>
<td>114</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>844</td>
<td>114</td>
<td>20</td>
</tr>
<tr>
<td>Corning</td>
<td>No</td>
<td>1565</td>
<td>102</td>
<td>30</td>
</tr>
<tr>
<td>FiberLogix</td>
<td>No</td>
<td>1555</td>
<td>101</td>
<td>24</td>
</tr>
<tr>
<td>FORC</td>
<td>No</td>
<td>600</td>
<td>105</td>
<td>10</td>
</tr>
<tr>
<td>Fujikura</td>
<td>No</td>
<td>1000</td>
<td>105</td>
<td>20</td>
</tr>
<tr>
<td>Nufern 1</td>
<td>No</td>
<td>3000</td>
<td>67</td>
<td>25</td>
</tr>
<tr>
<td>Nufern 2</td>
<td>No</td>
<td>1195/2050¹</td>
<td>119</td>
<td>26</td>
</tr>
<tr>
<td>Nufern 3</td>
<td>No</td>
<td>589</td>
<td>103</td>
<td>14</td>
</tr>
</tbody>
</table>

¹: only the two gratings made of that fiber had a different period.
C. Measurement Procedure

The irradiation tests of the CLPGs were made with the experimental arrangement shown in Fig. 1. By splicing a fiber mirror to one CLPG end we could measure the dip wavelength in reflection with our FBG interrogator FOS&S FBG-Scan 608. The device has eight channels, a wavelength repeatability <1 pm and a resolution of 1 pm. Usually we irradiate up to four gratings at the same time. A fifth grating (usually FBG) is 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 so that we could adjust our peak detection software to the corresponding spectrum shape: we fitted short straight lines to both flanks in a height that depended on the peak shape, mostly above the shoulders, preferably 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 (see [16]). To increase the stability of the grating spectra, each CLPG was inserted into a thin quartz capillary. The CLPG leads were not fixed to the capillary ends so that they remained stress-free during the measurements. The capillaries were closely mounted 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). Placing all sensors (CLPGs as well as Pt-100) on an aluminum plate guarantees that they show the same temperature changes during and after irradiation. The gratings leads were shielded with lead (Pb). One grating each of all fibers was irradiated with a dose rate of 0.87 Gy/s up to a dose of 100 kGy. The second grating of fibers 1, 4, 6, 7, and 8 was also irradiated with a dose rate of only 0.1 Gy/s up to a dose of 20 kGy in order to examine whether the radiation-induced DWS is independent of the dose rate, i.e., on the time necessary to reach respective dose values. This is a precondition for the suitability as a sensor for radiation dosimetry. Throughout this paper Gy always means Gy(SiO2). For measuring the temperature sensitivity of the CLPGs, the aluminum plate was placed in a climate chamber.

The RIA measurements were made as described in [26].

III. Results

A. Temperature Sensitivity of the CLPGs

As usual with FBGs, we first determined the temperature coefficient of the gratings to be able to compensate for the slight temperature increase of 0.6–1.0°C during irradiation with the higher dose rate. This was necessary since typical FBGs with a temperature coefficient of about 10.4 pm/°C [13] often show a radiation-induced wavelength shift of only 15–25 pm.

The sensitivity obtained for our CLPGs is shown in Table III. These values did not change after irradiation up to 100 kGy. They are in agreement with the values given for LPGs (30 pm/°C–100 pm/°C) in [17]. Both gratings made of fiber 6 were quite unstable so that a reliable measurement of the temperature coefficient was not possible.

B. Radiation-Induced Attenuation of the Fibers

Since the fiber material of our CLPGs remained unchanged, i.e., was not passivated by irradiation with high UV or femtosecond IR laser light intensities, we expected to observe some correlation between the RIA of the fibers and the radiation-induced DWS of the gratings made of these fibers. The RIA measurements were made at 1550 nm and with about the same dose rate (about 1 Gy/s) that was applied for our grating irradiations (about 0.9 Gy/s), apart from the Fujikura fiber. Here irradiation was performed with a dose rate of only 0.2 Gy/s up to a dose of only 10 kGy. However, irradiation of that fiber with 1 Gy/s would lead to only slightly higher RIA values.

Figs. 2(a), (b) show the attenuation increase during irradiation 2(a) as well as the relative annealing after the end of irradiation 2(b).

The RIA of the radiation hardest fibers (nos. 2, 3, 5) and of the most sensitive ones (nos. 4, 6, 7, 8) differs by more than a factor of 100. Fibers that show an enormously higher attenuation at 1550 nm also show a higher RIA down to the UV. Therefore according to the Kramers-Kronig relation [27] the radiation-induced refractive index increase should be distinctly higher for the fibers with an extremely high RIA. According to (1) it could be expected that CLPGs made of these fibers will show a higher DWS. But it should be kept in mind that a radiation-induced...
DWS of CLPGs can also be caused by radiation-induced compaction that would lead to a change of the grating period (see (1)) and is accompanied by an increase of the refractive index.

C. Radiation-Induced Dip Wavelength Shift

The results of the measurements with high dose rate up to the dose 100 kGy are shown in Figs. 3(a), (b). The left side 3(a) shows the DWS during irradiation. On the right side we see the relative annealing, i.e., the shift after the end of irradiation divided by the shift value at the end of irradiation. These DWSs are about a factor of 100–1000 higher than the Bragg wavelength shifts (BWSs) observed with different FBG types so that correction for the small temperature increase during irradiation could be omitted for all gratings, apart from that made of the Fujikura fiber (no. 5). CLPGs made of the fibers with low RIA (nos. 2, 3, and 5) actually show a lower DWS, but the DWS differences are much smaller than the RIA differences, apart from the CLPG made of the Fujikura fiber with a DWS of only about 40 pm. The low DWS of the grating made of the fiber Nufern 1 can not be explained so far. The reason might be a different cladding mode order (i) or a different order of refraction (N). The annealing curve of the Fujikura fiber grating is quite noisy since the DWS is about a factor of 100 lower than that of the other gratings so that the signal-to-noise ratio is very low. Despite the fact that the DWS values do not show exactly the same order as the RIA values, it could be interesting to compare the DWS with the RIA curve of the fiber from which the respective CLPG is made. In Fig. 4 we show that comparison for the two low RIA fibers 2 and 3 and in Fig. 5 that for the three high RIA fibers 4, 7, and 8. With the low RIA fibers the DWS shows distinct saturation already after a dose of about 10 kGy, whereas the RIA curves only show a bend at about 10 kGy but still increase at least up to 100 kGy. An opposite behavior is observed with the high RIA fibers. Here the RIA values show distinct saturation above about 20 kGy whereas the DWS curves only show a bend at about the same dose value but still increase up to at least 100 kGy. The curves for the ALCATEL and Nufern 1 fibers show a different behavior (Fig. 6). With both fibers the RIA and
DWS curves show a bend at about 10 kGy, but then RIA as well as DWS curve saturate with the ALCATEL fiber whereas both curves show a steady increase up to 100 kGy with the Nufern 1 fiber. With both fibers the DWS curves anneal faster than the RIA curves, whereas with fibers 2, 3, 4, and 8 the RIA curves anneal faster. Only with fiber 7 are the RIA and DWS annealing curves identical. So RIA and DWS show similarities as well as differences. This is not surprising since RIA of most of the SM fibers depends primarily on the fiber core material whereas the DWS according to (1) depends on radiation-induced changes of both the core material ($\Delta n_{c(c)}$) and the cladding material ($\Delta n_{c(f)}$). Furthermore possible effects of a radiation-induced compaction need not be correlated with the RIA of the respective fibers.

CLPGs can be used to sense their environment since the dip position is sensitive to the refractive index of the surrounding medium [18], [19]. This sensitivity can be reduced or even avoided by recoating the sensor fiber. As outlined in Section II.B., we therefore also studied two gratings made of fiber 1 that were recoated to see whether these gratings would show different radiation sensitivities. Both grating types showed the same radiation-induced DWS and exactly the same annealing behavior for irradiation with 0.9 Gy/s as well as with 0.1 Gy/s.

The high radiation sensitivity of the CLPGs suggests their use as radiation sensors. The results obtained from the irradiation with low dose rate (0.1 Gy/s) up to 20 kGy (Fig. 7) show that such sensors can detect radiation doses at least down to 10 Gy. The detection limit seems to be even lower and should be determined by irradiations with still lower dose rate. The step in the Nufern 1 curve might be due to the instability of CLPGs made of that fiber already mentioned (Sections II.A. and III.A.). Despite their suitability for the detection of very low radiation levels, such sensors cannot be used as yet for accurate measurements of the radiation dose. The reason for this is that the accumulated DWS anneals relatively rapidly after the end of irradiation, by about 15% after 10 hours. As a consequence the DWS measured after a certain dose depends on the dose rate, i.e., on the time to reach that dose. So the DWS measured with the dose rate of 0.87 Gy/s (Fig. 3(a)) is about 10–20% higher than that measured with the dose rate 0.1 Gy/s (Fig. 7). This fact is illustrated
in a Corning SMF-28 fiber was irradiated up to a gamma dose of 5 kGy. The authors did not find “any effect on the transmission spectrum”, whereas our CLPG made of a Corning SMF-28 fiber showed a DWS of nearly 3 nm at that dose. We do not know whether irradiation by a CO laser could also reduce the fiber sensitivity to ionizing radiation.

Question 2 is relatively easy to answer. The Bragg wavelength $\lambda_B$ of FBGs is given by the relation

$$\lambda_B = 2n_{Co} \Lambda_B,$$

with $\Lambda_B = \text{period of the Bragg grating}$. The radiation dose dependence of $\lambda_D$ and $\lambda_B$ can be obtained by taking the partial derivative of (1) and (2) with respect to the dose $D$:

$$\frac{\partial \lambda_D}{\partial D} = \frac{1}{N} \left[ \left( \frac{\partial n_{Co,eff}}{\partial D} - \frac{\partial n_{Cl,eff}}{\partial D} \right) \Lambda + \left( n_{Co,eff} - n_{Cl,eff} \right) \frac{\partial \Lambda}{\partial D} \right] \Lambda,$$

$$\frac{\partial \lambda_B}{\partial D} = 2 \left( \frac{\partial n_{Co}}{\partial D} \Lambda_B + n_{Co} \frac{\partial \Lambda_B}{\partial D} \right).$$

Multiplication of (3) and (4) with $\partial D/\partial \lambda_D$ or $\partial D/\partial \lambda_B$, respectively, leads to the equations

$$\frac{\partial \lambda_D}{\lambda_D} = \frac{\partial n_{Co,eff}}{n_{Co,eff}} - \frac{\partial n_{Cl,eff}}{n_{Cl,eff}} + \frac{\partial \Lambda}{\Lambda},$$

$$\frac{\partial \lambda_B}{\lambda_B} = \frac{\partial n_{Co}}{n_{Co}} + \frac{\partial \Lambda_B}{\Lambda_B}.$$

So the wavelength shifts $\Delta \lambda_D$ and $\Delta \lambda_B$ after a certain radiation dose $D$ can be estimated by the equations

$$\Delta \lambda_D = \lambda_D \left( \frac{\partial n_{Co,eff}}{n_{Co,eff}} - \frac{\partial n_{Cl,eff}}{n_{Cl,eff}} + \frac{\partial \Lambda}{\Lambda} \right),$$

$$\Delta \lambda_B = \lambda_B \left( \frac{\partial n_{Co}}{n_{Co}} + \frac{\partial \Lambda_B}{\Lambda_B} \right).$$

In both equations the relative length change $\Delta \Lambda/\Lambda$ after a dose of about 100 kGy is of the order $10^{-7}$ [28] and can be neglected [29]. For estimating the respective wavelength shifts one can make the following assumptions. $n_{Co}$ is about 1.47. The refractive index $n_{Cl}$ can be estimated from the well known equation

$$(NA)^2 = n_{Cl}^2 - n_{Co}^2.$$

NA is the numerical aperture of the fiber. With a typical value of NA of about 0.15 one gets $n_{Cl} = 1.462$ and $n_{Co} - n_{Cl} = 0.008$. From measurements with Bragg gratings one got for dose values of the order of 100 kGy a refractive index increase $\Delta n_{Co}$ at 1550 nm of about $5 \cdot 10^{-4}$ [12]. With these values one gets from (8) a change $\Delta \lambda_B$ of about 50 pm. Assuming that because of the lower dopant concentration in the cladding material $\Delta n_{Co}$ is only about 1/3 of $\Delta n_{Cl}$, one gets from (7) a change $\Delta \lambda_D$.

**IV. DISCUSSION**

Our discovery of extremely high radiation-induced DWS values of CLPGs raises at least three questions:

1. Why did previous irradiation tests of LPGs [7], [21]–[23] show no distinct DWS?
2. Why are the DWSs of CLPGs about 100–1000 times higher than the BWSs observed with FBGs?
3. Why does the radiation-induced DWS of the CLPGs not show the same order as the RIA of the fibers they are made of, or why are the observed DWS differences small compared with the huge RIA differences?

Question 1 can be answered by the following comments. The fibers of [21] and [22] were pure silica core fibers that usually show a very low RIA. With another low RIA fiber (our fiber no. 5) we also observed only very small DWS values. The authors also report that the arrangement of their LPGs at the irradiation facility did not enable them to perform precise DWS measurements. One LPG of [7] was written with a UV laser in a Ge-doped fiber. The authors argue that the UV light might have passivated their gratings against ionizing radiation. Another LPG was written with a CO laser in a N-doped fiber. For a dose of 9.3 kGy they report a DWS of +0.15 nm, but with an error of 0.3 nm, i.e., the resolution of their measurements seemed to be relatively poor. In [23] a LPG written by a CO laser
of 6.4 nm. This value is in good agreement with our measured values, despite the fact that we could not use the unknown values \( n_{C1}\text{eff}^{3}\) and \( \Delta n_{C1}\text{eff}^{3}\), and especially that we used a value for \( \Delta n_{C0}^{3}\) that was determined with FBGs written by an UV laser and not a perhaps distinctly higher refractive index increase in a material that was not exposed to UV light before gamma radiation.

For the third question exist a variety of answers. The RIA of most of the SM fibers is primarily caused by an attenuation increase of the core material that leads, according to the Kramers-Kronig-Relation, to an increase of its refractive index. However, the DWS (i.e., \( \Delta \lambda_{B1}^{3}\)) is not only proportional to the refractive index increase of the core material but (see (7)) proportional to the difference of the refractive index increases of core and cladding. Both materials are doped with one or even more elements, sometimes with varying depth distribution. So a CLPG can show a relatively small DWS despite a high \( \Delta n_{C0}^{3}\) when also the cladding material shows a high refractive index increase. The situation is complicated by the fact that one has to know the order of refraction (N) and the effective index increase of the \( i^{th}\) cladding mode, and that nearly nothing is known about the influence of the different doping elements and their concentration on the radiation-induced index increase. Furthermore one also has to consider the radiation-induced compaction. The compaction leads to a decrease of the grating period and is accompanied by a refractive index increase. The decrease in length can be neglected, as mentioned above. So far nothing is known about the relation between the increase in RIA and compaction, e.g., that fibers with a high RIA show a stronger compaction, or whether the compaction contributions to the refractive index increase of core and cladding material are different or not. However, that RIA and DWS curves show a bend at about the same dose seems to indicate that the RIA-induced part of the refractive index increase dominates since it is unlikely that a compaction-induced effect shows a bend at the same dose as the RIA curves.

V. CONCLUSION

It was our aim to find a fiber optic radiation sensor of high sensitivity, and with as great a measurement range as possible. The sensitivity (lower detection limit) of nearly all investigated CLPGs is acceptable and could perhaps further be improved by selecting core and cladding materials with greater difference of their refractive index increase. The order of refraction should be low, e.g., \( N = 1\), if possible (see (1)). A core material with saturation only at high dose levels has to be selected in order to extend the upper detection limit. To make the sensor suitable for dosimetry, the DWS should anneal as slowly as possible. According to (7) that would be enabled by a slow annealing of \( \Delta n_{C0}^{3}\) and a faster annealing of \( \Delta n_{C1}^{3}\). So far, one only knows the influence of some doping elements on magnitude and annealing behavior of the fiber RIA. However, for sensor applications, it would be necessary to know the radiation-induced increase in refractive index of SiO2 doped with a variety of frequently used elements in differing concentration. But for designing an optimal fiber one also has to wait for a better understanding of the properties and behavior of CLPGs, e.g., to determine \( n_{C1}\text{eff}^{3}\).

After a dose of 100 kGy we found radiation-induced changes of their transmission dip wavelength (DWS) of up to 10 nm, i.e., about 100 to 1000 times higher than the Bragg wavelength shift of different FBG types. Therefore CLPGs can e.g., be used for radiation sensing down to dose values of 10 Gy or even below. With some CLPGs the DWS increased up to our final dose of 100 kGy, whereas those made of the low RIA fibers showed a distinct DWS saturation already about above 10 kGy. Measurements with a dose rate that is about 10 times lower have shown that the observed DWS still depends on the dose rate so that accurate radiation dose measurements are not possible with these CLPGs so far.

The high DWS values of CLPGs compared to the BWS of FBGs can mainly be explained by the fact that the DWS is proportional to the large factor \( 1/(\Delta n_{C0}^{3} - \Delta n_{C1}^{3})\) instead of to the small factor \( 1/\Delta n_{C0}^{3}\), i.e., it is not necessary to assume a distinctly higher radiation-induced increase in refractive index of a fiber material that was not exposed to high UV light levels.

Of one of the fibers we also got recoated gratings, but recoating had no influence on their radiation sensitivity.

To look for a correlation between DWS of the gratings and the radiation-induced attenuation (RIA) of the fibers they were made of, CLPGs of eight single mode fibers with low, medium and very high RIA were fabricated. RIA as well as DWS curves during and after the end of irradiation (=annealing) are shown for all fibers. There seems to exist no clear correlation between RIA and DWS, and fibers with RIA values (in dB/m) that differ by more than a factor of 100 show differences of their grating DWS of only about a factor of two or three. But a true comparison is not possible since we do not know so far all necessary data of our CLPGs, like e.g., order of diffraction and cladding mode order. The manufacturer is still working on that problem. After a complete understanding of all grating properties it might be possible to design an optimized fiber for CLPGs with an enlarged measuring range as well as a dose rate independent (i.e., non-annealing) DWS so that they can be even used for radiation dosimetry. But because of their broad transmission dip, wavelength multiplexing of a higher number of CLPGs would not be possible, in contrast with FBGs with their narrow Bragg peak.

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REFERENCES


