Performance of Bragg and Long-Period Gratings Written in N- and Ge-Doped Silica Fibers under γ-Radiation

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Abstract

In-fiber Bragg and long-period gratings as well as Mach-Zehnder interferometers based on germanium- and nitrogen-doped silica fibers have been investigated under γ-rays. The majority of the experimental results suggest that both types of gratings in both types of fibers are stable with respect to γ-ray doses of up to 1.47 MGy.

I. INTRODUCTION

Photoinduced in-fiber Bragg and long-period cladding-mode-coupled gratings are good candidates for sensor applications in the nuclear industry and other radiation environments. Sensors of structural integrity, temperature, vibration, deformation, etc. can be easily realized using gratings to allow remote and distributed monitoring of structures and components within nuclear power plants [1 - 4]. In many cases, the gratings will have to operate under ionizing radiation. A detailed review of the specific potential applications of grating-based sensors in the nuclear industry was given in [1].

Investigation of radiation resistance of Bragg gratings written in germanium-doped silica fibers was started in [1, 5], where it was shown that the gratings retained their spectral properties after γ-irradiation up to 412 kGy. However, radiation induced color centers in Ge-doped fibers result in significant optical absorption in the near IR region [6], which calls into question the feasibility of sensors based on germanosilicate fibers.

The latest advance in the field of photosensitivity of silica-based fibers was the inscription of thermostable UV-induced Bragg [7] and thermo-induced long-period [8] gratings in novel nitrogen-doped silica fibers. The fibers themselves have excellent radiation-resistance (the induced absorption at 1.55 μm is as small as 0.003 dB/m after γ-irradiation to 10 kGy) [9]. Bragg gratings written in N-doped fibers with 193-nm light have refractive index modulation amplitudes up to 7×10^{-4} and remain stable during isochronal annealing to 700 - 800 °C [7]. Thermo-induced long-period gratings demonstrated even higher thermostability (900 - 1000 °C) [8]. Therefore, sensors based on gratings written in N-doped fibers hold much promise for nuclear applications, particularly at elevated temperatures.

The purpose of this work is to compare the effect of γ-irradiation on the spectral properties of gratings written in Ge- and N-doped silica fibers.

II. RESULTS AND DISCUSSION

Bragg gratings (Gr1 - Gr4) were photoimprinted in two N-doped fibers with different doping levels fabricated by the SPCVD technique [10]. The core-cladding index difference and the cut-off wavelength were $\Delta n = 0.015$, $\lambda_c = 0.94$ μm (fiber A) and $\Delta n = 0.042$, $\lambda_c = 0.88$ μm (fiber B), respectively. The gratings were written with an ArF-excimer laser using a phase mask with the irradiation parameters given in [7]. The grating parameters are given in table 1. Because N-doped fibers exhibit two types of photosensitivity (Type I and Type IIa), we prepared both grating types with approximately equal reflection coefficients to compare their radiation resistance. Gratings Gr1 and Gr3 were Type I, whereas Gr2 and Gr4 were Type IIa. The grating lengths were 3 mm and their spectral width ~ 0.3 nm. In addition, two Bragg gratings (Gr5, Gr6) with similar parameters were written in a Ge-doped fiber C ($\Delta n = 0.03$, $\lambda_c = 1.06$ μm) using a CW frequency doubled Ar^+-laser ($\lambda = 244$ nm).

We also tested a thermo-induced long-period grating written in an N-doped fiber by CO-laser radiation [8] (fiber A, grating period $\Lambda = 250$ μm, length L = 25 mm) and a UV-induced long-period grating written in a Ge-doped fiber ($\Delta n = 0.018$, $\lambda_c = 1.04$ μm, $\Lambda = 150$ μm, L = 25 mm). In addition, Mach-Zehnder interferometers [11] with a 30-mm sensitive

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part based on such long-period gratings were prepared and tested. As was previously shown, long-period gratings [12] and interferometers [11] allow very small changes in refractive index (~10^{-6}) to be measured.

The gratings were subjected to four successive γ-ray exposures using a ^{60}Co source at dose rates of 6.6 Gy/s (first three exposures) and 5.4 Gy/s (fourth exposure), the irradiation temperature being ~ 40 °C. The dose increments were 9.3, 17.8, 71.3, and 1370 kGy. Thus, the cumulative total dose after four exposures reached ~ 1.47 MGy. The transmission spectra of the Bragg gratings were recorded with a spectral resolution of ~ 0.1 nm within a few hours after finishing the irradiations. The reflection coefficients of all the gratings remained unchanged to an accuracy of about 5%. The Bragg wavelengths of the gratings written in N-doped fibers experienced a shift of 0.1 - 0.2 nm after the first irradiation (table 2) and underwent no further changes after the subsequent exposures (up to a total dose of 1.47 MGy). The Bragg wavelength shift after the first irradiation exceeded the experimental random error, which was about 0.05 nm. This shift was the strongest for the gratings written in fiber A and amounted to ~ 0.18 nm, which corresponds to an increase of the core refractive index of ~ 3×10^{-4}. Reference gratings written in the germanosilicate fiber were stable with respect to irradiation after the three first exposures in accordance with the earlier observations [1, 5]. This means that the refractive index remains unchanged to an accuracy of ~ 10^{-4}.

Table 1
Initial parameters of the Bragg gratings

Grating	Fiber	Grating type	Bragg wavelength, nm	Reflectivity, %
Gr1	A	Type I	1510.57	53.8
Gr2	A	Type Iia	1510.89	65.0
Gr3	B	Type I	1511.95	53.4
Gr4	B	Type Iia	1512.11	57.8
Gr5	C	Type I	1520.42	40.5
Gr6	C	Type Iia	1515.23	31.2

Table 2
Changes in the parameters of Bragg gratings after each γ-ray exposure with respect to the values obtained before the irradiation step

Dose, kGy	Change of reflection coefficient, % (first line in the cell); Bragg wavelength shift, nm (second line)					
	Gr1	Gr2	Gr3	Gr4	Gr5	Gr6
9.3	+0.5 +0.18	-1.0 +0.18	-1.0 +0.13	+1.0 +0.1	+0.5 +0.02	-1.5 +0.03
17.8	-2.5 +0.05	0.0 +0.02	-2.5 -0.01	-2.5 +0.01	-1.5 -0.04	+1.0 -0.05
71.3	+2.0 -0.03	-0.5 0.00	+0.5 +0.03	+1.0 -0.01	+2.5 -0.02	+2.5 +0.01
1370	-2.0 -0.02	-1.5 -0.06	+0.5 -0.03	+2.5 -0.04	Not measured	Not measured

Table 3
Changes in the parameters of long-period gratings and interferometers after each γ-ray exposure with respect to the values obtained before the irradiation step

Dose, kGy	Long-period grating in Ge-doped fiber (HE_{11}-HE_{19}, λ =1552 nm) Δλ, nm	Interferometer in Ge-doped fiber (λ =1560 nm) phase shift, rad	Long-period grating in N-doped fiber (HE_{11}-HE_{16}, λ = 1543 nm) Δλ, nm	Interferometer in N-doped fiber (λ =1610 nm) phase shift, rad
0.2	Not measured	Not measured	Not measured	+0.1
1.1	Not measured	Not measured	Not measured	-0.15
9.3	+0.35	+1.40	+0.15	Not measured
17.8	-0.25	+0.30	Not measured	Not measured
71.3	-0.35	+0.55	Not measured	Not measured

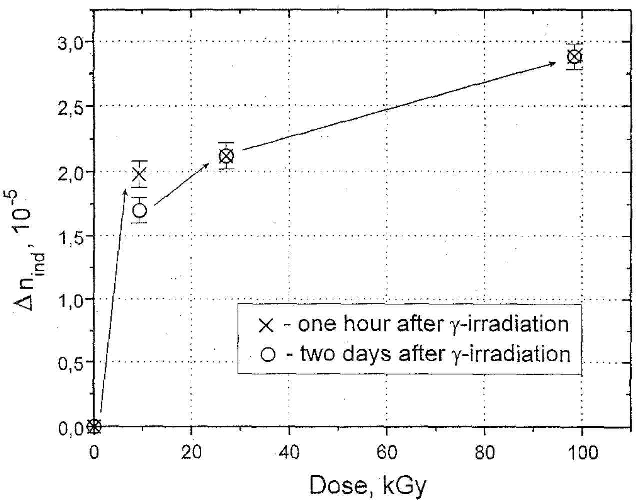

Figure 1: Refractive index change induced in the core of a Ge-doped fiber by γ-radiation.

After the fourth irradiation, the induced absorption did not allow us to measure the grating parameters in the Ge-doped fibers (table 2), while there was no significant reduction in transparency in the N-doped silica fibers, even after the fourth exposure. The interferometer and long-period grating based on an N-doped fiber did not show any changes in the parameters after γ-irradiations (table 3) to within experimental error. The error was ± 0.3 nm in measuring the resonant wavelength of the long-period grating and ± 0.15 rad in measuring the phase shift of the interferometer. Thus, the induced refractive index did not exceed 2×10^{-6}, which calls into question the result obtained on the Bragg gratings after the first irradiation. The long-period grating written in a Ge-doped fiber did not reveal any radiation induced changes either. However, there were significant phase shifts in the Mach-Zehnder interferometer based on this Ge-doped fiber. The first irradiation (9.3 kGy) increased the refractive index in the fiber core by 2.0×10^{-5}. In two days after the irradiation this value went down to 1.7×10^{-5}, which is probably associated with thermal decay of radiation induced color centers (fig.1). The subsequent irradiations up to a total dose of 100 kGy increased the induced refractive index only slightly (up to 2.8×10^{-5}). This phenomenon is believed to be due to certain radiation-induced absorption bands in the UV region which affect the refractive index via Kramers-Kronig relations [13, 14].

The apparent stability of gratings written in Ge-doped fibers with respect to γ-radiation is probably due to the effect of UV-radiation, which eliminates the precursors of γ-radiation-induced color centers in the process of grating writing, even in the dark regions of the interference pattern. The UV-dose in the bright regions necessary to write a grating is usualy several kJ/cm^2, whereas several J/cm^2 UV-irradiation induces the same value of absorption as 10 kGy of γ-irradiation [6]. Naturally, during grating writing there is some background (1 - 10 %) owing to the incoherent part of the UV-light or scattered light. It is this background that eliminates the color center precursors to harden the grating against γ-radiation.

III. Conclusions

In conclusion, we have investigated the γ-radiation stability of the spectral parameters of Bragg and long-period gratings written in germanium- and nitrogen-doped silica fibers. Long-period gratings written in both types of fibers as well as Bragg gratings written in Ge-doped fibers exhibited high resistance to γ-radiation. In this connection, the shift of the Bragg wavelengths of the N-doped fiber gratings after irradiation to ~ 10 kGy cannot be reconciled with the other observations, including stability of the N-doped fiber interferometer. We are inclined to believe that it might be an experimental error, and investigations are underway to clarify this inconsistency. If this is the case, Bragg and long-period gratings written in radiation-resistant N-doped silica fibers can find wide use in nuclear environments.

Interesting data was obtained on the Mach-Zehnder interferometer. The refractive index of Ge-doped silica increased as the result of γ-irradiation, while the grating parameters remained unchanged. Apparently, the UV radiation indirectly promotes grating stability by eliminating the precursors of γ-radiation induced color centers.

IV. Acknowledgments

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