Radiation-induced spectral changes in femtosecond point-by-point written FBGs in metal and polyimide-coated fibers


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Study of radiation-induced spectral changes of femtosecond laser written FBG in metal and polyimide coated fiber

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ABSTRACT

The influence of β-radiation exposure (the total dose up to 41.1 MGy and dose rate of 2.5 kGy/s) on the spectral characteristics of high and low reflective FBGs inscribed using femtosecond laser radiation in Ge-doped and pure-silica core fibers with polyimide and metal coating is presented. The largest Bragg wavelength induced shift (BWS) of +55 pm is observed in the case of weak reflective FBG (type I) inscribed in Ge-doped fiber. A comparable red shift in wavelength of +50 pm is observed in the case of high reflective FBG (type II), which is explained by an increase in the concentration of GeE^0-centers and, accordingly, an increase in the effective refractive index. Moreover, a significantly smaller BWS of -10 pm was obtained in the case of high reflective FBGs inscribed in pure-silica core fibers.

Keywords: Fiber Bragg gratings, radiation-induced wavelength shift, radiation induced losses.

1. INTRODUCTION

Fiber Bragg gratings (FBG) are widely used in optical sensing including harsh applications: high temperatures, hydrogen atmosphere, and ionizing radiation. The use of FBG sensors based on germanium doped fibers in environments with increased radiation background leads to the radiation-induced absorption (RIA) of light and radiation induced Bragg wavelength shift (BWS) that prevent long-term operation of FBG sensors and influence on measurements accuracy. These effects can be minimized when specialized radiation-resistant fibers are used, such as pure-silica core and fluoride fibers. However, these types of fibers are non-photosensitive for conventional UV radiation sources widely used for FBG writing. Thus, the FBG writing technology based on femtosecond laser radiation is promising in this case.

Despite the fact that the effects of gamma radiation [1], as well as fast neutrons arising during the operation of nuclear reactors [2], on FBGs have been studied in detail, there is no data on beta radiation (high-energy electrons with energy ~ 1 MeV) impact on optical fibers and FBGs inscribed inside them.

In this study, we investigate the influence of beta radiation exposure (the total dose up to 30.9 MGy for polyimide coated and 41.1 MGy for metal-coated fiber, dose rate of 2.5 kGy/s) on the spectral characteristics of FBGs (reflectivity, optical loss, Bragg wavelength shift) inscribed using femtosecond laser radiation in metal-coated (from Fiber Optics Research Center) and polyimide-coated (from Fibercore LTD) pure-silica core and Ge-doped optical fibers. The influence of thermal treatment (up to 300 °C in case of polyimide, up to 450 °C for Al-coated and Cu-coated fibers) before beta radiation exposure on FBG spectral characteristics is investigated.

A Bragg wavelength shift of about 50-55 pm is observed in both cases of type I and type II FBG inscribed in Ge-doped polyimide coated fiber at the total dose of 30.9 MGy. The high reflective FBG inscribed in a pure-silica core fibers have the minimum values of the displacements of resonance wavelengths of about -10 pm. The smallest change in...
transmission (0.15 dB) is observed for the pure-silica core fibers that opens the possibility for creating long-term radiation resistant fiber-optic sensors.

2. RESULTS AND DISCUSSION

Fiber Bragg gratings (FBGs) were inscribed by femtosecond laser radiation and point-by-point writing technique [3] in different fibers: Ge-doped polyimide coated fiber SM1500(9/125)P, pure-silica core polyimide coated fiber SM1500SC(7/125) and custom-made pure-silica core fiber coated with Cu and Al from Fiber Optics Research Center. The high reflective (R>95%) FBG (type II) with length of 5 mm and low reflective (R=10-20%) FBG (type I) was inscribed with pulse energy variation from 100 nJ to 300 nJ. Al and Cu metal protective coating was removed before FBG inscription by iron chloride etching. FBGs in polyimide coated fibers were inscribed through the protective coating.

The experimental setup for measuring the spectral characteristics of FBG under the action of a fast electron beam is shown in Fig. 1. The reflection and transmission spectra were measured using an 8-channel Astro A313 interrogator. To measure the transmission spectra, a circulator was inserted into the optical channel, which worked as an optical isolator preventing probing radiation passing to the FBG from the corresponding channel, and passed the radiation transmitted through the FBG from another channel (Fig.1a). According to this scheme, using 2 channels of the interrogator per FBG, it is possible to simultaneously measure transmission and reflection spectra of 4 FBGs. The FBG were placed on the grooves on metal plate located below the e-beam exit cone (fig. 1b). The local temperature of metal plate was measured by thermocouple.

An electron beam in our experiments was generated by pulse radio frequency (RF) accelerator ILU-6 having working frequency of 118 MHz. It generates pulsed beam of fast electrons with energy up to 2.5 MeV, its pulses have duration of 0.5 ms and pulse repetition rate up to 50 Hz. The length of e-beam exit cone is 980 mm and width of 4 cm. In our experiments pulse repetition rate was fixed at 15.5 Hz to maintain the same dose rate of 2.5 kGy/s.

Figure 1. Optical scheme of FBGs spectrum measurements based on 8 channels interrogator unit. (b) The image of β-radiation impact area and FBG location.
Figure 2. Dependance of FBG wavelength and transmission on time during fast electron beam impact at constant dose rate at 2.5kGy/s and during a relaxation process.

Figure 2 presents the dependence of the FBG wavelength inscribed in polyimide-coated fibers as a function of time during β-radiation impact and during the relaxation process. The total time of β-radiation impact was 206 min, which corresponds to a total dose of 30.9 MGy, and consisted of two stages of 103 min and a time interval (38 min) without exposure. Then, during 17 hours, the FBG parameters were measured, which show the dynamics of color centers.
relaxation. A sharp change in the wavelength at the beginning of radiation impact is explained by an temperature increase of the metal substrate from 24 °C to 180 °C due to the absorption of high-energy electrons. After impact of radiation, a shift of the reflection wavelength is observed due to cooling of the substrate to the initial temperature at which the final FBG spectra were measured and shown in Fig. 3 in comparison with the initial spectra. The temperature of the substrate was controlled by the thermocouples located near the FBG. As can be seen from the presented data, the largest Bragg wavelength induced shift (BWS) of +55 pm is observed in the case of weak reflective FBG (type I) inscribed in Ge-doped fiber (table I). A comparable shift in wavelength of + 50 pm is observed in the case of high reflective FBG (type II). This red shift of the wavelength was also observed in the case of γ-radiation impact to FBG inscribed in the Ge-doped fiber [4], which is explained by an increase in the concentration of GeE’-centers and, accordingly, an increase in the effective refractive index. Moreover, a significantly smaller BWS was obtained in the case of FBGs inscribed in pure-silica core fibers: 20 pm in the case of weak reflective FBG (type I), and -10 pm in the case of high reflective FBG. This shift to shorter wavelengths was also observed in the case of impact to γ - radiation on FBG inscribed in pure-silica core fiber [4]. In addition to the minimum wavelength shift, this type of FBG has a minimum transmittance variation (0.15 dB), while for FBGs recorded in the Ge-doped fiber this value is (0.44 dB and 0.3 dB for FBG type II and I, respectively). For these reasons, to create sensors based on FBG in areas exposed to β-radiation, it is necessary to use high reflective FBG inscribed in pure-silica core fiber. This type of fiber has also shown great radiation resistance compared to Ge-doped fiber in the case of impact of γ-radiation [5].

Figure 3. FBG spectra before e-beam impact (black line) and after e-beam impact (red line) with total dose of 30.9 MGy: low reflective FBG (type I) inscribed in Ge-doped fiber (a), low reflective FBG (type I) inscribed in pure-silica core fiber (b), high reflective FBG (type II) inscribed in Ge-doped fiber (c), high reflective FBG (type II) inscribed in pure-silica core fiber (d).
For further study of this type of optical fibers under the impact of β-radiation, we measured the reflection and transmission spectra of high reflective FBGs inscribed in pure-silica core fibers and metal coating (Cu and Al). In this case, FBGs were preliminarily annealed at 450 °C for 45 h. The total impact time of β-radiation in this case was 275 min, which corresponds to a total dose of 41.1 MGy. The comparison of initial and spectra after exposure at the same temperature are presented in Fig. 4. BWS of -20 and -35 pm is observed for Al and Cu-coated fiber, respectively. This shift to shorter wavelengths coincides with the case of high reflective FBG inscribed in a pure-silica core fiber with a polyimide coating and with the case of BWS observed when exposed to γ-radiation for the same fiber. However, unlike the case of γ-radiation, where an increase in the temperature of preliminary annealing of FBG reduces BWS, in our case, an increase in the temperature of annealing led to an increase in BWS, which requires further research in this area.

Figure 4. FBG spectra before e-beam impact (black line) and after e-beam impact (red line) with total dose of 41.1 MGy: high reflective FBG (type II) inscribed in Al-coated pure-silica core fiber (a), high reflective FBG (type II) inscribed in Cu-coated pure-silica core fiber (a)

Table 1 Results of FBG spectral variation after fast electron beam impact.

<table>
<thead>
<tr>
<th>#</th>
<th>Fiber</th>
<th>Parameters</th>
<th>FBG type</th>
<th>R, %</th>
<th>λ, nm</th>
<th>Δλ, pm</th>
<th>ΔT, dB</th>
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</thead>
<tbody>
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<td>1</td>
<td>SM1500(9/125)P</td>
<td>Ge-doped, Polyimide coating</td>
<td>Type II</td>
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<td>50</td>
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<tr>
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<td>Ge-doped, Polyimide coating</td>
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<td>15</td>
<td>1530</td>
<td>55</td>
<td>0.3 dB</td>
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<tr>
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<td>SM1500SC(9/125)P</td>
<td>Pure silica core, Polyimide coating</td>
<td>Type II</td>
<td>&gt;95</td>
<td>1540</td>
<td>-10</td>
<td>0.15 dB</td>
</tr>
<tr>
<td>4</td>
<td>SM1500SC(9/125)P</td>
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<td>Type I</td>
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<tr>
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<td>Pure silica core, Cu-coated</td>
<td>Type II</td>
<td>&gt;95</td>
<td>1560</td>
<td>-35</td>
<td>-</td>
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<tr>
<td>6</td>
<td>FORC Al-coated</td>
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<td>Type II</td>
<td>&gt;95</td>
<td>1570</td>
<td>-20</td>
<td>-</td>
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</tbody>
</table>
3. CONCLUSION

It is shown that highly reflective FBG (type II) inscribed in a pure-silica core fiber by femtosecond laser pulses is resistant to β-radiation exposure. In this case the measured Bragg wavelength shift is -10 pm after exposure of β-radiation with a dose rate of 2.5 kGy/s and a total dose of 30.9 MGy. Along with the minimum values of induced losses in the case of pure-silica core fiber, this type of fiber is promising for creating long-term radiation resistant fiber-optic sensors. In case of Ge-doped fibers the measured BWS for both low and high reflective FBG at the same β-radiation exposure conditions are in range of 50-55 pm that coincides with typical BWS behavior observed in case of γ-radiation for Ge-doped fiber. But the opposite BWS behavior was shown in case of β-radiation exposure of pre-annealed FBG inscribed in pure-silica core fibers with increase BWS at temperature increase of thermal treatment from 300 °C to 450 °C.

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REFERENCES


