Effects of Gamma and Electron Beam Irradiation on FBG and DFB-FL

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Abstract. This paper reports the comparative experimental study concerning the irradiation effects of gamma-ray and electron beam on fiber Bragg grating (FBG) and distributed feedback fiber laser (DFB-FL). The obvious reflection wavelength shifts are observed for FBGs and DFB-FLs without evident changes in reflectivity and bandwidth under the current experimental irradiation condition, up to 60 kGy gamma radiation and 100 kGy electron beam radiation, respectively. Especially for DFB-FLs, evident attenuation in output power is observed and the rising tendency of the attenuation under increasing irradiation dose is demonstrated as well. Thus, the DFB-FLs are more suitable for radiation detection as compared to passive FBGs.

1. Introduction

Optical fiber based sensing technology has been widely applied in many fields for its unique advantages, such as small size, light weight and immunity to electromagnetic interference. When optical fiber and fiber Bragg grating (FBG) are applied in a nuclear environment, they are facing different irradiation conditions, such as X-ray, gamma ray, neutron radiation, and electron beam. Previously, the effects of gamma and neutron radiation on different optical fibers and FBGs have been researched and reported [1-9]. Radiation induced attenuation (RIA) is a typical and significant effect for various optical fibers, such as Ge-doped silica fiber and Er-doped silica fiber. Besides RIA, radiation induced peak shift of the reflection spectrum is a common effect for FBG. The 0.1 nm blue shift and the 20-50 pm red shift of FBG reflection were found [2]. Furthermore, the radiation induced peak shift shows a saturable tendency for increasing irradiation dose. For example, the maximum shifts about 20 pm and 80 pm were found for FBGs written on Ge-doped fiber and hydrogen-loaded fiber under gamma irradiation up to 1.5 MGy dose [3]. In addition, the coating condition was also an important factor influencing the shift value. Theoretical explanations on RIA and radiation induced wavelength shift by gamma radiation have been proposed [3]. Very few reports on electron beam radiation effect on FBGs are available [10]. DFB-FL is a short-cavity fiber laser with a phase-shifted grating in a section of active fiber acting as the laser cavity. DFB-FL has a robust single longitudinal
mode laser emission with a narrow linewidth in kHz. Since its perfect characteristics, such as narrow linewidth and compact size, it is very attractive in high sensitive hydroacoustic sensing application as sensing probe or laser source seed. According to our knowledge, the radiation induced effects on DFB-FL had not been reported, yet. In this paper, besides the irradiation experiment on FBGs, the irradiation results of gamma and electron beam radiation on DFB-FL are reported for the first time. The radiation induced effects are summarized and discussed.

2. Sample Fabrication
Before grating fabrication, hydrogen loading for the fiber is necessary. The hydrogen loading process is to keep the fiber in a chamber of 12 Mpa pressure for 2 weeks. Normal FBGs were fabricated in hydrogen-loaded normal single mode silica optical fiber (Corning SM28e+). Two FBG samples written in the hydrogen-loaded polarization maintaining silica fiber (Fujikura PM1550) were investigated as well. All of the FBGs were fabricated by the phase mask technique and 248nm pulsed ultraviolet (UV) laser (Coherent Industrial 100T) whose pulse energy is fixed as 12 mJ at 200 Hz repetition rate. The UV beam reaching fiber is filtered to 1mm width with a slit. The phase mask is mounted on a piezoelectric transducer (PZT) stage (PI, P-752.11c) with nanometer resolution. The effective exposure so as to the grating strength is controlled by changing the moving speed of the UV laser. The fabrication setup diagram is shown in figure 1.

![Figure 1. Schematic diagram for grating fabrication technique.](image1)

The cavity of DFB-FL is a section of phase-shifted grating engraved on Er-doped optical fiber (Nufern, Esf3/125). The phase-shifted gratings studied in our experiment were fabricated with dithering phase mask technique and a 244 nm continuous UV laser (Coherent Sabre Motored) [11]. The phase-shifted grating lengths of these samples were about 30 mm to 40 mm. The phase-shifted grating emits laser at the Bragg wavelength when it is pumped through a wavelength division multiplexer (WDM) with a 980 nm laser diode (LD). The schematic diagram for DFB-FL is illustrated in figure 2.

![Figure 2. Schematic diagram for DFB-FL.](image2)

The samples including FBGs and DFB-FL gratings had been annealed for 16 hours at 120 °C to stabilize the gratings. The coating in grating region was stripped off and no recoating after the grating fabrication was applied.

3. Irradiation Experiment
The FBG and DFB-FL samples prepared as above were irradiated under different gamma radiation and electron beam doses in batches. The irradiation of the investigated samples was performed using the 60Co the research irradiator type GC-5000, BRIT (India), which has an irradiation chamber volume of 5000 cm³ and is operated at “Horia Hulubei” National Institute of Physics and Nuclear Engineering. The sketch of the irradiator is illustrated in figure 3 (left). The samples for irradiation were placed during the irradiation in the middle of the irradiation chamber and about 10 cm above the base. The samples were tested with varying gamma doses of 2, 12, 36, and 60 kGy, at a dose rate of 4.4 kGy/h. The irradiation process was carried out at about 36 °C slightly above the room temperature.
The irradiation dose and total dose were measured, off-line, with one standard deviation of 3.3 %, by using an ethanolchlorobenzen dosimetry system with oscillometric readout method. The system is traceable at the National Physical Laboratory, through RISOE HDRL.

Electron beam irradiation was performed at the linear accelerator facility in the National Institute for Laser, Plasma and Radiation Physics, as shown in figure 3 (right). The accelerator operating parameters were: beam diameter 16 cm @ 60 cm from output window; beam uniformity in transversal plane ± 10 %; pulse duration 4 µs; pulse energy 5.5 MeV; beam current 3 µA. The exposure doses and the respective dose rates were: 5 kGy (22 Gy/s), 50 kGy (26, 7 Gy/s), 100 kGy (53 Gy/s). For our irradiation experiment, the dosimetry was based on graphite calorimeters with the following characteristics: sensitivity 0.75 kGyC-1; energy range 1.5 to 12 MeV; dose range 0.5 kGy to 30 kGy; measurement uncertainty 5%. On-line dosimetry was done in this case.

Figure 3. Sketch of the gamma irradiation (left) and photo of the linear accelerator facility (right).

4. Results and Discussions
Under the experimental conditions detailed above, the reflection and transmission spectra of the gratings were measured and compared before and after the irradiation experiments, using an optical spectrum analyzer (Yokogawa AQ6370C, 0.02nm resolution). Similarly, the output powers from the DFB-FLs were measured and compared, using an optical power meter (EXFO, FPM-600). All our tests on FBG and DFB-FL characteristics were carried out off-line about 40 days later after the irradiation experiment and most of radiation induced temporary effects should have been annihilated. Thus we consider what we have tested and reported here are mostly radiation induced long-term effects. Typical radiation characteristics of the FBGs are shown by three cases in figure 4: (a) an SM-FBG (FBG written in conventional Corning SM28e+) before and after gamma irradiation of 36 kGy; (b) a PM-FBG (FBG written in polarization maintaining fiber, Fujikuar PM1550) before and after gamma irradiation of 60 kGy; (c) an SM-FBG before and after electron irradiation of 50 kGy. The results shown in Figure 4 agree with previous reports [2, 7], that gamma radiation induces attenuation and reflective wavelength shift of FBGs, while there is no certain wavelength shift trend, red shift or blue shift, for gamma or electron irradiation and no evident increasing tendency in the shift was observer for increasing irradiation dose in our experiments.

Same as the case of other previously published data, no evident differences in reflectivity and bandwidth were observed [2, 7]. All results on irradiation induced wavelength shift are summarized in table 1 and 2. Evident peak shift of the reflection was observed in the case of each FBG and DFB-FL.
Figure 4. Reflection and transmission spectra of 3 FBGs under different irradiation; (a) SM-FBG (FBG-03) under 36 kGy gamma irradiation, (b) PM-FBG (FBG-15) under 60 kGy gamma irradiation, (c) SM-FBG (FBG-07) under 50 kGy electron irradiation.

Table 1. Summary on irradiation induced wavelength shift by Gamma ray.

| $\gamma$ dose (kGy) | Sample Code | Length (mm) | Wavelength shift (nm) |
|---------------------|-------------|-------------|-----------------------|
| 2                   | FBG-01      | 10          | -0.064                |
| 2                   | FBG-13      | 15          | -0.006                |
| 2                   | DFB-01      | 40          | -0.06                 |
| 2                   | DFB-09      | 44          | -0.042                |
| 12                  | FBG-02      | 10          | -0.052                |
| 12                  | FBG-14      | 15          | 0.029                 |
| 12                  | DFB-02      | 40          | Broken                |
| 12                  | DFB-10      | 40          | -0.042                |
| 36                  | FBG-03      | 10          | -0.06                 |
| 36                  | FBG-15      | 15          | 0.004                 |
| 36                  | DFB-03      | 45          | -0.02                 |
| 36                  | DFB-11      | 40          | -0.036                |
| 60                  | FBG-04      | 10          | -0.05                 |
| 60                  | FBG-16      | 15          | 0.018                 |
| 60                  | DFB-04      | 35          | -0.03                 |
| 10                  | DFB-12      | 40          | -0.031                |
Table 2. Summary on irradiation induced wavelength shift by Electron ray.

| Dose (kGy) | Sample Code | Length (mm) | Wavelength shift (nm) |
|------------|-------------|-------------|-----------------------|
| 5          | FBG-06      | 10          | -0.1                  |
| 5          | FBG-10      | 15          | -0.06                 |
| 5          | DFB-06      | 40          | -0.01                 |
| 50         | FBG-07      | 10          | -0.06                 |
| 50         | FBG-11      | 15          | 0.04                  |
| 50         | DFB-07      | 45          | -0.04                 |
| 100        | FBG-08      | 15          | 0.034                 |
| 100        | FBG-12      | 15          | 0.02                  |
| 100        | DFB-08      | 45          | -0.02                 |

Figure 5. Characteristics of DFB-FL before and after gamma and electron irradiation: (a) DFB-11 under 36 kGy gamma irradiation, (b) DFB-07 under 50 kGy electron irradiation.

Two DFB-FL samples under different gamma irradiation and electron beam irradiation conditions are compared in figure 5. All results of gamma induced power loss of DFB-FLs are summarized in table 3. All results of electron induced power loss of DFB-FLs are summarized in table 4. For these DFB-FLs, the radiation induced power loss was observed and found to be nearly proportional to the irradiation dose, for both gamma and electron irradiation, as shown in figure 6 and figure 7, respectively.

From the experimental results, the radiation induced power loss in DFB-FL increases with the doses of gamma radiation and electron radiation, respectively. This suggests that the semi-quantitative radiation dosimetry by DFB-FL is possible.

Table 3. Laser efficiency decrease with the increasing irradiation dose for Gamma ray.

| $\gamma$ dose (kGy) | Sample Code | Length (mm) | Output power before irradiation ($\mu$W) | Output power after irradiation ($\mu$W) | Difference | $RIARIA/Length$ |
|---------------------|-------------|-------------|----------------------------------------|----------------------------------------|-----------|----------------|
| 2                   | DFB-01      | 40          | 73                                     | 60.6                                   | -12.4     | 0.81/20.25    |
|                     | DFB-09      | 44          | 18                                     | 9.8                                    | -8.2      | 2.64/60       |
| 12                  | DFB-10      | 40          | 187                                    | 62                                     | -125      | 4.79/119.8    |
|                     | DFB-02      | 40          | Broken                                 | -                                       | -         | -             |
| 36                  | DFB-11      | 40          | 160                                    | 43.8                                   | -116.2    | 5.63/140.8    |
|                     | DFB-03      | 45          | 240                                    | 97                                     | -143      | 3.93/87.3     |
| 60                  | DFB-12      | 40          | 149                                    | 37.5                                   | -111.5    | 6.0/150       |
Table 4. Laser efficiency decrease with the increasing irradiation dose for Electron ray.

| Sample Code | Length (mm) | Output power before irradiation (μW) | Output power after irradiation (μW) | Difference (μW) | RIA (dB) | RIA/Length (dB/m) |
|-------------|-------------|--------------------------------------|------------------------------------|-----------------|----------|------------------|
| DFB-06      | 40          | 180                                  | 95                                 | -85             | 2.78     | 69.5             |
| DFB-07      | 45          | 112                                  | 24.8                               | -87.2           | 6.55     | 145.6            |
| DFB-08      | 45          | 136                                  | 25.8                               | -110.2          | 7.22     | 160.4            |

Since the laser cavity of DFB-FL has a section of pigtail fiber about 0.5 m at the output port which was also irradiated by the same radiation dose, the radiation induced laser attenuation must include RIA of pigtail fiber at both 1550 nm and 980 nm. The RIA of pigtail fiber at 980 nm led to the reduction of pump power entering into laser cavity. The RIA of pigtail fiber at 1550 nm led to the reduction of laser emission arriving at power meter. Since the negligible grating strength mentioned before, the increase of cavity loss could be decided which led to the laser efficiency decrease. As for the specific cavity loss of DFB-FL, the radiation induced difference in characteristics of the Er-doped fiber should be measured in the meantime. Hence, the quantitative measurement of the used fiber characteristics need be carried out in the future investigation.

5. Conclusion
Irradiation experiments including gamma radiation and electron beam radiation on FBGs and DFB-FLs were carried out. Evident peak wavelength shift was observed while no evident changes in reflectivity and bandwidth for FBG gratings was present. Besides the wavelength shift, a noticeable output power drop was found for the irradiated DFB-FLs. For gamma and electron beam irradiation experiments, a decreasing tendency in laser output efficiency with increasing irradiation dose is obvious, which suggests the possibility of the radiation dosimetry by DFB-FL.

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Figure 6. Gamma radiation effect on DFB-FL output power.

Figure 7. Electron radiation effect on DFB-FL output power.
References

[1] Grard S, Kuhnhenn J, Gusarov A, Brichard B, Uffelen M, Ouerdane Y, Boukenter A and Marcandella C. 2013 IEEE Transactions on Nuclear Science 60 (3) 2015.

[2] Gusarov A, Vasiliev S, Medvedkov O, MckenzieI and Berghmans F 2007. RADECS 2007. 9th European Conference on. IEEE, 1.

[3] Perry M, Niewczas P and Johnston M 2012 IEEE Sensors Journal 12 (11) 3248.

[4] Gusarov A, Fernandez A, Vasiliev S, Medvedkov O, Blondel M and Berghmans F 2002 Nuclear Instruments and Methods in Physics Research B 187 79.

[5] Gusarov A, Berghmans F, Fernandez P, Dearis O, Defosse Y, Starodubov D, Decreton M, Megret P and Blondel M 2000 IEEE Transactions on Nuclear Sciences 47 (3) 688.

[6] Niay P, Bernage P, Douay M, Fertein E, Bayon J, Georges T, Monerie M, Ferdinand P, Rougeault S and Cetier P 1994 IEEE Photonics Technology Letters 6 (11) 1350.

[7] Vasiliev S, Dianov E, Golant K, Medvedkov O, Tomashuk A, Karpov V, Grekov V, Kurkov A, Leconte B and Niay P 1997. RADECS 97. Fourth European Conference on. IEEE 1997, 480.

[8] Kim Y, Ju S, Jeong S, Lee S and Han W 2016 Optics Express 24 (4) 3910.

[9] Ju S, Kim Y, Linganna K, Kim Y and Han W 2020 Photonic Sensors 10 16.

[10] Sporea D, Stâncâlie A, Becherescu N, Becker M and Rothhard M 2014 Sensors (Basel) 14 (9) 15786.

[11] Qi H, Song Z, Guo J, Wang C, and Peng G 2013 Optics Express 21 (9) 11309.