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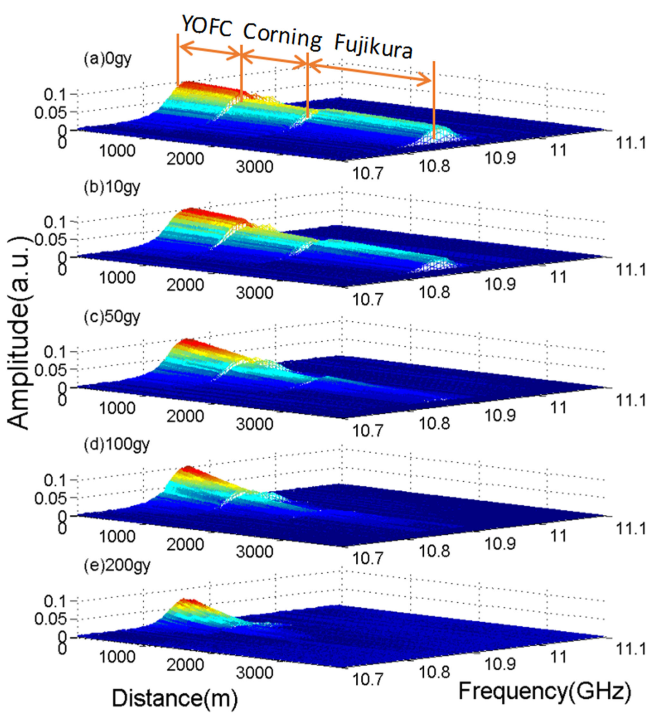

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Investigation of the Radiation Effect on BOTDR Under Low Space Radiation Doses

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Abstract: To verify the feasibility of Brillouin optical time domain reflector (BOTDR) applied in space station, three kinds of commercial fibers, YOFC fiber (about 1 km), Corning fiber (about 1 km) and Fujikura fibers (about 1.5 km), have been radiated by Co^{60} in radiation experiment. Based on the Brillouin Gain Spectrum (BGS) along sensing fiber, we analyze power curve of Brillouin backscattered light, Brillouin Frequency Shift (BFS) along sensing fiber and spatial resolution carefully. The results indicate that radiation has little effect on BFS when signal-to-noise ratio (SNR) is large enough. However, since radiation will lead to radiation-induced attenuation, the amplitude of BGS will decrease accordingly. And if the SNR becomes small enough, the accurate BFS cannot be obtained. For the stressed fiber section of BOTDR, the result shows that radiation has little effect on the strain coefficient at the total radiation dose of 200 Gy, but radiation will deteriorate the spatial resolution of BOTDR with the increase of radiation dose. These results are good references for the introduction of BOTDR to space station.

Index Terms: Brillouin optical time domain reflector, space radiation.

1. Introduction

Brillouin optical time domain reflector (BOTDR) is one of the most outstanding distributed optical fiber sensing techniques. This technique has been widely applied in large structural health monitoring field, because BOTDR has the ability to monitor temperature and strain [1], [2]. Considering the successful application of BOTDR on ground, space engineers have also paid much attention to the technique recently. Here, we also want to introduce BOTDR to the structural health monitoring of space station. However, there exists harsh radiation in space. Even if BOTDR is applied inside space station, it will still suffer radiation. Radiation will deteriorate the optical performance of sensing fiber in BOTDR [3]. Therefore, it's necessary to research the radiation effect on BOTDR.

In fact, researchers have carried out a lot of investigation on the application of distributed optical fiber sensing technique in special application scenarios, such as Brillouin optical sensors applied in ultra-high temperature environment [4], [5], Brillouin optical sensors with singlemode-multimode-singlemode optical fiber [6], and distributed optical sensors with multicore fiber [7]. And as for the application in radiation environment, from 1980s, the application of optical fiber in radiation environment has also attracted the attention of researchers. Especially, radiation-induced attenuation and color center concentration in optical fiber have been given in [Ref. [3]. And the radiation model of optical fiber in radiation environment has also been given in [Ref. [8], which indicates the basic relationship among radiation dose, radiation rate and the fiber attenuation detailly.

Based on these previous important works on the performance of optical fiber in radiation environment, some researchers have also begun to experimentally investigate the radiation effects on the performance of different distributed fiber sensing systems, such as Optical Frequency Domain Reflectometry [9] and Raman distributed temperature fiber-based sensors [10]. However, few analyses on radiation effect on BOTDR have been reported. In ref. [11], the radiation effect on Brillouin Optical Time Domain Analysis (BOTDA) with 10 m sensing fiber has been investigated, whose sensing principle is also based on the Brillouin back scattered light. The difference is that BOTDA is based on the stimulated Brillouin back scattered light, while, BOTDR is based on the spontaneous Brillouin back scattered light. In addition, considering both BOTDR and BOTDA are distributed sensing techniques, it is not enough to investigate the radiation performance of distributed fiber sensing systems only for 10 m sensing fiber.

Considering the high prices of anti-radiation optical fiber, it's not a good choice for engineers to use anti-radiation fiber as the sensing fiber of BOTDR applied in space station, because it is an application of large structural health monitoring. In this paper, to obtain the radiation performance of BOTDR in space environment, three kinds of commercial fibers, YOFC fiber (about 1 km), Corning fiber (about 1 km) and Fujikura fibers (about 1.5 km), have been radiated by Co^{60} in radiation experiment. Based on the Brillouin Gain Spectra (BGS) along sensing fiber, we further analyze power curve of Brillouin backscattered light, Brillouin Frequency Shift (BFS) along sensing fiber and spatial resolution carefully. These results will be helpful for the introduction of BOTDR to space station.

2. Fundamental Theory

BOTDR utilizes spontaneous Brillouin backscattered light in optical fiber as basic sensing principle. And the scattered light undergoes a Doppler frequency shift which depends on acoustic velocity. The BFS can be described as [12]

$$\upsilon_B = \frac{2nV_a}{\lambda} \tag{1}$$

where Va is the phonon velocity, n is the refractive index of fiber and λ is the vacuum wavelength of incident light. The exponential decay of the acoustic waves determines the shape of BGS which shows characteristics of Lorentzian profile [13]

$$g_B(\upsilon) = g_0 \frac{(\Gamma \upsilon_B/2)^2}{(\Gamma \upsilon_B/2)^2 + (\upsilon - \upsilon_B)^2} \tag{2}$$

where $\Gamma\nu_B$ is the full-width at half maximum, g_0 is the Brillouin gain coefficient. $g_B(\nu)$ is the gain coefficient at different frequencies. ν_B is the peak frequency.

BFS has a linear relationship with the temperature and strain over a wide range which can be described as [14]

$$\Delta\nu_B = C_{\nu,T}\Delta T + C_{\nu,\varepsilon}\Delta\varepsilon \tag{3}$$

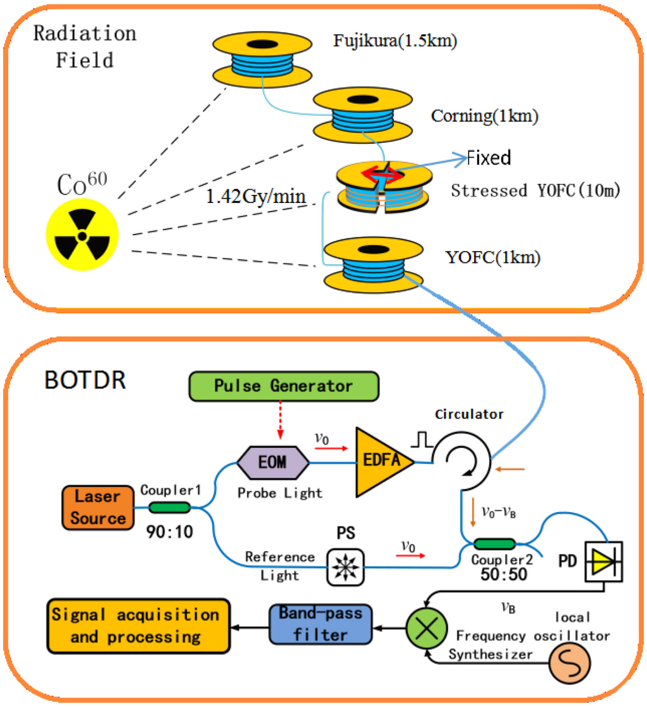

Fig. 1. Experimental setup of radiation effect on the BOTDR system.

where Cv,T and Cv,ε are coefficients of temperature and strain respectively. So the key of BOTDR sensing technique is to measure the BFS to obtain the variation of strain and temperature along sensing fiber.

And to find the position with the variation of strain- or temperature, the equation should be mentioned is [15]

$$z = \frac{c \times t}{2n} \tag{4}$$

where c is the speed of light in vacuum, n is the refractive index in the fiber core.

3. Experiment and Result Analysis

As to verify the feasibility of BOTDR in space sensing field, a radiation experiment has been carried out carefully. Fig. 1. shows the principle diagram of our experiment. The Brillouin backscattered light generated from the fiber sample enters the optical circulator and couples with the reference light in optical coupler 2. And then the beat signal will be detected and converted to electrical signal by photodiode (PD). Then, based on the microwave frequency sweeping technique [16], the signal can be converted to low frequency field. Finally, after the signal passes the band-pass filter, the BGS along sensing fiber can be obtained.

In our experiment system, the wavelength of laser source is 1550 nm. And the pulse width of optical signal will be modulated into 40 ns by pulse generator. The accuracy in frequency measurement is about ± 1 MHz. To simulate actual space radiation environment, Co^{60} [17] with a dose rate of 1.42 Gy/min is used as our radiation source. According to China's aerospace industry standard, the total absorbed doses are 200 Gy (measured in water). In addition, the environment of radiation experiment is kept at room temperature. Considering the harm of radiation generated by Co^{60} to human beings, the experiment was carried out in a special radiation laboratory. We put the sample optical fiber into the radiation field and testers must be outside the laboratory during the

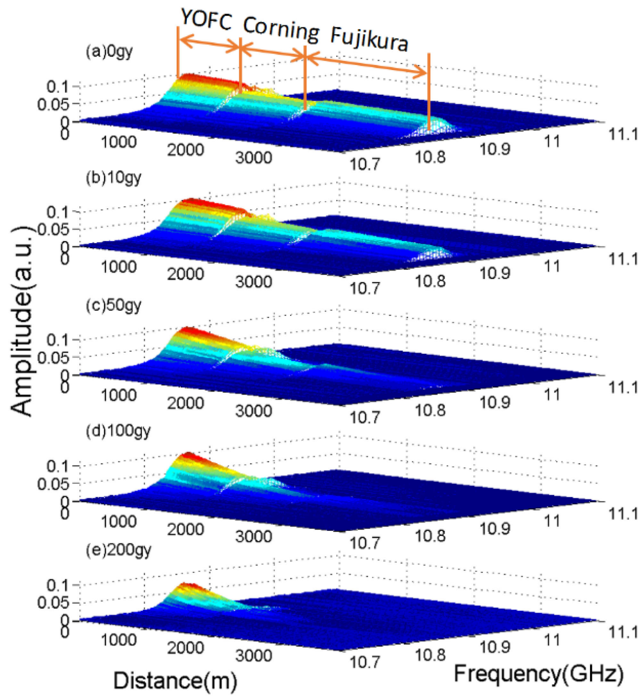

Fig. 2. BGS along the sensing fiber at different radiation doses: (a) 0gy (b) 10gy (c) 50gy (d) 100gy (e) 200gy.

radiation. The end of the optical fiber has been pulled out of the laboratory for the measurement of BOTDR. As showed in Fig. 2.

Many well-known manufacturers own the ability to produce anti-radiation optical fiber. However, considering that BOTDR is used in large structural health monitoring, it's not a good choice for engineers to use anti-radiation fiber due to the high prices. And in our experiment, we test three kinds of famous G.652.D single mode commercial fibers, which are widely used in engineering field, to analyze their sensing performance in radiation environment. These tested fibers are YOFC fiber (about 1 km), Corning fiber (about 1 km) and Fujikura fibers (about 1.5 km).

Notably, various defects will be generated in the optical fiber under radiation, which are called color centers generated by irradiation. That will increase the loss of optical fiber, which is usually called by radiation induced attenuation [18]. However, the defects formed under radiation are unstable, which can be self-healing to a certain extent. That is usually called by the annealing of radiation damage. Generally, the radiation process of optical fiber is a dynamic process between defect generation and defect repair, and the recovery effect is most obvious in the initial period after radiation stops [8]. To avoid the annealing of radiation damage caused by the long measurement time, we connect these three kinds of commercial fibers by fusion splice technique. With this method, the radiation performance of BOTDR with three kinds of fibers can be measured at the same time. Therefore, the test time can be shortened easily.

Radiation experiment results in [11] show that temperature and strain coefficients of BOTDA are little affected by gamma-radiation up to 10 MGy doses, which is 50, 000 times as large as 200 Gy in our radiation experiment. Considering that BOTDR and BOTDA both utilize the frequency shift of Brillouin backscattered light for sensing, we expect that the temperature and strain coefficients of BOTDR will also change little for 200 Gy gamma-radiation dose. To verify the expected conclusion, we add a fixed stress at the end of YOFC fiber by opening a small seam on the fiber spool. The stressed fiber section is about 7 meters as shown in Fig. 1. And we can use the stressed fiber section to analyze the radiation effect on the variation of BFS at stressed fiber section. If the BFS caused by such stress has little change at 200 Gy, then the temperature and strain coefficients can

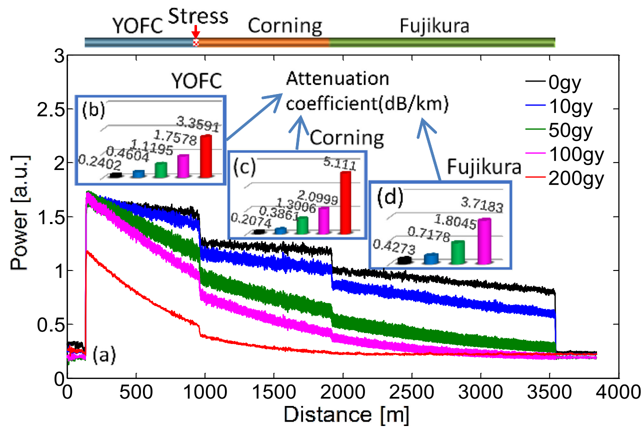

Fig. 3. (a) Power curve of Brillouin backscattered light as a function of distance. (b) (c) and (d) show the attenuation coefficients for different commercial fibers calculated at different radiation doses. (b) YOFC. (c) Corning. (d) Fujikura.

be considered unchanged. And the measurement time can be shortened to avoid the annealing of radiation damage caused by the long measurement time.

We select 10 Gy, 50 Gy, 100 Gy and 200 Gy as the break points. The radiation will stop while each break point arrives. At the incident end of the sensing fiber, the light signal received at different time corresponds to the Brillouin backscattered light generated by the fiber at different positions. And the amplitude of Brillouin scattered light at different frequency can be obtained by sweeping frequency method. Then the BGS along fiber can be obtained by plotting the amplitude of different frequencies at different times in the figure, as showed in Fig. 2. From the figure, the BFS along each fiber changes little at different doses. However, the amplitude attenuation of each fiber becomes larger with the increase of radiation dose. The BGS along Fujikura fiber has almost been submerged in noise when radiation dose reaches 50 Gy. And the same phenomenon also appears in Corning fiber when radiation dose reaches 200 Gy. Because the increase of radiation dose will enhance the color center effect of fiber [3]. While, the color center will increase the transmission loss of detecting light and the Brillouin backscattered light.

Furthermore, there exist some drop of magnitude and some offset of amplitude in two connection points among three kinds of fibers. The magnitude drop is caused by the loss of fusion splice. As we know, in single-mode fiber, Brillouin peak frequency is directly proportional to the effective refractive index of the fiber and the acoustic velocity in the fiber. Therefore, the Brillouin peak frequency is different since the composition of the three kinds of sample fibers is different.

As for BOTDR system, we should pay more attention to the attenuation coefficient, the BFS along sensing fiber and spatial resolution of BOTDR. Since our fiber sample is spliced by 1 km YOFC, 1 km Corning and 1.5 km Fujikura, the length of fiber sample reaches about 3.5 km. As a result, the key parameters of BOTDR can't be showed clearly merely according to Fig. 2. Therefore, based on the results of Fig. 2, we will further analyze detailedly the radiation effect on the power curve of Brillouin back scattered light, BFS along fiber and the spatial resolution for BOTDR at different radiation doses in the following analysis.

Fig. 3(a) shows the power curve of Brillouin backscattered light along three kinds of fibers at different doses. It can be seen that power decreases with the increase of transmission distance. And with the increase of radiation dose, the attenuation coefficients increase obviously for all three kinds of fibers. We further calculate the attenuation coefficients of these fibers at different radiation doses, and show them separately in Fig. 3(b) (c)and (d). The results indicate that compared to YOFC fiber and Corning fiber, Fujikura fiber has the biggest attenuation coefficients in each radiation dose (0 Gy, 10 Gy, 50 Gy, 100 Gy). In addition, it should be noted that the performance of Corning fiber is better when the radiation doses are 0 Gy and 10 Gy. However, when radiation doses are 50 Gy, 100 Gy and 200 Gy, the attenuation coefficients of YOFC fiber are smaller than

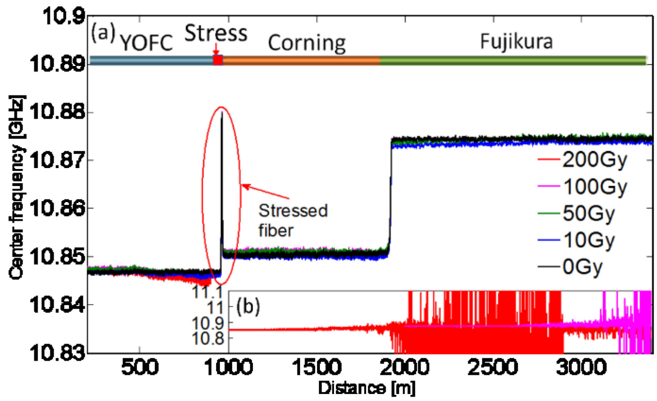

Fig. 4. (a) BFS along sensing fiber as a function of distance. (b) Fitting results of fiber section with weak signal.

that of Corning fiber. That means although Corning fiber performs better than YOFC fiber under 10 Gy in radiation-induced attenuation, YOFC fiber is a better choice when radiation doses are more than 50 Gy.

In fact, physical and chemical changes, such as discoloration, hardening and brittleness, will occur in optical fiber under the effect of radiation. And in the microstructure, various defects are generated which will worsen the transmission performance of optical fiber. The defects are called color centers, which will increase the loss of optical fiber. That is radiation induced attenuation.

The three kinds of optical fibers selected in this paper are all commercial optical fibers. In order to improve the transmission performance of optical fibers, the manufacturers will mix other elements in the production of optical fibers. Due to the different production processes, therefore, the anti-radiation properties of the three kinds of optical fibers are different. So, the selection of most suitable sensing fiber must be based on the ground radiation experiment results according to the radiation environment of application scenario.

In BOTDR system, the frequency distribution at any position of the sensing fiber obeys characteristics of Lorentzian profile. BFS can be obtained by Lorentz fit based on the different frequency points at sampling point. Then the BFS curve along the sensing fiber can be obtained by connecting the BFSs of all sampling positions along the fiber, as showed in Fig. 4. Because the BGS along Fujikura (at 100 Gy and 200 Gy) and Corning (at 200 Gy) is too weak to obtain the accurate BFS by Lorenz fit, we give the fitting results separately in Fig. 4(b) to make the figure clear.

From Fig. 4(a), BFSs under different radiation doses (10 Gy, 50 Gy, 100 Gy, 200 Gy) reproduce the case of background (0 Gy) well. It indicates that 200 Gy gamma-radiation has little effect on the BFS when BOTDR is applied in the structural health monitoring in space station.

The result seems a little different from the ones of radiation experiment in [ref. [11], they find that the HGe-doped optical fiber presents a radiation-induced-Brillouin frequency shift of about 18 MHz at 10 MGy. In fact, it is not contradictory, because 10 MGy, which is used in this experiment, is 50,000 times as large as 200 Gy used in our radiation experiment. Based on the result of radiation experiment in [ref. [11], the BFS in the case of 200 Gy can be evaluated easily, and the same conclusion will be also found that the radiation has little effect on the BFS of BOTDA under the dose of 200 Gy. However, since radiation will increase radiation-induced attenuation, which can't be ignored at 200 Gy, the BGS amplitude along the fiber will decrease accordingly. And if the signal-to-noise ratio (SNR) becomes small enough, the accurate BFS cannot be obtained. Fig. 4(b) illustrates this point. When radiation dose is 100 Gy, a clear BFS curve can still be obtained until 3000m. However, when radiation dose reaches 200 Gy, only the BFS curve for the first 2000 m can be clearly obtained.

As a sensing technique, it's also important to investigate the BFS at stressed section. In Fig. 4(a), the red circle is corresponding to the BFS at stressed fiber section. We zoom the part of red circle and use spline interpolation method to obtain Fig. 5. From Fig. 5, the variation in BFS for stressed

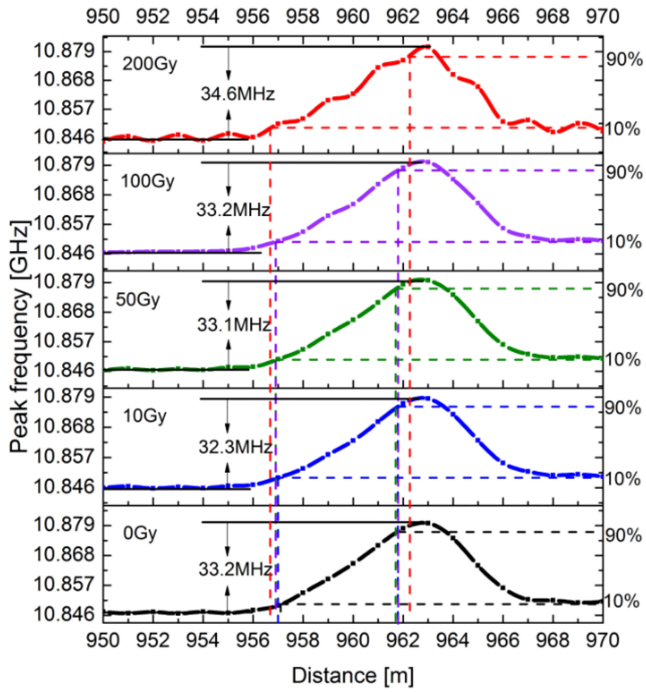

Fig. 5. BFS and spatial resolutions at different radiation doses at stressed fiber section.

fiber section is 33.2 MHz at 0 Gy. And when the radiation dose reaches 10 Gy, 50 Gy, 100 Gy and 200 Gy, the variations in BFS are 32.3 MHz, 33.1 MHz, 33.2 MHz and 34.6 MHz respectively. Compared to the variation at 0 Gy, the variations in BFS increases -1.1 MHz, −0.1 MHz 0 MHz and 1.4 MHz at 10 Gy, 50 Gy 100 Gy and 200 Gy. Since the measurement accuracy of our BOTDR system is about ±1 MHz, it can be considered that the variation in BFS are not affected by 200 Gy when the fiber surfers the fixed stress. In other words, the strain coefficient will not be affected when BOTDR is applied in space station.

Besides BFS, the spatial resolution is another important parameter of sensing system. In practical application, we usually calculate the length between the positions corresponding to 10% and 90% of maximum value in BFS and take this length as the spatial resolution of sensing system [19]. The spatial resolutions of BOTDR have been marked in Fig. 5 at different radiation doses. The spatial resolutions are 4.7m, 4.8m, 4.8m, 4.9 m and 5.5 m at 0 Gy, 10 Gy, 50 Gy, 100 Gy and 200 Gy respectively. Firstly, it should be noted that optical pulse width is 40 ns in the radiation experiment. Thus the theoretical spatial resolution should be 4m. But actual spatial resolution is 4.7 m at 0 Gy. This difference is mainly caused by the components and algorithm of our BOTDR system.

From results in Fig. 5, the spatial resolution changes little under 100 Gy, but increases 0.8 m at 200 Gy. The BFS obtained by fitting is not smooth along fiber, and the unsmooth curve will lead to errors in the calculation of spatial resolution. As for the unsmooth curve, the reason is that the SNR has decreased obviously after 200 Gy dose, which can be seen clearly from Fig. 2(e). And the small SNR deteriorates the precision of fitting results, which in turn increases the spatial resolution. Therefore, the space designers should consider the increase of spatial resolution carefully according to the practical demand.

4. Conclusion

In conclusion, three kinds of famous commercial fibers, YOFC fiber (about 1 km), Corning fiber (about 1 km) and Fujikura fibers (about 1.5 km), have been radiated up to 200 Gy by Co^{60}. The results indicate that the Fujikura fiber has the worst performance for all radiation doses under 200 Gy in these three kinds of fibers. And for the Corning fiber and the YOFC fiber, although Corning fiber performs better than YOFC fiber under 10 Gy in radiation-induced attenuation, YOFC fiber is better when radiation doses are more than 50 Gy. That means the selection of fiber has to be made by special radiation experiment according to the application scenario. Through this experiment, we verified the feasibility of BOTDR applied in space station. The results indicate that when SNR is large enough, radiation has little effect on the BFS. However, since radiation will lead to radiation-induced attenuation, the amplitude of BGS will decrease accordingly. And if the SNR becomes small enough, the accurate BFS along sensing fiber cannot be obtained. That means the radiation will obviously decrease the maximum detectable range of BOTDR. For the stressed fiber section of BOTDR, the result shows that radiation has little effect on the strain coefficient. However, when SNR becomes small enough, radiation will deteriorate the spatial resolution of BOTDR. Therefore, if space engineers want to apply BOTDR in space station, more attention should be payed to the radiation-induced attenuation and spatial resolution in the practical application. These results are good references for the introduction of BOTDR to space engineering field.

References

[1] L. Teng *et al.*, "Temperature-compensated distributed hydrostatic pressure sensor with a thin-diameter polarization-maintaining photonic crystal fiber based on brillouin dynamic gratings," *Opt. Lett.*, vol. 41, no. 18, pp. 4413–4416, 2016.

[2] X. Y. Bao and L. Chen, "Recent progress in distributed fiber optic sensors," *Sensors*, vol. 12, no. 12, pp. 8601–8639, 2012.

[3] H. Yashima, H. Mitera, and Y. Itoh, "Radiation-induced loss and color-center concentration in optical fiber," *Electron. Lett.*, vol. 19, pp. 11–12, 1983.

[4] P. B. Xu, D. X. Ba, W. M. He, H. P. Hu, and Y. K. Dong, "Distributed brillouin optical fiber temperature and strain sensing at a high temperature up to 1000 °C by using an annealed gold-coated fiber," *Opt. Express*, vol. 26, no. 23, pp. 29724–29734, 2018.

[5] P. B. Xu *et al.*, "1200 °C high-temperature distributed optical fiber sensing using Brillouin optical time domain analysis," *Appl. Opt.*, vol. 55, no. 21, pp. 5471–5478, 2016.

[6] P. B. Xu *et al.*, "Bend-insensitive distributed sensing in singlemode-multimode-singlemode optical fiber structure by using brillouin optical time-domain analysis," *Opt. Express*, vol. 23, no. 17, pp. 22714–22722, 2015.

[7] Z. Y. Zhao, M. Tang, and C. Lu, "Distributed multicore fiber sensors," *Opto-Electron. Adv.*, vol. 3, no. 2, pp. 18–34, 2020.

[8] R. H. West and A. P. Lenham, "Characteristics of light induced annealing in irradiated optical fibres," *Electron. Lett.*, vol. 18, no. 11, pp. 483–484, 2007.

[9] S. Rizzolo *et al.*, "Vulnerability of OFDR-based distributed sensors to high gamma-ray doses," *Opt. Express*, vol. 23, no. 15, pp. 18997–19009, 2015.

[10] C. Cangialosi *et al.*, "Effects of radiation and hydrogen-loading on the performances of raman distributed temperature fiber sensors," *J. Lightw. Technol.*, vol. 33, no. 12, pp. 2432–2438, 2015.

[11] X. Phéron *et al.*, "High gamma-ray dose radiation effects on the performances of brillouin scattering based optical fiber sensors," *Opt. Express*, vol. 20, no. 24, pp. 26978–26985, 2012.

[12] M. Niklès, L. Thévenaz, and P. Robert, "Brillouin gain spectrum characterization in single-mode optical fiber," *J. Lightw. Technol.*, vol. 15, no. 10, pp. 1842–1851, 1997.

[13] M. Li, W. X. Jiao, X. Z. Liuwu, Y. J. Song, and L. Q. Chang, "A method for peak seeking of BOTDR based on the incomplete brillouin spectrum," *IEEE Photon. J*, vol. 7, no. 5, Oct. 2015, Art. no. 7102110.

[14] T. R. Parker, M. Farhadiroushan, V. A. Handerek, and A. J. Rogers, "Temperature and strain dependence of the power level and frequency of spontaneous brillouin scattering in optical fiber," *Opt. Lett.*, vol. 22, no. 11, pp. 787–789, 1997.

[15] M. Li, W. X. Jiao, X. P. Zhang, Y. J. Song, H. Q. Qian, and J. J. Yu, "An algorithm for determining the peak frequency of BOTDR under the case of transient interference," *IEEE J. Sel. Top. Quant.*, vol. 23, no. 2, Mar./Apr. 2017, Art. no. 5601105.

[16] F. Wang, C. H. Zhu, C. Q. Cao, and X. P. Zhang, "Enhancing the performance of BOTDR based on the combination of FFT technique and complementary coding," *Opt. Express*, vol. 25, no. 4, pp. 3504–3513, 2017.

[17] J. Ma, M. Li, L. Y. Tan, Y. P. Zhou, S.Y. Yu, and Q. W. Ran, "Experimental investigation of radiation effect on erbium-ytterbium co-doped fiber amplifier for space optical communication in low-dose radiation environment," *Opt. Express*, vol. 17, no. 18, pp. 15571–15577, 2009.

[18] D. L. Griscom, M. E. Gingerich, and E. J. Friebele, "Radiation-induced defects in glasses: Origin of power-law dependence of concentration on dose," *Phys. Rev. Lett.*, vol. 71, no. 7, pp. 1019–1022, 1993.

[19] Y. K. Dong, H. Y. Zhang, L. Chen, and X. Y. Bao, "2 cm spatial-resolution and 2 km range brillouin optical fiber sensor using a transient differential pulse pair," *Appl. Opt.*, vol. 51, no. 9, pp. 1229–1235, 2012.