Gamma Radiation Tests of Radiation-Hardened Fiber Bragg Grating Based Sensors for Radiation Environments

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***Abstract*—In the framework of a KIC InnoEnergy funded project radiation-hardened Fiber Bragg Gratings (FBG) are developed to withstand high levels of radiation dose at high temperatures for their implementation in temperature- and strain sensors for nuclear facilities, accelerators or space. This paper presents gamma radiation test results obtained at room and elevated temperature in hardened FBGs as well as in the optical fibers used for their production. It is shown that radiation-induced Bragg wavelength shift (BWS) is below ±2 pm corresponding to ±0.2°C and does not influence the sensor performance even after a total dose of 200 kGy(SiO_2) and operating temperature up to 350°C.**

***Index Terms*—Gamma-ray effects, Fiber gratings, Optical fiber testing, Optical fiber sensors**

I. INTRODUCTION

FIBER Bragg gratings enable the development of all-optical sensors for a multitude of applications [1]. Their excellent performance and sensitivity made them interesting candidates for the use in radiation environments, such as accelerators, nuclear facilities and space. Many performance studies about the behavior of FBGs under ionizing radiation were done [2], leading to the accumulation of knowledge to minimize the influence of the radiation-induced BWS causing direct errors on the sensor reading. Ionizing radiation leads to the generation of defects and, at especially at higher dose values, to density variations, which cause the Bragg peak to change mainly through two effects: the radiation-induced attenuation (RIA) and the radiation-induced Bragg wavelength shift (RI-BWS). The first reduces the fiber transmission, and as a consequence decreases the amplitude of the reflected Bragg peak and ultimately prevents the Bragg peak from being detected. The RI-BWS causes an error on the sensing parameter measurements by shifting the whole peak and therefore the determined position by some extent.

AREVA and Laboratoire Hubert Curien patented a procedure for fabricating FBGs resistant to severe environments mixing both high radiation dose up to MGy level and temperature higher than 250°C, hereafter named RadHard FBGs [3]. These results are today at the basis of a European project granted by KIC InnoEnergy called HOBAN (Development of Hard Optical Fiber BrAgg GratiNgs Sensors [4]), whose aim is developing and marketing radiation-resistant FBG-based temperature and strain monitoring systems, with their associated instrumentation, suitable for harsh nuclear environment characterized by temperatures up to 350°C and total accumulated dose up to 1 MGy(SiO_2).

The approach to develop radiation-hard FBGs was based on the decision to use radiation-tolerant Fluorine-doped single-mode fibers (SMF) because they are known to have lower RIA values compared to other SMF [5] in the targeted dose range.

In previous publications we already presented results about details of the development process regarding FBG production methods and conditions, dose rate dependence and response to high dose levels of X-rays in commercial fibers [6][7][8][9]. In contrast to previous work, in this paper we will present results obtained on the most promising FBGs written in a new F-doped single-mode fiber provided by iXBlue under gamma radiation.

II. EXPERIMENTAL METHODS

A. Irradiation procedure

As already outlined in [9] the irradiations were carried out at the TK1000A Co-60 facility at Fraunhofer INT produced by Isotopentechnik Sauerwein. The activity for the fiber irradiation was 8.6 TBq and about 21 TBq for the FBG irradiation due to a reloading in-between. The point-like

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radioactive pellet is placed relative to the irradiated object (optical fiber sample or group of FBGs) in a defined distance yielding a precisely determined dose rate and non-uniformity in the sample.

Dose rates around the source at various positions and distances are constantly measured with calibrated ionization chambers manufactured by PTW with ISO17025 certified traceability to national standards. Based on that, a numerical model gives dose rate, dose rate uncertainty, and non-uniformity at any given position and time.

B. Irradiation of the single-mode fiber

The fiber under test is the one used for the inscription of FBGs at the Laboratory Hubert Curien in Saint Etienne. It is a Fluorine-doped single mode fiber manufactured by iXBlue in Lannion (France). The fiber has cladding and core size diameters of 125 µm and about 7 µm, respectively, and an attenuation of 0.3 dB/km at 1550 nm with acrylate coating.

The gamma irradiation test is made to confirm the expected low radiation response and therefore be a good candidate fiber for radiation-resistant FBGs [5].

The measurement setup consists of three light sources, several optical switches, two power meters and a spectrometer [9]. Two of the light sources are custom made SLED and LD sources with wavelengths of 1570 nm and 1312 nm, respectively, and high stability. The third source is a TQ8111 white-light source manufactured by Advantest. Optical switches by Sercalo guide the light from a selected light source to up to two samples in the irradiation chamber. Additionally a reference channel is measured by introducing a coupler. The optical power of the two discrete sources is measured with HP8153x precision power meters by Agilent. The light power while starting the RIA measurements was -20 dBm. The spectral transmission of the white-light source is measured with an OceanOptics NIRquest array spectrometer. All used equipment is calibrated and traceable to national standards. A detailed description can be found elsewhere [10]. During the online measurements the two discrete light powers are measured one after the other followed by the respective reference channels. Every ten discrete measurements a transmission-, dark-, and reference spectrum of the fiber is taken. The whole setup is situated in a thermally stabilized measurement booth (the temperature variation during the campaign as below ±0.5°C).

The fibers are wound stress free onto Aluminum sample spools with a diameter of 6 cm and a width of 1 cm. The sample length was 125 m. For irradiation the radioactive pellet is ejected from its shielding position into the center of the spool within less than 0.5 s. The total time of irradiation was about 85 h. The samples were in ambient air at a temperature of 24°C.

The mean dose rate in the fiber sample was 0.7 Gy(SiO_2)/s with an expanded uncertainty of 7%. The non-uniformity was 37% due to the rather thick layer of fiber wound onto the spool.

Online measurements are done with the sample installed at the deactivated irradiation facility for 20 h to check the consistency and stability of the setup. Then the irradiation of 84.75 h is started after which the annealing is observed for another 31 h.

For analysis the measurement channels are compensated with the reference channels to decrease the influence of potential drifts of the light sources.

C. Irradiation of the FBGs

The FBGs tested under gamma radiation were optimized for radiation hardness and temperature stability in previous phases of this project. As detailed elsewhere [6][8], these gratings were written with the phase mask technique by a femtosecond laser at 800 nm. For the laser parameters, the pulse width was fixed between 60 fs and 150 fs, the repetition rate was 100 Hz, whereas the power density at the focal spot was higher than 10^{13} W/cm². Moreover a scan of the laser beam along the entire core was performed at 5 Hz frequency and 12 µm range, to homogenize the induced refractive index change in the core. The length of the gratings was 5 mm. In order to improve the high temperature and radiation resistance of the gratings [3], these were subjected to a 15 minutes lasting thermal treatment at 750°C.

The aim of this campaign was to confirm the radiation response in extension to the X-ray irradiations also under gamma radiation at different temperatures.

During the whole campaign a total of 18 FBGs were irradiated at three different temperatures.

As presented before [9], the FBGs were uncoated and mounted without mechanical load in grooves engraved in an Aluminum plate and placed below the irradiation source. The fiber leads of the gratings were fixed on one side whereas the other side was not mounted to the base plate. This sample setup decouples any mechanical influence from the base plate to the FBGs. Heating and cooling (without radiation) of this sample arrangement confirmed the isolation of the mechanical response between the Aluminum and the gratings which led to the determination of a temperature sensitivity coefficient for the FBGs of 10.4 pm/°C. Temperature measurements on two sides of the FBGs were used to obtain the temperature variation during irradiation, since the ionizing radiation leads to a slight temperature increase that is compensated in the analysis of the results.

The samples are mounted on a temperature regulated plate with a range from room temperature to 350°C. The Bragg wavelength of up to 8 FBGs is measured with a FOS&S FBG-Scan 608 with an integrated switch. The spectra are stored every 5 minutes for each channel in a file for further analysis. The peak position is determined by fitting a straight line to the slopes of the peak in a defined height, typically 3 dB below the maximum.

The distance between the center of the source and the FBGs was 4.1 cm. The mean dose rate in the FBGs was 1.0 Gy(SiO_2)/s with an uncertainty of 5% and a non-uniformity of 6%. Temperatures were measured at two positions directly at the FBGs and in various positions around the setup with an uncertainty of ±1°C. Additionally one FBG was positioned outside the irradiation chamber together with

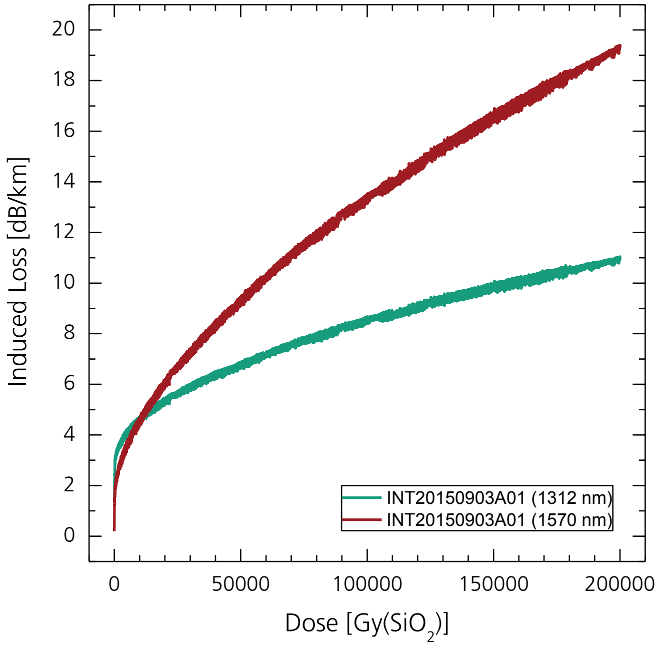

Fig. 1. Radiation-induced loss at 1312 nm and 1570 nm in a Fluorine-doped single-mode fiber at room temperature [9].

the interrogator in a thermally stabilized measurement booth to detect any systematic drifts or external influences on the setup.

III. RESULTS AND DISCUSSION

A. *Fluorine-doped Single-mode fiber*

The results for the radiation induced loss at the two discrete wavelengths are shown in Fig. 1 up to a total dose of 200 kGy(SiO$_2$). Except for the first phase up to roughly 10 kGy(SiO$_2$) the induced loss is lower at 1312 nm which is typical for this type of fiber as already shown in [11].

In comparison with other F-doped SMF the RIA values are slightly higher which is likely to be caused by parameter optimization for the production of FBGs [9].

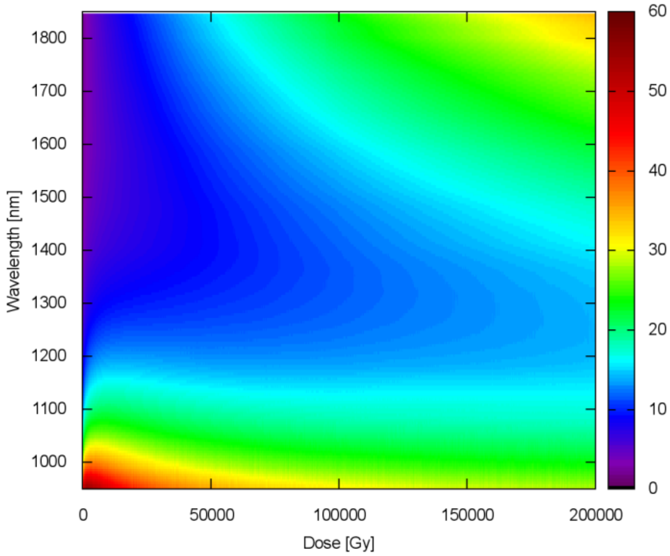

Fig. 2. Radiation-induced loss in color scale representing dB/km between 950 nm and 1850 nm in a Fluorine-doped single-mode fiber at room temperature as a function of dose [9].

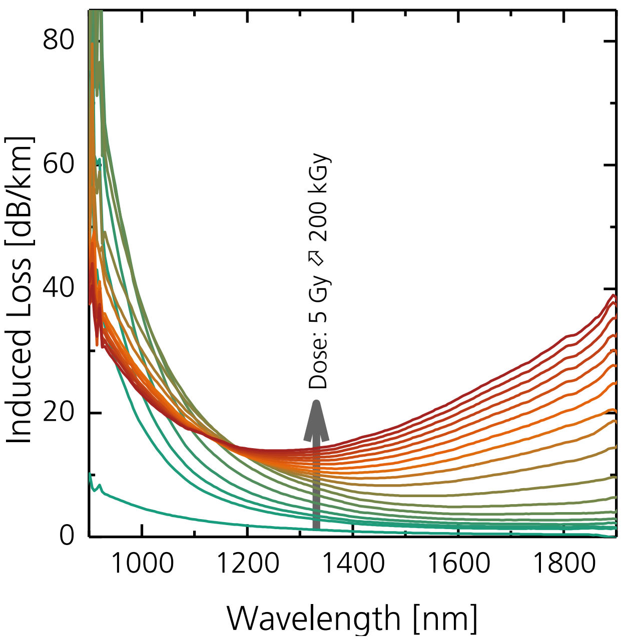

Fig. 3. Spectral radiation-induced loss as a function of wavelength at increasing dose values between 5 Gy and 200 kGy in a Fluorine-doped single-mode fiber at room temperature.

The spectral dependency of the RIA as a function of dose is shown in the color-plot of Fig. 2. The observation of Fig. 1 that the minimum of the RIA decreases with increasing dose from larger wavelengths to lower values is confirmed.

After a total dose of 200 kGy(SiO$_2$) the minimum RIA corresponds to a wavelength of about 1250 nm.

This is due to the slowly increasing absorption centers in the infrared that gain influence on the spectral attenuation.

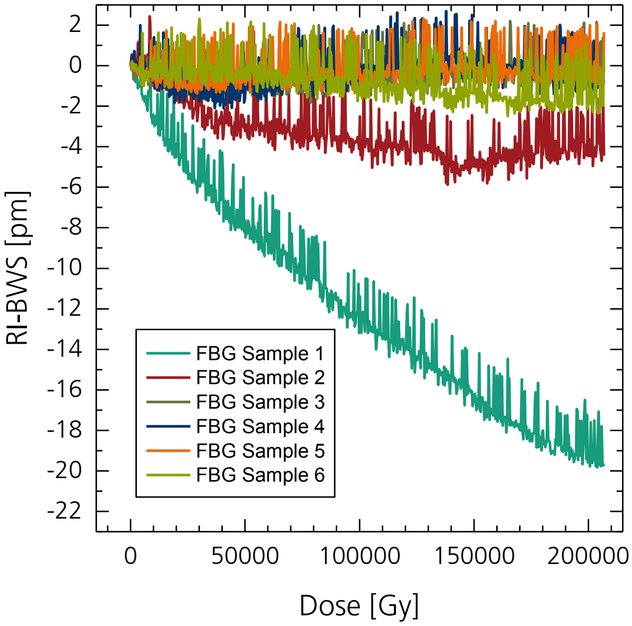

Fig. 4. Radiation-induced BWS at room temperature for six FBGs as a function of dose (two samples from [9]).

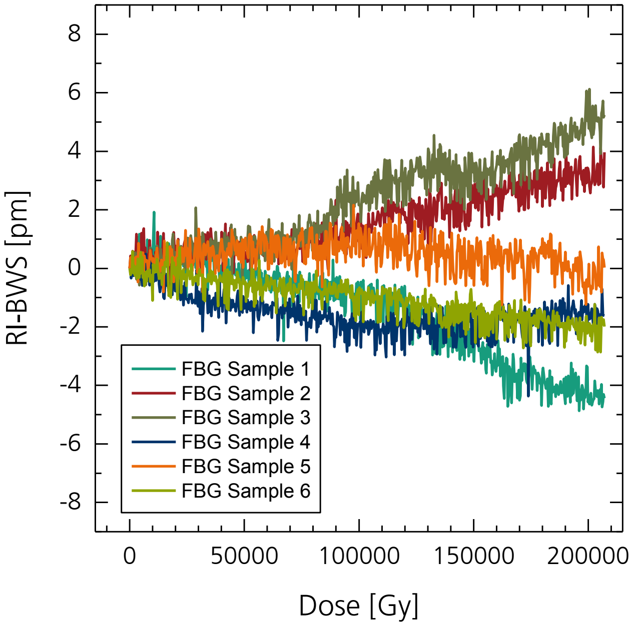

Fig. 5. Radiation-induced BWS at 100°C for six FBGs as a function of dose dose (two samples from [9]).

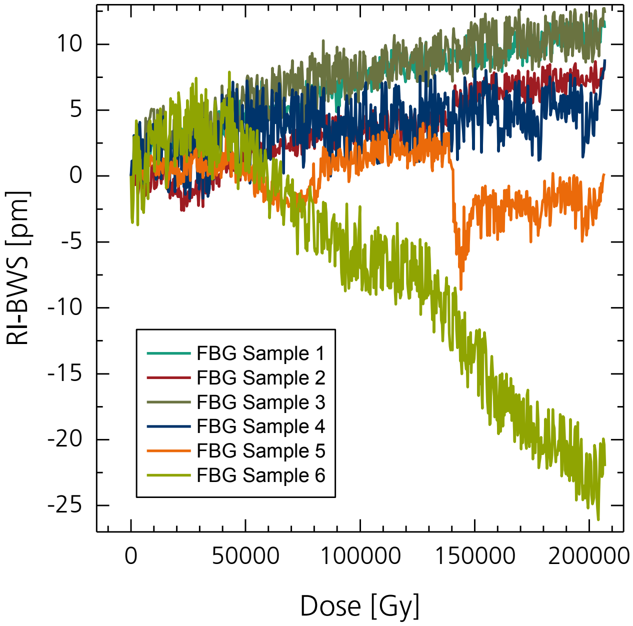

Fig. 6. Radiation-induced BWS at 335°C for six FBGs as a function of dose.

Contrary to the attenuation induced in the infrared region, the one at shorter wavelengths increases quickly immediately after the irradiation start, before slightly decreasing.. This is also highlighted in Fig. 3 where the radiation-induced attenuation is plotted as a function of wavelength for several dose values.

B. *Radiation hard Fiber-Bragg-Gratings*

The FBGs produced at LabHC showed excellent radiation resistance under X-ray irradiation at different temperatures. In the following the results obtained under Co-60 gamma radiation will be shown.

In Fig. 4 the radiation-induced Bragg wavelength shift at room temperature for six FBGs is shown. Even though a relatively high noise is present, the overall change of the Bragg wavelength is clearly below 2 pm confirming the excellent radiation hardness of the produced FBGs, except for FBG sample 1. This FBG showed instability even before irradiation, suggesting that some problem happened during the annealing procedure performed after inscription or by placing the grating on the aluminum plate for the irradiation test, for example, the grating had to be fixed on the plate because of the presence of some impurity in its grave. The result of this FBG suggests that the annealing procedure after inscription did not happen correctly, leading to a much larger radiation induced variation. The probable reason was a misalignment of the grating in the oven so that the needed temperature was not reached at this specific FBG.

But within the five correctly treated FBGs the high reproducibility is demonstrated.

Since the foreseen applications in nuclear facilities demand also reliable operation at higher temperatures the following Fig. 5 shows the results at 100°C for another six FBGs, complemented by the results shown in Fig. 6 at 335°C.

Again, at 100°C the irradiation induces no noticeable change of the Bragg wavelength and confirms these gratings as radiation hard over a wide range of temperatures.

During the irradiation at 335°C, one of the six gratings, Sample 6, shows again higher radiation sensitivity, in particular its Bragg peak blue-shifts with increasing dose. However, it is known that the main effect of a thermal treatment at high temperature on a grating is a blue-shift; as a consequence, we thought that the recorded shift on this FBG is not induced by radiation but by the high temperature. Probably the pre-irradiation thermal treatment was not well performed, yielding to a grating instable at temperatures as high as 335°C.

The sudden jump observed around 140 kGy(SiO_2) in the signal of the grating Sample 5, instead, can be caused by a mechanical relaxation during the irradiation.

The RI-BWS of less than ±2 pm (including noise) up to a total dose of 200 kGy(SiO_2) corresponds to a temperature influence on the measurement of ±0.2°C.

In literature, good results on radiation-resistant gratings written with femtosecond laser have been already shown by Henschel et al. [12]. However, their gratings, which were subjected to a pre-annealing at only 250°C, showed a red-shift up to few pm under gamma-irradiation at room temperature up to the accumulated dose of 100 kGy(SiO_2). The results presented here on our Rad-Hard FBGs [3] exhibit no noticeable shift (lower than ±5pm) up to the accumulated gamma-dose of 200 kGy(SiO_2) at different irradiation temperatures, between room temperature and 335°C. These confirm the radiation resistance of our Rad-Hard gratings in harsh environments mixing both gamma-rays and high temperatures.

Through continuous variation of individual parameters during the development of the inscription process, stable and reproducible radiation-hardened FBGs can be produced.

IV. CONCLUSIONS

It has been demonstrated that radiation-hardened Fiber Bragg Gratings can be produced with the patented process developed by Laboratoire Hubert Curien. It was confirmed that the radiation resistance already shown under X-ray irradiation is also found under gamma radiation, which is a more representative environment for nuclear applications.

As a next step the FBGs will be optimized in their optical properties to match the sensor constraints while keeping their radiation hardness intact. Ultimately the optimized and qualified FBGs will be integrated into sensor elements for implementation in the final application.

REFERENCES

[1] K. O. Hill, Y. Fujii, D. C. Johnson and B. Kawasaki, “Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication,” *Appl. Phy. Lett.*, vol. 32, no. 10, pp. 647-649, 1978. doi:10.1063/1.89881

[2] A. Gusarov and S. Hoeffgen, “Radiation effects on fiber gratings,” *IEEE Trans. Nucl. Sci.*, vol. 60, pp. 2037-2053, Jun. 2013. doi:10.1109/TNS.2013.2252366

[3] AREVA and Laboratoire Hubert Curien, “Procédé de fabrication d'une fibre optique traitée pour capteur de température résistant aux radiations.” France Brevet 13 62691, 16 December 2013.

[4] http://www.innoenergy.com/innovationproject/our-innovation-projects/hoban/ (Last accessed 2017-12-21)

[5] S. Girard, J. Kuhnhenn, A. Gusarov, B. Brichard, M. Van Uffelen, Y. Ouerdane, A. Boukenter and C. Marcandella, “Radiation effects on silica-based optical fibers: recent advances and future challenges,” *IEEE Trans. Nucl. Sci.*, vol. 60, pp. 2015-2036, Jun. 2013. doi: 10.1109/TNS.2012.2235464

[6] A. Morana, S. Girard, E. Marin, C. Marcandella, P. Paillet, J. Périsse, J.-R. Macé, A. Boukenter, M. Cannas and Y. Ouerdane, “Radiation tolerant Fiber Bragg Gratings for high temperature monitoring at MGy dose levels,” *Opt. Lett.*, vol. 39, no. 18, pp. 5313-5316, Sep. 2014. doi:10.1364/OL.39.005313

[7] A. Morana, S. Girard, E. Marin, S. Rizzolo, C. Marcandella, P. Paillet, J. Périsse, J. Kuhnhenn, J. Grelin, G. Melin, T. Robin, B. Cadier, A. Boukenter, Y. Ouerdane and J.-R. Macé, “HOBAN project: towards the development of radiation-tolerant fiber-based temperature sensors for nuclear industry,” in *24th International Conference on Optical Fibre Sensors*, Curitiba, Brazil, Proc. SPIE 96347Z, (September 28, 2015); doi:10.1117/12.2195063

[8] A. Morana, S. Girard, E. Marin, J. Périsse, J.S. Genot, J. Kuhnhenn, J. Grelin, L Hutter, G. Mélin, L. Lablonde, T. Robin, B. Cadier, J.-R. Macé, A. Boukenter, and Y. Ouerdane, “Radiation-Hardened Fiber Bragg Grating Based Sensors for Harsh Environments,” accepted for publication in *IEEE Trans. Nucl. Sci.*, doi:10.1109/TNS.2016.2621165

[9] J. Kuhnhenn, U. Weinand, A. Morana, S. Girard, Senior Member, IEEE, E. Marin, J. Périsse, J.S. Genot, J. Grelin, L Hutter, G. Mélin, L. Lablonde, T. Robin, B. Cadier, J.-R. Macé, A. Boukenter, and Y. Ouerdane, “Gamma Radiation Tests of Radiation-Hardened Fiber Bragg Grating Based Sensors for Radiation Environments,” in *Proc. of Radiation Effects in Components and Systems*, Bremen, Germany, 2016.

[10] J. Kuhnhenn, S. K. Höffgen and U. Weinand, “Quality Assurance for Irradiation Tests of Optical Fibers: Uncertainty and Reproducibility,” in *IEEE Trans. Nucl. Sci.*, vol. 56, pp. 2160-2166, Aug. 2009. doi:10.1109/TNS.2009.2019605

[11] T. Wijnands, L. K. De Jonge, J. Kuhnhenn, S. K. Höffgen and U. Weinand, “Optical Absorption in Commercial Single Mode Optical Fibers in a High Energy Physics Radiation Field,” in *IEEE Trans. Nucl. Sci.*, vol. 55, pp. 2216-2222, Aug. 2008. doi:10.1109/TNS.2008.2001859

[12] H. Henschel, D. Grobnic, S. K. Höffgen, J. Kuhnhenn, S. J. Mihailov and U. Weinand, “Development of Highly Radiation Resistant Fiber Bragg Gratings,” in *IEEE Trans. Nucl. Sci.*, vol. 58, pp. 2103-2110, Aug. 2011. doi:10.1109/TNS.2011.2160204