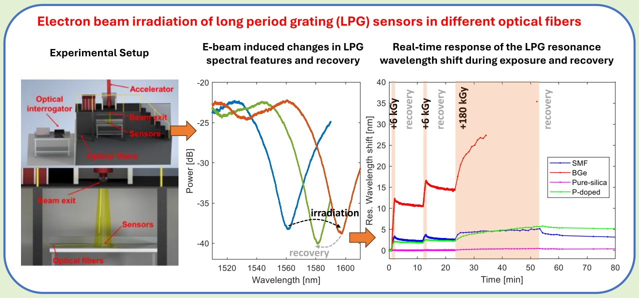
Electron Radiation Impact on Long Period Gratings in Different Optical Fibers

Andrei Stancalie, Flavio Esposito, *Member, IEEE*, Razvan Mihalcea, Laura Mihai, *Member, IEEE*,
Daniel Ighigeanu, Anubhav Srivastava, Stefania Campopiano, *Member, IEEE*,
and Agostino Iadicicco, *Member, IEEE*



***Abstract*—We report for the first time on the effects of electron radiation on the spectral properties of long period grating (LPG) sensors fabricated in various commercially available single-mode silica optical fibers, namely, standard SMF28, a B/Ge co-doped fiber, a pure-silica core fiber, and a P-doped fiber. These LPGs were exposed to a 5.5-MeV e-beam with a dose rate of 6 kGy/min and a total accumulated dose of 192 kGy. The impact is discussed in terms of the real-time resonance wavelength shift, depending on the fiber type. To better understand the benefits and limits of utilizing this technology in specific applications, we also investigated the long-term recovery of the devices following exposure, with intermediate evaluations at 21 h, eight days, six months, and 12 months after irradiation is finished. The main findings are that LPG in B/Ge co-doped fiber is responding up to 192 kGy, with a resonance wavelength shift exceeding 35 nm and no evidence of saturation. In addition, we demonstrated its long-term data storage potential, showing a 45% recovery toward initial values after post-irradiation stabilization. On the contrary, pure-silica core fiber maintains radiation-hardening properties against electrons. This study is the first to test the limitations of LPGs fabricated in both sensitive and radiation-hardened optical fibers, subjected to high dose rates, with a focus on both the temporary and permanent electron-induced effects.**

***Index Terms*— Dosimetry, electrons, fiber gratings, long period gratings (LPGs), optical fiber sensors, optical fibers, radiation.**

Received 23 October 2024; revised 25 November 2024; accepted 27 November 2024. Date of publication 9 December 2024; date of current version 14 January 2025. This work was supported in part by European Union-Next Generation EU under the Italian National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.3, through "Telecommunications of the Future" (PE00000001-Program "RESTART") under Grant CUP E63C22002070006; and in part by the National Interest Infrastructure Facility IOSIN–CETAL at INFLPR and National Projects through the Romanian Ministry of Research, Innovation and Digitization under Grant 666PED/2022 and Grant ELI-RO/RDI/2024_039. The associate editor coordinating the review of this article and approving it for publication was Dr. Xuehao Hu. *(Corresponding author: Flavio Esposito.)*

Andrei Stancalie, Razvan Mihalcea, and Laura Mihai are with the Center for Advanced Laser Technologies (CETAL), National Institute for Laser, Plasma and Radiation Physics, 077125 Magurele, Romania (e-mail: andrei.stancalie@inflpr.ro; razvan.mihalcea@inflpr.ro; laura.mihai@inflpr.ro).

Flavio Esposito, Anubhav Srivastava, Stefania Campopiano, and Agostino Iadicicco are with the Department of Engineering, University of Naples "Parthenope," 80143 Naples, Italy (e-mail: flavio.esposito@uniparthenope.it; anubhav.srivastava001@studenti.uniparthenope.it; stefania.campopiano@uniparthenope.it; agostino.iadicicco@uniparthenope.it).

Daniel Ighigeanu is with the Accelerators Department, National Institute for Laser, Plasma and Radiation Physics, 077125 Magurele, Romania (e-mail: daniel.ighigeanu@inflpr.ro).

Digital Object Identifier 10.1109/JSEN.2024.3508885

I. INTRODUCTION

RESEARCH on the effects of ionizing radiation on optical fibers has been gaining growing attention for years, as they are getting integrated into increasingly complex systems and infrastructures [1], [2]. Optical fibers are essential in various fields, from telecommunications to military [3] and space applications [4], where exposure to radiation is a major concern. Studies in this field aim to understand the degradation mechanisms [5], [6], [7] and develop solutions to mitigate these effects [8]. Protective methods include the use of special materials, improving manufacturing techniques, and developing radiation-resistant optical fibers [9]. The integration of optical fibers into critical infrastructures, such as communication networks for nuclear power plants [10], satellites [11], and spacecraft, requires a deep understanding of their behavior in high-radiation environments. Research in this area is essential to ensure the reliability and longevity of the systems in such environments. Ionizing radiation can cause various effects on optical fibers, such as signal attenuation, changes in spectral characteristics, and performance losses [12], [13]. These effects depend on several factors, including the type and dose of radiation, the composition and structure of the fiber, and the operating conditions [7].

On the other hand, structures fabricated in optical fibers, such as gratings, have demonstrated an excellent ability to quantify both the effects of ionizing radiation on the component materials [14] as well as key parameters of the radiation itself, such as the accumulated local dose [15]. The dual capability of optical fiber sensors to evaluate both critical parameters such as relative humidity, temperature, or strain in contaminated areas [16], and also radiation metrics is invaluable in a range of applications. For instance, in medical settings, these sensors ensure the safety and efficacy of radiation therapies by monitoring doses with high precision [17], [18]. In nuclear power plants, they help assess the integrity of materials exposed to radiation, contributing to the safe operation and maintenance of the facilities [19]. Furthermore, in space missions, where materials are subjected to high levels of cosmic radiation, optical fiber sensors may play a critical role in ensuring the reliability and longevity of spacecraft components [20].

Radiation tests on optical fiber sensors require well-calibrated sources of ionizing radiation and standardized dosimetry systems. Most studies have focused on the gamma-ray, X-ray, and neutron effects [15], while the most popular devices characterized were fiber Bragg gratings (FBGs) fabricated either in standard silica fibers [21], micro-structured/photonic crystal fibers [22], or polymer ones [23].

Electron radiation effects, however, have only been addressed in a limited number of scientific reports. FBGs fabricated in standard and radiation-hardened optical fibers were subjected to an e-beam up to 8-kGy accumulated dose, quantifying the radiation effects based on calorimetry [24], while in [25] the authors report on the induced effects as dependent on FBG fabrication method, namely, point by point or plane by plane. In all cases, the spectral changes exhibited by the devices were very low, in general not higher than a few hundred pm [26].

Currently, there is no report in the literature to address the e-beam-induced effects on long period gratings (LPGs). These have demonstrated a very high potential for use in various radiation field applications [27]. For example, in [28], we demonstrated the capacity of an LPG in B/Ge co-doped fiber to withstand a gamma dose of 52 kGy (at 2.6-kGy/h dose rate) without reaching a saturation level and exhibiting a shift of approximately 10 nm; that pure-silica core and F-doped fibers proved their efficiency as radiation-hardened types, with the resonance wavelength stable in a region under 0.7 nm. Moreover, an LPG fabricated in a B/Ge co-doped optical fiber was also tested at the European Organization for Nuclear Research (CERN) under proton radiation with a fluence of $4.4\cdot10^{15}$ p/cm^2 over the absorbed dose of 1.16 MGy while exhibiting a shift of ~44 nm [29]. These works highlighted that, depending on the optical fiber in which they are manufactured, LPGs have a significantly greater capacity to react in correlation with the accumulated dose, exhibiting shifts of the resonance wavelength with orders of magnitude higher than FBGs [30]. However, despite the investigations under gamma, neutrons, and protons [31], there is no evidence when exposed to electron radiation.

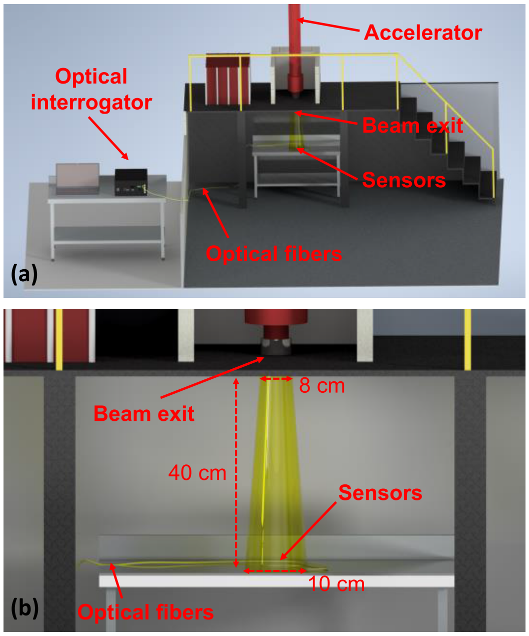


Fig. 1. Electron accelerator and setup (a) overview and (b) zoom on beam exit and fiber sensors location.

In this work, studies on electron radiation impact were conducted on four different optical fibers, in which the inscription of LPG was performed by the electric arc discharge technique. The selected fibers include: SMF28 as a standard reference for comparative evaluation against specialty optical fibers as well as being one of the most extensively characterized in literature; a B/Ge co-doped fiber because of high radiation sensitivity demonstrated in previous works; a pure-silica core fiber for the radiation-hardened behavior; and a P-doped fiber as it has garnered attention in several applications in radiation environments [12], [32]. For the purpose of the work, a linear electron accelerator was employed to expose the gratings simultaneously, at the same dose rate of 6 kGy/min and up to 192-kGy accumulated dose. Real-time radiation-induced effects as well as long-term recovery changes over a one-year period were observed.

II. PRINCIPLE OF OPERATION AND METHODS

A. LPG Preparation

LPGs are typically created through periodic modulation of the refractive index (RI) in the optical fiber core. This process enables coupling from the fundamental core mode to certain resonant cladding modes, resulting in dips in the transmission spectrum at wavelengths that meet the phase-matching condition

$$\lambda_{\mathrm{res}}(\mathrm{m}) = [n_{\mathrm{eff,co}} - n_{\mathrm{eff,cl}}(\mathrm{m})] \cdot \Lambda \tag{1}$$

where $\lambda_{\mathrm{res}}(\mathrm{m})$ is the resonant wavelength between the core and the mth cladding mode; Λ is the grating period; and $n_{\mathrm{eff,co}}$

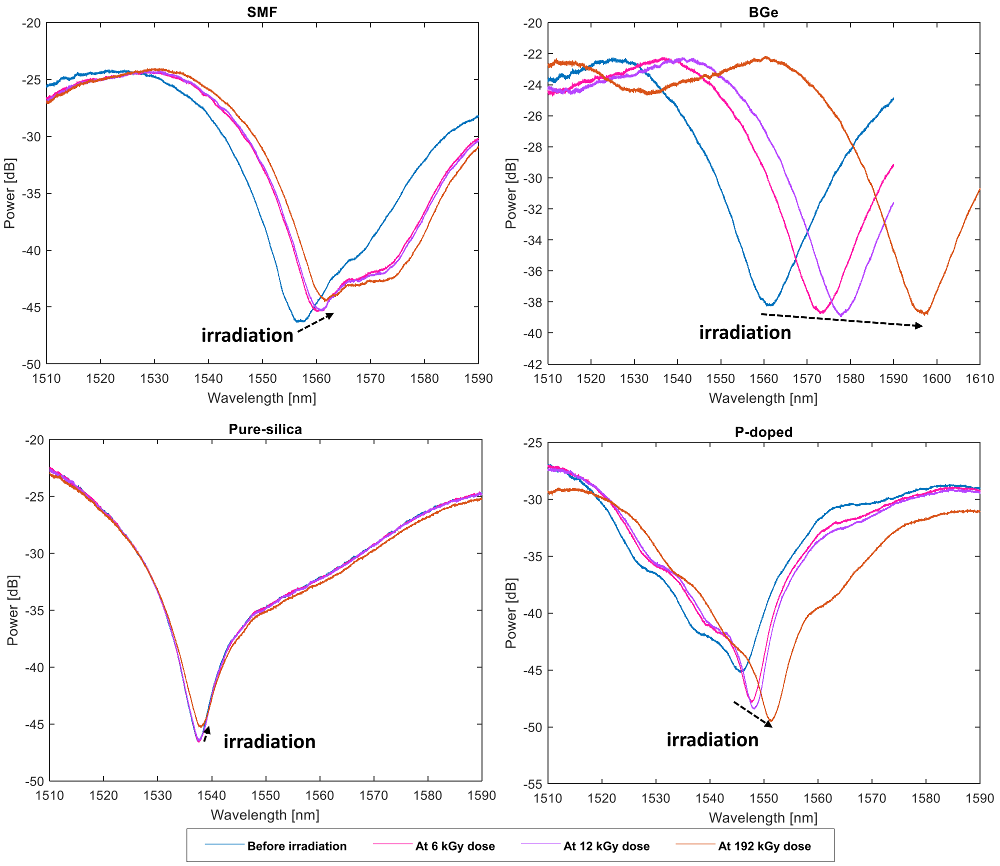


Fig. 2. LPG spectra acquired during irradiation phases corresponding to different doses: before irradiation and after 6-, 12-, and 192-kGy total absorbed dose.

and $n_{\text{eff},\text{cl}}(m)$ represent the effective RIs of the core and the mth order cladding mode, respectively.

For the purpose of the work, the following commercially available single-mode silica optical fibers were selected: standard Ge-doped Corning SMF28, pure-silica core with F-doped cladding Nufern S1310, photosensitive B/Ge co-doped Fibercore PS1250/1500, and P-doped FORC P-SM-5. The compositions of the fibers are further summarized in Table I. The LPGs were created using the arc discharge method in the abovementioned fibers, as detailed in our previous research [33]. This technique allows for the processing of a wide variety of fibers, not limited to photosensitive ones. Briefly, the grating is formed by applying milliseconds of lasting electrical discharge to a section of uncoated optical fiber while maintaining constant pulling tension. This leads to a modification of the RI due to the relaxation of drawing stresses and a slight tapering of the fiber shape. The process is repeated by moving the fiber by the grating period after each discharge using a translation stage with micrometric precision. The period of the LPG was adjusted to the specific fiber in order to have the coupling near sixth-order cladding mode within 1540–1560 nm, according to Table I. For each fiber under test, after grating fabrication, a 15-cm-long section of the same, including the LPG area, was spliced to a standard single-mode patch cord.

Although transmission configuration is trivial in the case of LPG investigations, in the current scenario, efforts were dedicated to convert them to reflection configurations. The aim was to decrease the cross-sensitivity to the external effects such as strain/bending induced given the high sensitivity of the LPG in general to such mechanisms. For this reason, all LPG was cut at one end with a 90° angle, further applying a thin coating of silver-based painting on the fiber tip. This approach was successfully tested and reported previously [28].

TABLE I
OPTICAL FIBER AND LPG PARAMETERS

Fiber model	Core composition	Cladding composition	LPG id	LPG period Λ
Corning SMF28	Ge-doped	Pure-silica	SMF	395 μm
Fibercore PS1250/1500	B/Ge co-doped	Pure-silica	BGe	300 μm
Nufern S1310	Pure-silica	F-doped	Pure-silica	440 μm
FORC P-SM-5	P-doped	P-doped	P-doped	395 μm

B. E-Beam Irradiation Setup

Radiation tests were carried out by using a traveling-wave linear accelerator powered by a 2-MW peak power tunable EEV M5125 magnetron operating in the S-band (2992–3001 MHz). To achieve maximum output power P_{EB} for a given pulse duration t_{EB} and repetition frequency f_{EB}, the optimal settings were: $E_{\text{EB}} = 5.5$ MeV, $I_{\text{EB}} = 130$ mA, and $P_{\text{EB}} = 670$ W, with $f_{\text{EB}} = 250$ Hz and $t_{\text{EB}} = 3.75$ μs. The resulting dose rate was 6 kGy/min and the irradiation was performed 40 cm far from the beam exit. Fig. 1(a) illustrates an overall picture of the electron accelerator and measurement setup, whereas Fig. 1(b) shows the details of the beam exit and sensor location.

The LPGs under test were acquired using an SM125 Micron Optics 4-channel optical interrogator via 20-m-long connecting fibers. The data acquisition was performed in real time during the irradiation, within the range of 1510–1590 nm. While the interrogation equipment was placed in a shielded room, the LPGs were centrally placed within the e-beam region. One J-type thermocouple was placed near the gratings location to address any temperature-induced effects on the LPG and to perform the required data corrections, so extract solely the radiation-induced effects on the key spectral parameters. The dosimetry at a specific distance from beam exit was conducted both prior to and after the experiment utilizing graphite calorimeters, calibrated at Risø High Dose Reference Laboratory.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. E-Beam Exposure of LPGs

The experimental session was divided into three phases. The first two consisted of successive exposures of 6-kGy accumulated dose (1-min exposure) followed by a 10-min break each. These phases aimed twofold: to observe the reproducibility of the induced effects and to check the variation of the resonance wavelength as dependent on previously accumulated dose. The third phase consisted of continuous irradiation of 180 kGy (30-min exposure). In this case, the focus was on testing the limitations of the LPGs in terms of the saturation level of the wavelength shift and the radiation-induced attenuation (RIA), as observed at a high dose rate. Overall, the total accumulated dose was 192 kGy after about 52 min from the beginning of the experiment.

For each selected LPG, Fig. 2 plots the spectra corresponding to the end of each irradiation phase, i.e., after an accumulated dose of 6, 12, and 192 kGy, compared with the pristine spectra (before irradiation). Overall, a redshift of the LPG attenuation bands can be observed, with the magnitude strongly depending on the absorbed dose and the fiber type. The most radiation-sensitive device has been the B/Ge LPG and the most resistant one in pure-silica core fiber. As the LPG resonances are related to the core and cladding refractive indices through the effective RIs of the modes involved in the coupling mechanism [according to (1)], the main reason for the LPG shift is the radiation-induced RI change (RIRIC) occurring in the fiber core [31]. Besides the RIRIC, information about the RIA through the monitoring of the power level of the baseline can also be obtained from Fig. 2. Here, small changes can be observed in all cases, except for P-doped fiber exhibiting an attenuation of about 3 dB at the highest dose, with a trend similar to previous works that were focused on gamma induced variations and literature [28], [34].

For the deeper observation of electron-induced effects, the real-time variation of the resonance wavelengths for all four LPGs is plotted in Fig. 3(a). The three irradiation phases are represented by the shaded regions, followed by a short stabilization time of around 30 min after the last exposure. Overall, it can be confirmed that the exposure induced a redshift in the resonance wavelengths for all LPGs during the irradiation, combined with a slight recovery as the irradiation is stopped. The magnitude of redshift, recovery, and trends are strongly dependent on the fiber type.

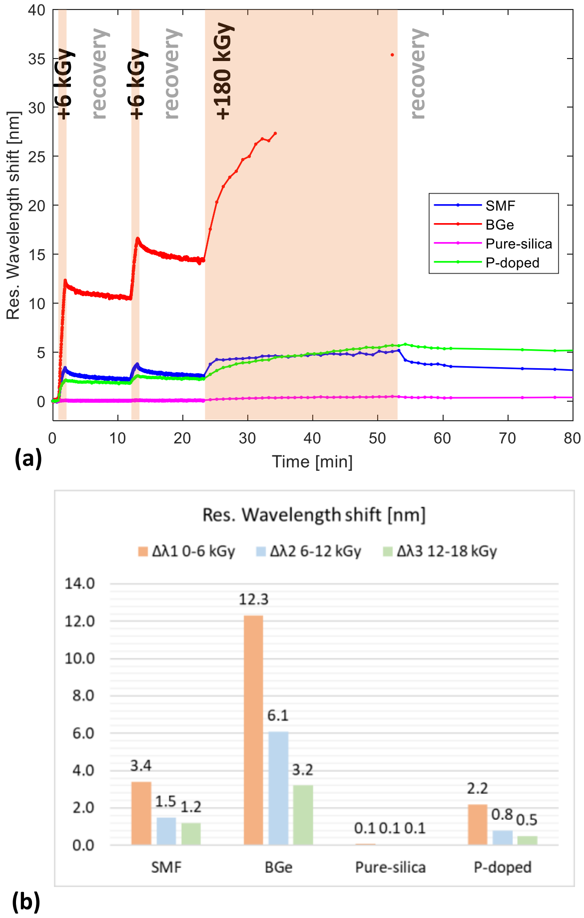


Fig. 3. (a) Real-time wavelength shift of the LPGs during e-beam radiation at 6 kGy/h in three phases, i.e., exposing to 6-, 6-, and 180-kGy radiation dose (up to 192-kGy total accumulated dose). The shadowed regions are marking the different irradiation phases. (b) Wavelength shifts after an additional exposure to 6-kGy dose, starting from different previously accumulated doses (0, 6, and 12 kGy).

The highest variation was experienced by the B/Ge LPG; however, the peak tracking was not possible after about 35 min because the redshift moved the attenuation band beyond the upper limit of the instrumentation range (1590 nm). Nevertheless, although real-time monitoring was not possible in this case, once the maximum accumulated dose was reached, the LPG transmitted spectra were measured by using an optical spectrum analyzer with a broader range, permitting to observe a wavelength shift of about 35 nm at the end of the irradiation [red marker in Fig. 3(a)]. Differently, in the case of LPGs in SMF and P-doped fiber the wavelength shift saturated to a value between 5 and 6 nm. Finally, trivial changes were obtained for the pure-silica core fiber LPG with changes below 0.5 nm.

Fig. 3(a) also reveals that, after the redshift of the resonant wavelengths, the LPGs suddenly exhibit a slight relaxation

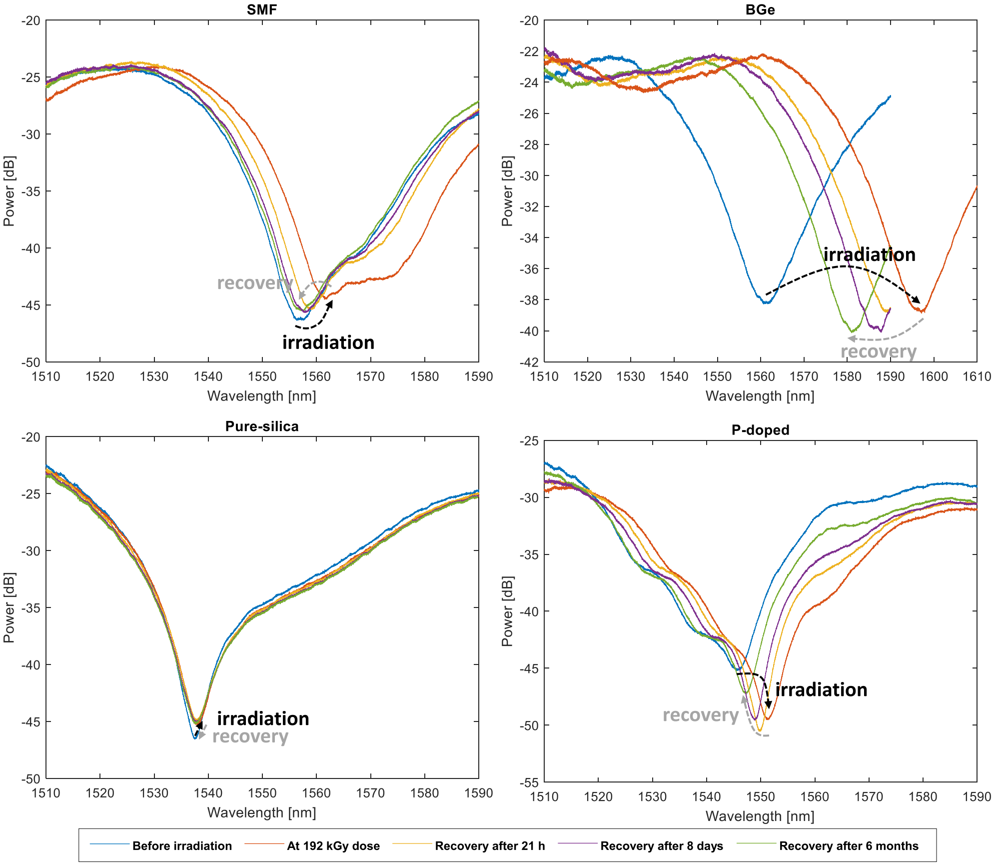


Fig. 4. LPG spectra acquired during different stages: before irradiation; after 192-kGy maximum total dose; during recovery after 21 h, after eight days, and after six months after irradiation stopped.

toward lower wavelengths to recover the pristine position when the radiation is switched off (unmarked regions), in agreement with the literature [35]. The phenomenon is evident for both B/Ge and SMF LPGs equally after phases 1 and 2, whereas it was trivial for the P-doped fiber. Finally, after the irradiation was turned off in phase 3, a long-term recovery has been observed too after 52 min, which will be discussed in Section III-B with details.

Finally, in order to evaluate the changes depending on previously accumulated dose, Fig. 3(b) summarizes the wavelength shift after an additional 6-kGy dose, i.e., after 1-min exposure, for each of the three phases: $\Delta\lambda_1$ considering the shift from pristine condition (0 kGy) to 6-kGy dose, $\Delta\lambda_2$ for the shift from 6 kGy (plus after 10-min recovery) to 12 kGy, and $\Delta\lambda_3$ for the shift from 12 kGy (plus after 10-min recovery) to 18 kGy. These data clearly highlight that the changes decrease with previously accumulated dose, i.e., $\Delta\lambda_1 > \Delta\lambda_2 > \Delta\lambda_3$ for all the fibers. The corresponding sensitivities are reported in Table II, which were calculated using a linear approximation, i.e., dividing the wavelength shift $\Delta\lambda_i$ of the corresponding interval by a 6-kGy dose. Here, one can observe, for example, a decrease in sensitivity when moving from the range 0–6 kGy to 12–18 kGy of 65%–80% depending on fiber type. Moreover, these data translate into the possibility for B/Ge LPG within the 0–6-kGy range (i.e., when the sensitivity is maximum) of detecting a minimal dose of about 0.5 Gy, in case of readout setup with the 1-pm resolution, whereas, for SMF and P-doped LPGs the minimal detectable doses are 2 and 3 Gy, respectively, under the same conditions.

TABLE II
SUMMARY OF THE SENSITIVITIES (S) TO AN ADDITIONAL 6-KGY EXPOSURE, CALCULATED FOR DIFFERENT PREVIOUSLY ACCUMULATED DOSES (0, 6, AND 12 KGY)

LPG id	S_1 0-6 kGy [pm/kGy]	S_2 6-12 kGy [pm/kGy]	S_3 12-18 kGy [pm/kGy]
SMF	570	257	198
BGe	2057	1015	533
P-doped	358	128	77

It is worth pointing out that, despite the physical difference between electron and gamma radiations due to the absence of both the mass at rest and charge of gamma radiation, the results plotted in Fig. 3(a) show a similar trend as compared with the responses of LPGs within same fiber types and exposed to gamma irradiation from [28]. We can observe that the same relationship of order was maintained for the mentioned fibers. Specifically, the most responsive is always the B/Ge LPG whereas SMF and P-doped show a similar smaller behavior; finally, LPG in pure-silica core fiber is confirmed as the most resistant. As currently there is no previous report regarding the electron irradiation effects on LPGs, the attention can be focused on the few reports involving FBGs for comparison. The results of B/Ge LPG are in agreement with [26]. In fact, the authors found that X-rays and protons induce comparable redshifts of the FBGs in the Ge-doped or B/Ge co-doped fibers up to the dose of 10 kGy; moreover, the grating in the B/Ge co-doped fiber was found to be the most sensitive to electrons at higher doses with respect to X-rays. Another study is reported in [25], where different femtosecond fabricated FBGs in SMF28 were irradiated under gamma and electron up to 15 kGy obtaining similar (blue) shifts between the two radiation conditions in the case of plane-by-plane method, and significantly higher shift under electron in the case of point-by-point inscription. Therefore, it is evident that the fabrication process is also affecting the radiation response.

B. Long-Term Recovery Mechanism

Although the study of the effects of different ionizing radiations on optical fiber devices is of large interest, their recovery (amount and duration) is a less investigated aspect. Depending on the application, one may need the information acquired by a device to be stored and preserved after the application, for that information to be available for a long time or to be sequentially accumulated, such as in the case of a dosimeter in radioprotection scenarios. These effects arise primarily from the interaction of radiation with the material of the fiber (glass and dopant ions), leading to the formation of color centers or point defects and the breaking of chemical bonds. When the irradiation is turned off, certain recovery mechanisms begin to mitigate this damage, such as thermal annealing, which can cause defects to recombine or migrate; dopant ions can slowly migrate back to their original positions, reducing defect density; opposite charge carriers that were separated may recombine naturally over time [6].

Usually, such analysis is limited to a few hours/days after the irradiation session [35]. Here, for the first time, long-term post-irradiation recovery effects of up to one year are reported. The LPGs were preserved at room temperature and data were collected at different time intervals, i.e., after 21 h, after eight days, after six months, and after 12 months from the end of irradiation.

Fig. 4 plots the LPG spectra under different conditions: 1) before irradiation; 2) after accumulating a maximum dose of 192 kGy; 3) after short relaxation of 21 h; 4) after eight days; and 5) after total recovery, i.e., resonance wavelength being stabilized in six months. It is visible that after the irradiation, a progressive and partial recovery starts, which practically ends within six months. This mechanism manifests by modifying the spectra toward the initial reference prior to radiation exposure, experiencing a blueshift.

For a better comparison, the summary of the wavelength shift during recovery is numerically represented in Fig. 5(a), where the information about recovery after 12 months is also included. It can be observed that, although in the case of SMF or Nufern pure-silica core fiber, the difference in wavelength from the initial one is very small, a complete return to the initial values does not occur for any of the LPGs. In the case of the B/Ge LPG, the radiation sensitivity demonstrated for other radiation types is maintained [31]. Moreover, what is of notice is that this grating becomes permanently affected by the radiation, the recovery being around 45% and remained stable at that value. Concerning the P-doped fiber, while the recovery was almost trivial in the case of lower doses and short observation times (phases 1 and 2 in Fig. 2), it becomes more similar to SMF fiber after the dose reaches 192 kGy.

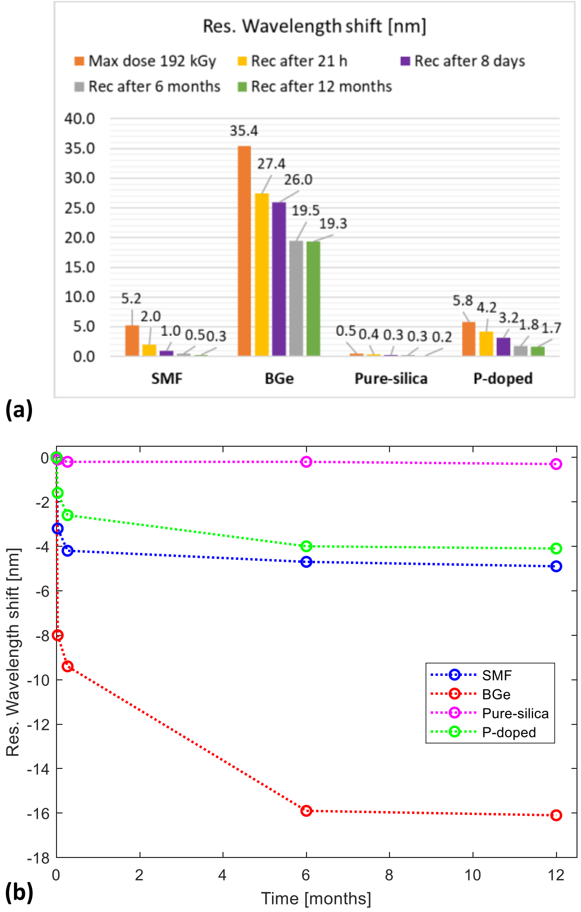


Fig. 5. (a) Summary of the wavelength shift with respect to before irradiation condition: after 192-kGy accumulated dose; recovery after 21 h, after eight days, after six months, and after 12 months irradiation finished. (b) Wavelength shift versus time during recovery, where the initial condition is the value at a maximum accumulated dose of 192 kGy.

In addition, Fig. 5(b) illustrates the temporal evolution of the resonance wavelength during the recovery phase of 12 months. Here, the reference value for each grating is taken at a maximum total dose of 192 kGy. It is clearly visible that in all cases, half of the wavelength shift is recovered during the first day, while there is no significant variation from 6 to 12 months.

IV. CONCLUSION

In this work, we have investigated for the first time the electron radiation-induced real-time effects on LPG sensors inscribed in standard and specialty fibers. Besides comparing commercially available fibers with four different compositions (Ge-doped, B/Ge-doped, pure silica, and P-doped), we have reported on the long-term relaxation mechanisms occurring after the exposure, starting from the initial hours up to one year. The effects on the sensitivity due to radiation, specifically the resonance wavelength shift as a direct function of the accumulated dose, are discussed with respect to prior irradiation. In particular, the LPG in B/Ge co-doped fiber demonstrates exceptional versatility across an extended dose range, providing a response from low doses up to a little under 200 kGy with a variation of the resonance wavelength of more than 35 nm and no saturation. Furthermore, we have demonstrated its long-term information-storing capacity, with a 45% recovery toward initial values after post-irradiation stabilization. While pure-silica core fibers retain their radiation-hardening properties against electrons with no more than 0.5-nm resonance variation, the LPG fabricated in P-doped fiber exhibits similar performance as the one in SMF28. However, after long-term monitoring, none of the fibers above show full radiation annealing at room temperature, demonstrating the permanent induced effects in the fiber composition. Based on these findings, although the LPGs in both SMF28 and P-doped fibers respond to electron radiation, the ones written in B/Ge co-doped fiber retain their suitability for radiation detection purposes due to their high sensitivity; differently, the LPGs in pure-silica core fibers proved their radiation-hardened behavior; thus, their use is suggested for measuring other parameters (e.g., temperature and humidity) in electron particle exposed environments.

REFERENCES

[1] J. Perdigues et al., “HYDRON: The ESA initiative towards optical networking in space,” in *Proc. Eur. Conf. Opt. Commun. (ECOC)*, Bordeaux, France, Sep. 2021, pp. 1–4, doi: 10.1109/ECOC52684.2021.9605702.

[2] G. Breglio et al., “Innovative photonic sensors for safety and security, part III: Environment, agriculture and soil monitoring,” *Sensors*, vol. 23, no. 6, p. 3187, Mar. 2023, doi: 10.3390/s23063187.

[3] M. Kyselak, J. Vavra, K. Slavicek, D. Grenar, and L. Hudcova, “Long distance military fiber-optic polarization sensor improved by an optical amplifier,” *Electronics*, vol. 12, no. 7, p. 1740, Apr. 2023, doi: 10.3390/electronics12071740.

[4] M. Roche et al., “Solar particle event detection with the LUMINA optical fiber dosimeter aboard the international space station,” *IEEE Trans. Nucl. Sci.*, vol. 71, no. 8, pp. 1580–1588, Aug. 2024, doi: 10.1109/TNS.2024.3368137.

[5] Y. Morita and W. Kawakami, “Dose rate effect on radiation induced attenuation of pure silica core optical fibres,” *IEEE Trans. Nucl. Sci.*, vol. 36, no. 1, pp. 584–590, Feb. 1989, doi: 10.1109/23.34505.

[6] S. Girard et al., “Overview of radiation induced point defects in silica-based optical fibers,” *Rev. Phys.*, vol. 4, Nov. 2019, Art. no. 100032, doi: 10.1016/j.revip.2019.100032.

[7] S. Girard et al., “Radiation effects on silica-based optical fibers: Recent advances and future challenges,” *IEEE Trans. Nucl. Sci.*, vol. 60, no. 3, pp. 2015–2036, Jun. 2013, doi: 10.1109/TNS.2012.2235464.

[8] S. Girard et al., “Recent advances in radiation-hardened fiber-based technologies for space applications,” *J. Opt.*, vol. 20, no. 9, Sep. 2018, Art. no. 093001, doi: 10.1088/2040-8986/aad271.

[9] Y. Deng and J. Jiang, “Optical fiber sensors in extreme temperature and radiation environments: A review,” *IEEE Sensors J.*, vol. 22, no. 14, pp. 13811–13834, Jul. 2022, doi: 10.1109/JSEN.2022.3181949.

[10] V. S. Gnyrya et al., “A technique for conducting of reactor in-situ tests of optical fibres and FBG-sensors intended for in-vessel applications in thermonuclear facilities,” *Fusion Eng. Des.*, vol. 191, Jun. 2023, Art. no. 113787, doi: 10.1016/j.fusengdes.2023.113787.

[11] W. Ma, H. Dong, Y. Li, and L. Fan, “Structural health monitoring of satellite board based on high-performance fiber optic grating sensor,” *Opt. Fiber Technol.*, vol. 83, Mar. 2024, Art. no. 103659, doi: 10.1016/j.yofte.2024.103659.

[12] A. L. Tomashuk, M. V. Grekov, S. A. Vasiliev, and V. V. Svetukhin, “Fiber-optic dosimeter based on radiation-induced attenuation in P-doped fiber: Suppression of post-irradiation fading by using two working wavelengths in visible range,” *Opt. Exp.*, vol. 22, no. 14, pp. 16778–16783, Jul. 2014, doi: 10.1364/OE.22.016778.

[13] A. Gallet et al., “Radiation-induced attenuation in aluminum- and aluminum-thulium-doped optical fibers,” *Appl. Opt.*, vol. 62, no. 16, p. E24, Jun. 2023, doi: 10.1364/ao.480576.

[14] F. Esposito et al., “Optical properties of thin films monitored in real-time at high gamma radiation doses using long period fiber gratings,” *Opt. Laser Technol.*, vol. 176, Sep. 2024, Art. no. 111019, doi: 10.1016/j.optlastec.2024.111019.

[15] A. Morana et al., “Radiation effects on fiber Bragg gratings: Vulnerability and hardening studies,” *Sensors*, vol. 22, no. 21, p. 8175, Oct. 2022, doi: 10.3390/s22218175.

[16] G. Berruti et al., “A comparative study of radiation-tolerant fiber optic sensors for relative humidity monitoring in high-radiation environments at CERN,” *IEEE Photon. J.*, vol. 6, no. 6, pp. 1–15, Dec. 2014, doi: 10.1109/JPHOT.2014.2357433.

[17] S. O’Keeffe et al., “A review of recent advances in optical fibre sensors for in vivo dosimetry during radiotherapy,” *Brit. J. Radiol.*, vol. 88, no. 1050, Jun. 2015, Art. no. 20140702, doi: 10.1259/bjr.20140702.

[18] A. Gierej et al., “Mass-manufacturable scintillation-based optical fiber dosimeters for brachytherapy,” *Biosensors Bioelectron.*, vol. 255, Jul. 2024, Art. no. 116237, doi: 10.1016/j.bios.2024.116237.

[19] G. Laffont, R. Cotillard, N. Roussel, R. Desmarchelier, and S. Rougeault, “Temperature resistant fiber Bragg gratings for on-line and structural health monitoring of the next-generation of nuclear reactors,” *Sensors*, vol. 18, no. 6, p. 1791, Jun. 2018, doi: 10.3390/s18061791.

[20] A. Rovera, A. Tancau, N. Boetti, M. L. D. Vedova, P. Maggiore, and D. Janner, “Fiber optic sensors for harsh and high radiation environments in aerospace applications,” *Sensors*, vol. 23, no. 5, p. 2512, Feb. 2023, doi: 10.3390/s23052512.

[21] A. Gusarov and S. K. Hoeffgen, “Radiation effects on fiber gratings,” *IEEE Trans. Nucl. Sci.*, vol. 60, no. 3, pp. 2037–2053, Jun. 2013, doi: 10.1109/TNS.2013.2252366.

[22] A. Morana et al., “Radiation-induced effects on fiber Bragg gratings inscribed in highly birefringent photonic crystal fiber,” *IEEE Trans. Nucl. Sci.*, vol. 66, no. 1, pp. 120–124, Jan. 2019, doi: 10.1109/TNS.2018.2886167.

[23] I. Chapalo et al., “Temperature and RH response of few-mode polymer CYTOP/XYLEX FBGs: Gamma-radiation tuning of sensing properties,” *J. Lightw. Technol.*, vol. 42, no. 18, pp. 6262–6268, Jun. 15, 2024, doi: 10.1109/jlt.2024.3420129.

[24] D. Sporea, A. Stăncălie, N. Becherescu, M. Becker, and M. Rothhardt, “An electron beam profile instrument based on FBGs,” *Sensors*, vol. 14, no. 9, pp. 15786–15801, Aug. 2014, doi: 10.3390/s140915786.

[25] A. Theodosiou et al., “Comparative study of γ- and e-radiation-induced effects on FBGs using different femtosecond laser inscription methods,” *Sensors*, vol. 21, no. 24, p. 8379, Dec. 2021, doi: 10.3390/s21248379.

[26] T. Blanchet et al., “X-ray, proton, and electron radiation effects on type i fiber Bragg gratings,” *IEEE Trans. Nucl. Sci.*, vol. 65, no. 8, pp. 1632–1638, Aug. 2018, doi: 10.1109/TNS.2018.2823771.

[27] A. Stancălie et al., “Arc-induced long period gratings in standard and speciality optical fibers under mixed neutron-gamma irradiation,” *Sci. Rep.*, vol. 7, no. 1, p. 15845, Nov. 2017, doi: 10.1038/s41598-017-16225-4.

[28] F. Esposito et al., “The impact of gamma irradiation on optical fibers identified using long period gratings,” *J. Lightw. Technol.*, vol. 41, no. 13, pp. 4389–4396, Jul. 1, 2023, doi: 10.1109/JLT.2022.3191163.

[29] G. M. Berruti et al., “Analysis of uncoated LPGs written in B-Ge doped fiber under proton irradiation for sensing applications at CERN,” *Sci. Rep.*, vol. 10, no. 1, p. 1344, Jan. 2020, doi: 10.1038/s41598-020-58049-9.

[30] D. Sporea, A. Stăncalie, D. Neguţ, G. Pilorget, S. Delepine-Lesoille, and L. Lablonde, “Comparative study of long period and fiber Bragg gratings under gamma irradiation,” *Sens. Actuators A, Phys.*, vol. 233, pp. 295–301, Sep. 2015, doi: 10.1016/j.sna.2015.07.007.

[31] F. Esposito, A. Srivastava, S. Campopiano, and A. Iadicicco, “Radiation effects on long period fiber gratings: A review,” *Sensors*, vol. 20, no. 9, p. 2729, May 2020, doi: 10.3390/s20092729.

[32] A. V. Faustov et al., “Comparison of gamma-radiation induced attenuation in al-doped, P-doped and Ge-doped fibres for dosimetry,” *IEEE Trans. Nucl. Sci.*, vol. 60, no. 4, pp. 2511–2517, Aug. 2013, doi: 10.1109/TNS.2013.2273273.

[33] R. Ranjan, F. Esposito, A. Iadicicco, A. Stancalie, D. Sporea, and S. Campopiano, “Comparative study of long-period gratings written in standard and fluorine-doped fibers by electric arc discharge,” *IEEE Sensors J.*, vol. 16, no. 11, pp. 4265–4273, Jun. 2016, doi: 10.1109/JSEN.2016.2546549.

[34] D. D. Francesca et al., “Qualification and calibration of single-mode phosphosilicate optical fiber for dosimetry at CERN,” *J. Lightw. Technol.*, vol. 37, no. 18, pp. 4643–4649, Sep. 15, 2019, doi: 10.1109/JLT.2019.2915510.

[35] P. Mesonero-Santos et al., “Effect of low-doses of gamma radiation on electric arc-induced long period fiber gratings,” *Sensors*, vol. 21, no. 7, p. 2318, Mar. 2021, doi: 10.3390/s21072318.

Andrei Stancalie received the Ph.D. degree in physics from "Politehnica" University of Bucharest, Bucharest, Romania, in 2015, focusing on the metrological characterization of optical fiber sensors.

He is currently a Senior Researcher with the Photonics Department, Center for Advanced Laser Technologies, National Institute of Laser, Plasma, and Radiation Physics, Magurele, Romania. He oversees the Optical Fibers Laboratory, where his research is dedicated to characterizing photonic devices, particularly studying the effects of ionizing radiation on optical components, and testing and optimizing optical fibers and fiber gratings for use in radiation environments.

Flavio Esposito (Member, IEEE) received the M.Sc. degree in electronic engineering from the University of Naples "Federico II," Naples, Italy, and the Ph.D. degree in information engineering from the University of Naples "Parthenope," Naples.

He is currently an Assistant Professor (tenure-track) of Electronics with the Department of Engineering of the University of Naples "Parthenope." His research activity is focused on the design, simulation, fabrication, and characterization of novel fiber-optic devices. His work currently involves the development and application of sensors for biochemical measurements, radiation-exposed environments, environmental monitoring, and structural health monitoring.

Dr. Esposito received the Outstanding Reviewer award from Sensors in 2019, IEEE SENSORS JOURNAL in 2020, and IEEE PHOTONICS TECHNOLOGY LETTERS in 2023. He is an Editorial Board Member of Sensors, Photonics and Biosensors. He serves as an Associate Editor for IEEE Sensors Letters and IEEE Sensors Reviews.

Razvan Mihalcea is currently pursuing the Ph.D. degree with the Faculty of Applied Sciences, "Politehnica" University of Bucharest, Bucharest, Romania.

He is currently an Engineer at the Photonics Department of CETAL, INFLPR, Fiber Optics Laboratory, Magurele, Romania. His research interests include the development of fiber-optic-based setups for laboratory characterization as well as for real-time investigations of optical fiber sensors in ionizing radiation environments such as nuclear facilities.

Laura Mihai (Member, IEEE) received the B.Sc. degree in physics (computational physics), and the M.Sc. and Ph.D. degrees in environmental physics and meteorology from the Faculty of Physics, University of Bucharest, Bucharest, Romania, in 2004, 2009, and 2012, respectively.

She was a Senior Scientist at the Photonic Investigations Laboratory, Center for Advanced Laser Technologies, National Institute of Laser, Plasma, and Radiation Physics, Magurele, Romania. In this role, she oversees the laboratory infrastructure at the Optical Metrology Platform and Terahertz Spectroscopy. Her research focuses on characterizing the effects of ionizing radiation in rare-earth-doped glasses, with the goal of advancing the development of more sensitive detection devices for ionizing radiation. In addition, she is committed to developing robust systems and protocols for the precise characterization, calibration, and validation of spectrometers used in field and remote sensing applications within the Earth sciences.

Daniel Ighigeanu received the Ph.D. degree in electrical engineering from the "Politehnica" University of Bucharest, Bucharest, Romania.

He is currently a Senior Researcher at the National Institute for Laser Plasma and Radiation Physics, Bucharest, Romania, and specializes in technologies and applications of particle accelerators. He is involved in the development of original installations and unconventional technologies with electron beams and microwaves for materials processing and performs technological irradiation. He is responsible for the operation of the ALID-7 electron linear accelerator and coordinates the accelerator handling team.

Anubhav Srivastava received the M.Sc. (Tech.) degree in engineering physics (specialization in instrumentation) from the National Institute of Technology (NIT), Warangal, Telangana, India, and the Ph.D. degree in information and communication technology and engineering from the University of Naples "Parthenope," Naples, Italy.

He is currently working as a Postdoctoral Researcher with the Department of Engineering, University of Naples, Parthenope, focusing his research on optical fiber sensors and their applications in multifaceted domains. He was at the Electro-Optical Instruments Research Academy (ELOIRA), Defence Research and Development Organization (DRDO), Hyderabad, India, and Central Scientific Instruments Organization (CSIO), Council of Scientific and Industrial Research (CSIR), Chandigarh, India, as an Industrial Project Trainee.

Stefania Campopiano (Member, IEEE) received the master's (cum laude) degree in electronic engineering from the University of Naples Federico II, Naples, Italy, and the Ph.D. degree in electronic engineering from the Università della Campania L. Vanvitelli, Caserta, Italy.

She is a Full Professor of Electronics and Optoelectronics with the University of Napoli "Parthenope," Naples. She is the author of over 200 printed works, including international journals and conferences, co-author of patents, and reviewer for several journals. Her research interests include the development of novel fiber-optic sensors for the measurement of physical, chemical, and biological parameters.

Dr. Campopiano is the Chair of the IEEE Sensors Council Italy Chapter.

Agostino Iadicicco (Member, IEEE) received the master's (Hons.) degree in electronic engineering from the Second University of Napoli, Naples, Italy, in 2002, and the Ph.D. degree in information engineering from the Department of Engineering, University of Sannio, Benevento, Italy, in 2005.

In 2006, he joined the Università di Napoli "Parthenope," Naples, where he is a Full Professor. He is currently the Coordinator of Ph.D. program in information and communication technology and engineering. Since 2002, his research activity has been focused on optoelectronics and photonics devices for sensing and communications applications. He is currently involved in the design, realization, and testing of novel in-fiber devices in standard and unconventional fibers, including polarization maintaining and photonic bandgap fibers. His work in this area encompasses the development and practical application of sensors for the measurement of a range of physical, chemical, and biological parameters.

Dr. Iadicicco serves as an Associate Editor for the IEEE SENSORS JOURNAL and has been a tutor of several Ph.D. students.

Open Access funding provided by 'Università degli Studi di Napoli "Parthenope"' within the CRUI CARE Agreement