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PMMA OPTICAL FIBRE IRRADIATED WITH CO-60 FOR OPTICAL FIBRE SENSORS

Michal Jelinek[1]*, Ales Jancar[2], Tadeas Zbozinek[1], Bretislav Mikel[1]

[1]Institute of Scientific Instruments of the Czech Academy of Sciences, Královopolská 147, 612 00 Brno, Czech Republic
[2]Masaryk University, Botanicka 15, 612 00 Brno, Czech Republic

Abstract. *Plastic optical fibres (POF) made of polymethyl methacrylate (PMMA) have several advantages over traditional optical fibres, including lower cost, the possibility of larger diameters and better mechanical resistance. These properties make them an attractive option for sensor technologies, including radiation dosimetry. This paper compares PMMA optical fibre with pure silica core optical fibre. Both fibres are useful for ionising radiation measurements. To evaluate the effect of ionising radiation, we have developed and designed a measurement system that allows continuous measurement of attenuation during the ionising radiation irradiation process. We used a technique that measured changes in laser power transmitted through an optical fibre at a constant gamma radiation dose rate.*

Keywords: *PMMA optical fibres, silica optical fibres, ionising radiation, radiation-induced attenuation, Ionising radiation measurement*

1. INTRODUCTION

At present, methods for measuring ionising radiation are constantly being developed and improved. New techniques are being developed to characterise better the radiation being measured and those that can measure higher doses. However, high doses of ionising radiation can damage the measuring equipment. In particular, the electronic systems of these systems are very sensitive and can be destroyed. Locations that pose a real challenge for these measurement systems are places with high levels of electromagnetic radiation, high temperature and limited space, such as particle accelerators, tokamaks, etc. Currently, these locations are addressed through indirect film measurements or electronic measurements in non-hazardous areas, with the activity at the desired location calculated based on facility models. However, continuous measurement systems suitable for these applications are not yet available.

In recent years, optical fibres have been used to continuously measure ionising radiation in such places. However, understanding the resistance, sensitivity, and structural changes of optical fibres when exposed to ionising radiation is crucial to setting up the measurement. Two methods are commonly used for measuring ionising radiation with optical fibres. In the direct method, the optical fibre is irradiated, and changes in its state are analysed. In the indirect method, optical fibre is a medium to transport signals, such as light, from a scintillation material.

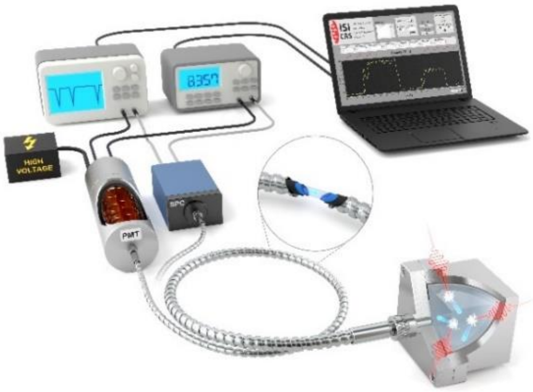

Figure 1. Ionising radiation measurement setup using optical fibre to transmit scintillation light from the scintillator to the photodetector [1].

Using a scintillation material that converts the incident radiation into visible light, which is then transmitted to an electronic detector through optical fibres, is shown in Figure 1 [1]. Even optical fibres that are used only for the transmission of scintillation radiation are exposed to a limited extent to the measured radiation. This can lead to structural damage and additional attenuation of the optical signal [2]. Therefore, understanding the behaviour and attenuation of optical fibres during irradiation is crucial for accurately assessing ionising radiation levels using sensor systems. The properties of optical fibres under radiation change by three mechanisms: radiation-induced attenuation (RIA), radiation-induced

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*E-mail of the corresponding author - jelinmi@isibrno.cz emission (RIE), and refractive index (RI) change. The magnitude of these changes depends on the properties of the fibres used, the radiation environment and the specific application parameters [3, 4].

2. THEORY OF OPTICAL FIBRES GAMMA RADIATION EFFECTS

Ionising radiation affects most materials, not excluding optical fibres. The radiation effect is less or more significant depending on the composition of the optical fibres. For many applications based on optical fibres, it is essential to know the resistance, sensitivity and changes in the structure of the fibres when exposed to ionising radiation. The response of optical fibres to ionising radiation depends on the composition of the optical fibre (choice of dopants in the core and cladding, impurity levels, stoichiometry) and also on the physical properties of the glass (temperature, strain, etc.), which strongly depend on the manufacturing parameters (pre-moulding and drawing process). These intrinsic parameters of optical fibres are usually unavailable because they are typically considered confidential by the fibre manufacturers.

2.1. Effect of gamma radiation on silica fibres

Knock-on and ionisation processes involve two main radiation-matter interactions in forming defects. Direct atomic displacements, known as knock-on damage, can occur in silica if the incoming particle imparts sufficient energy to the glass matrix. The threshold energy of the shift is approximately 10 eV for O and 18 eV for Si. The threshold energy values specified represent the minimum energy required for this displacement to occur for oxygen and silicon atoms in the silica matrix. If the incoming particle has an energy below these threshold values, it may not have enough energy to cause direct atomic displacements in the material.

As for ionisation processes and related radiolytic processes, electrons from the valence band can be transferred to the conduction band with a certain kinetic energy, which depends on the energy of the incoming particles. At the same time, a hole is created in the valence band. The resulting electron-hole pairs can recombine either radiatively (luminescence) or non-radiatively. In the latter case, the energy is dissipated by phonon formation or secondary radiolytic processes, which can lead to the formation of point defects. Moving charges may also be trapped at pre-existing or radiation-induced spots. External effects such as photobleaching or heat treatment are required to release the carriers from these traps.[3].

Three macroscopic effects can be observed in silica glasses during irradiation: radiation-induced attenuation (RIA), radiation-induced emission (RIE) and refractive index change.

Radiation-induced attenuation (RIA) corresponds to an increase in the attenuation of the glass due to the rise in absorption caused by radiation-induced defects. It is a wavelength and time-dependent effect. Radiation-induced emission (RIE) corresponds to light emission within irradiated samples. It can be luminescence from pre-existing or radiation-induced point defects excited by incident particles (radiation-induced luminescence, RIL) or Cherenkov emission.

At least two mechanisms compete with each other during the irradiation pulse: a strong RIA effect and a strong RIE effect, which masks the RIA for this fibre (spectral analysis shows that the RIE effect is mainly represented by Cherenkov radiation). After the end of the irradiation pulse, the RIA dominates, and the transmission in the filament decreases strongly. Filament transmission partially recovers during and after irradiation due to the thermal bleaching of point defects induced by radiation at room temperature. At longer times after irradiation, only point defects that are stable at the measurement temperature contribute to the RIA.

Of these various phenomena, RIA is usually the main limiting factor for fibre optic integration in a radiation environment. RIA should be considered, especially when RIA-tolerant optical fibres are used. The amplitudes of these macroscopic changes strongly depend on the properties of the fibres under test, the radiation environment, and the application parameters[3, 4].

2.2. Effect of gamma radiation on plastic optical fibres

Plastic fibres undergo significant changes when exposed to irradiation, including crosslinking, degradation, alterations in unsaturated bonds, and the generation of free radicals. These changes can affect the properties of the polymer material [5, 6]. Crosslinking and irradiation degradation noticeably impact the molecular weight and distribution. The degradation by irradiation involves the breakdown of the polymer's primary bonds due to high-energy radiation. As the absorbed radiation dose increases, the polymer's molecular weight decreases, and some polymer molecules break down into monomer molecules. The primary materials used in plastic optical fibres are polymethyl methacrylate (PMMA), polystyrene (PS), and polycarbonate (PC). PMMA and PC mainly experience radiation degradation when exposed to radiation, while PS undergoes radiation cross-linking. The damage caused by radiation increases the transmission loss of the plastic optical fibres (POF) [7, 8].

3. MEASUREMENT SET-UP

We present our developed and validated method for measuring optical fibre attenuation caused by ionising radiation. This method allows us to continuously monitor fibre attenuation in real-time

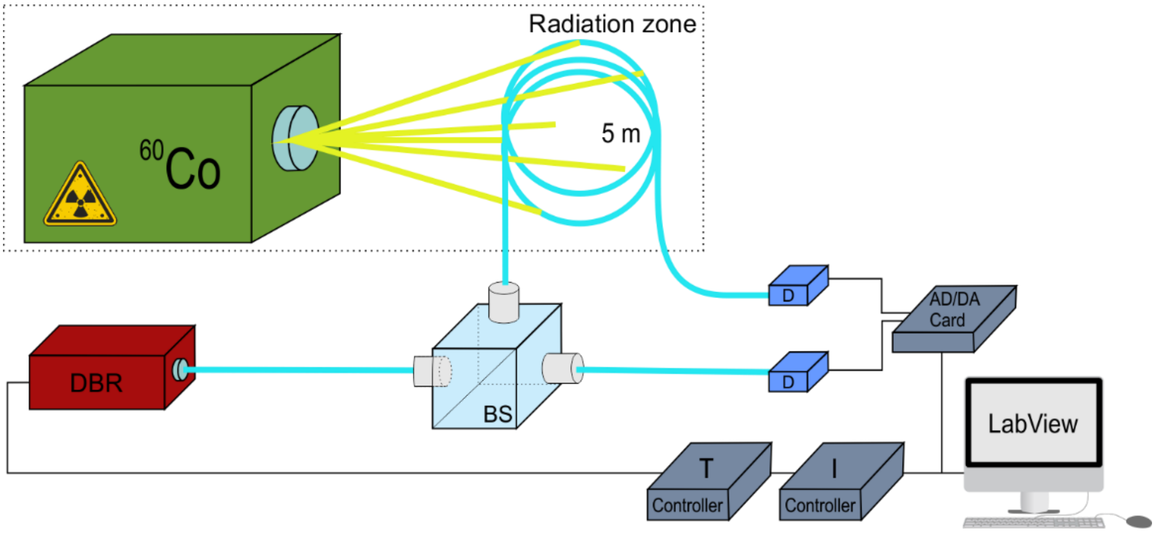

Figure 2. Schematic of continuous measurement of optical fibre attenuation under irradiation with ^{60}Co ionising source.

during irradiation by ionising radiation (see Figure 2). We use a DBR laser as the optical radiation source to measure the attenuation, with a wavelength of 632.8 nm developed at ISI [9]. The laser output is connected to the optical fibre via an optical collimator and fed into the BS optical light divider, divided into a reference and a measuring arm. In the reference arm, the light is coupled into a 1 m long optical fibre placed outside the ionising radiation source. It compensates for temperature effects on the fibre and potential laser power instability. The light is coupled to a 7 m long measuring optical fibre in the measuring arm. The irradiated part of this measuring fibre is 5 m long. The optical output of these two fibres we measure using identical silicon detectors with the same gain and identic power supply. The irradiation room is located underground where the environmental conditions (temperature, pressure, humidity) are relatively constant. The temperature in the irradiation room was at 21±1 °C during the measurement period.

The irradiation source was the cobalt source TERABALT T100, located in the company VF a.s. [10]. The ionising radiation source is in a shielded laboratory on a rolling platform, which guarantees a wide range of applications and setups of experiments (Figure 3). The source of the ionizing radiation is the isotope cobalt 60 with the typical spectrum in (Figure 4) and photo peaks at energies of 1173.2 keV and 1332.5 keV. Dose rate can be controlled by collimation technique and the irradiated object's distance.

We selected a PMMA ($(C_5O_2H_8)_n$) optical fibre and pure silica fibre (SiO_2) first to compare. PMMA fibre from Mitsubishi ESKA™ has a core diameter of 1 mm, an insertion loss of 0.25 dB/m at 650 nm, a numerical aperture of 0.58 and a temperature range of use <-55; 105 > °C. The pure silica fibre FP1000URT has a core diameter of 1 mm, insertion loss of 12 dB/Km at 850 nm, a numerical aperture of 0.5, and a temperature range of use <-40; 85 > °C.

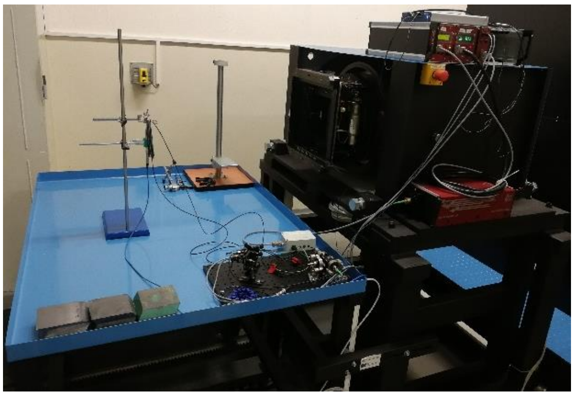

Figure 3. Photo of the fibre optic measurement assembly placed in front of the ^{60}Co - Terabalt T100 irradiation source

The whole optical fibre is covered with shrink wrap to prevent ambient light from binding to the optical fibre and affecting the results. In addition, the shrink wrap adds more mechanical resistance to the optical fibre.

4. RESULTS

The intensity of the laser radiation passing through the measured optical fibre is affected by the increasing degradation of the optical fibre located in the ionising radiation zone. This change is compared with a reference fibre outside the ionising radiation zone. The two fibres are affected by the same temperature, pressure and other external influences.

The Beer-Lambert law was used to convert the change in voltage at the laser intensity detector to the attenuation of the optical fibre in dB/km (1)

$$RIA = -\frac{10}{L}\log\left[\frac{P_T(\alpha,t)}{P_T^0(\alpha)}\right]\left[\frac{dB}{km}\right], \qquad (1)$$

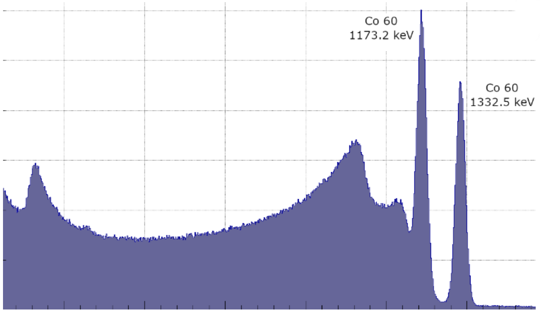

Figure 4. Typical gamma-ray spectrum of ^{60}Co with photo peaks at 1173.2 keV and 1332.5 keV.

where L is the irradiated length of the test fibre, PT(α, t) – is the measured optical power in the irradiated test fibre, and $P_T^0(\alpha)$ – is the optical power of the reference fibre, which is not irradiated.

The optical fibres were irradiated with a total dose of 9 kGy with a dose rate of 41.22 Gy/hr for the PMMA optical fibre and 46.88 Gy/hr for the silica optical fibre. The different distances from the ionising source caused the total dose rate difference. The difference was due to the possibilities of wrapping the optical fibre diameters into a coil and the consequent possibility of placing it close to the ionising radiation source. The dependence of the optical fibre attenuation on the gamma dose rate is a critical aspect. In some cases, the effect of radiation on the fibre may be more pronounced at higher dose rates. This dependence is related to the kinetics of radiation-induced processes in the fibre material. Therefore, we tried to achieve the same dose rate when measuring both optical fibres.

Figure 5 shows the voltages on the detectors measuring the measuring fibre and the reference PMMA fibre throughout the irradiation by the ionising source. The graph shows that the laser power is not stabilised, but the resulting voltage changes are visible on the measurement and reference fibres. After converting the detector voltages to the RIA (1) of each point in the plot, we obtain a linear plot of the attenuation versus radiation dose, as shown in Figure 5. The attenuation of the PMMA optical fibre reached 533 dB/km after exposure to a cumulative ionising radiation dose of 9 kGy. After the end of irradiation, relaxation takes place in the optical fibre and the voltage starts to increase as the attenuation of the optical fibre decreases. After 100 hours from the end of irradiation, the attenuation of the PMMA optical fibre decreased linearly to 380 dB/km. It can be estimated that the attenuation decrease is not final and will continue.

Figure 6 shows the voltages on the silica optical fibre and reference optical fibre detectors. Silica optical fibres have more minor voltage differences across the detectors during irradiation. After converting the detector voltages to the RIA (1) of each point in the graph, we obtain a plot of attenuation versus radiation dose, as shown in Figure 7. The attenuation of the silica optical fibre reached 90 dB/km after irradiation with a cumulative dose of 9 kGy. The attenuation of silica optical fibre is approximately six times lower compared to PMMA plastic fibre. After 100 hours from the end of irradiation, the attenuation of the silica optical fibre has decreased to 80 dB, which is approximately 89 %

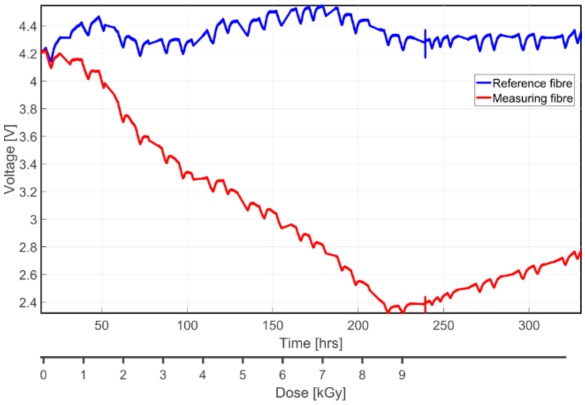

Figure 5. The voltage difference between the measuring and reference fibres on optical detectors measuring the attenuation of plastic PMMA fibres when irradiated with a ^{60}Co source with a total dose of 9 kGy and a dose rate of 41.22 Gy/hr.

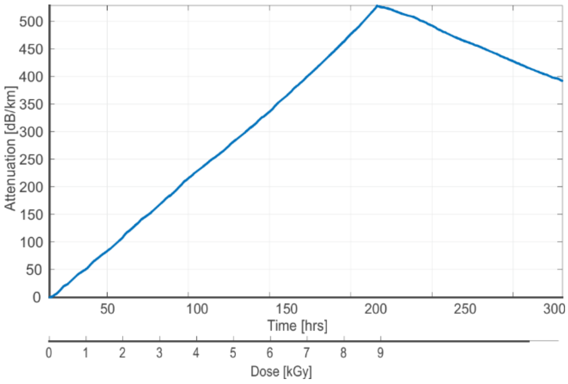

Figure 6. The attenuation of plastic PMMA fibres under irradiation with a ^{60}Co source with a total dose of 9 kGy and a dose rate of 41,22 Gy/hr.; conversion to fibre attenuation in dB/km.

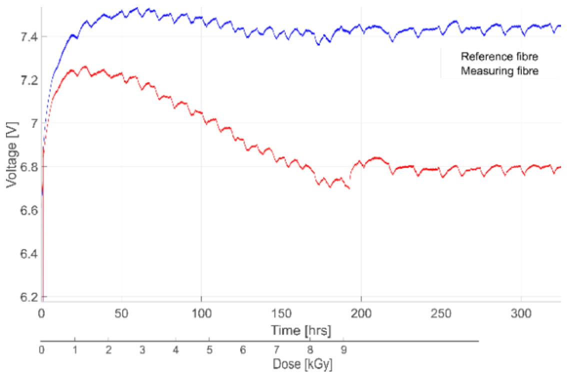

Figure 7. The voltage difference between the measuring and reference fibres on optical detectors measuring the attenuation of optical silica fibres when irradiated with a ^{60}Co source with a total dose of 9 kGy and a dose rate of 46.88 Gy/hr.

of the maximum attenuation. From the relaxation time of the optical fibre, it can be estimated that this attenuation is already finite. The irradiation process shows a relatively rapid increase in attenuation at the beginning of the irradiation; after reaching an attenuation of approximately 10 dB/km, the increase in attenuation is linear.

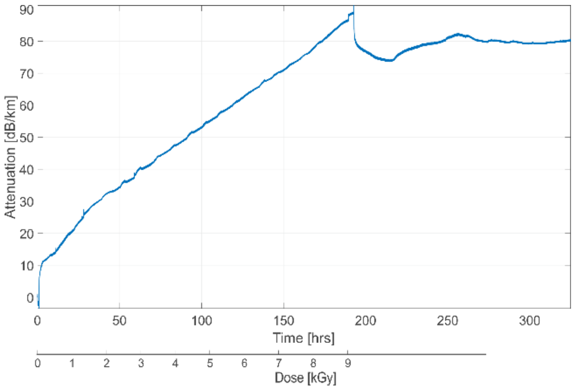

Figure 8. The attenuation of silica fibres under irradiation with a ^{60}Co source with a total dose of 9 kGy and a dose rate of 46,88 Gy/hr; conversion to fibre attenuation in dB/km.

5. CONCLUSIONS

In this paper, we presented a method for continuous measurement of the effect of ionising radiation ^{60}CO on the attenuation of PMMA and pure silica optical fibres. The total dose rate of the ^{60}Co ionising radiation source was 9 kGy with a dose rate of 41.22 Gy/hr. for the PMMA optical fibre and 46.88 Gy/hr. for the silica optical fibre. After irradiation, the PMMA optical fibre achieved a total attenuation of 533 dB/km. The increase in optical attenuation in the PMMA fibre was linear, and the fibre relaxed linearly after the irradiation ended. The pure silica fibre achieved an attenuation of 90 dB/km after irradiation. The increase in optical attenuation in the pure silica fibre was initially exponential. After a dose of approximately 50 Gy, the attenuation became linear, with the relaxation of the fibre after the end of irradiation and a reduction of 11% in the total attenuation after 100 hours.

The Minor attenuation vs radiation dose in silica fibre, compared to PMMA fibre, is attributed to the inherent radiation-resistant properties of silica, its higher threshold for knock-on damage, and the stable crystalline structure. The higher threshold energy for knock-on damage in silicon implies that, to induce significant atomic displacements, a higher-energy radiation source is required. The threshold energy for knock-on damage in silica is relatively high (around 18 eV), indicating that it takes a significant amount of energy for atoms to be displaced. Polymethyl methacrylate (PMMA), being an organic material, may be more vulnerable to radiation damage. Organic compounds often have lower radiation resistance compared to inorganic materials like silica.

PMMA optical fibre is more suitable for measuring ionising radiation by the direct method if optical fibre is taken as the sensing medium; on the other hand, pure silica optical fibre is preferable for using optical fibre as a transport medium because of the approximately six times lower attenuation. The advantage of using PMMA optical fibre as a sensing medium is the linear attenuation profile during irradiation and the linear attenuation profile during optical fibre relaxation.

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