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STUDY ON THE DEVELOPMENT OF A NEW SINGLE MODE OPTIC FIBER RADIATION DOSIMETER FOR ELECTRON BEAMS

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Abstract. Preliminary results, obtained in the study of single mode optical fiber properties, in order to develop a new radiation dosimeter sensitive to high energy electron beams, are presented in this paper. Optical fiber irradiation was performed at the ALIN-10 accelerator of the National Research and Development Institute for Laser, Plasma and Radiation Physics (INFLPR). This study is based on the physical degradation effect of the optical fiber due to electron beam exposure. This effect can be determined through the measurement of the radiation induced attenuation that is proportional to the exposure dose. Attenuation in the optic fiber was measured before, during and after electron beam exposure for two types of single mode optic fibers and for two wavelength values. The results of the measurements lead to the conclusion that these types of optical fiber can be used for measuring either high or low doses of irradiation.

Key words: single mode optical fiber, radiation dosimeter, radiation, attenuation.

1. INTRODUCTION

In recent years, a miniature fiber-optic radiation sensor based on an organic scintillator was developed. Organic scintillators can be used as dosimeters because they emit visible light proportional to the absorbed electron and gamma dose rate.

An optical fiber is usually made of plastic or glass, which is used to guide the light signal from a scintillator probe to light measuring devices such as a photomultiplier tube (PMT), photodiode, and optical power-meter. As a light pipe, the optical fiber has many advantages such as good flexibility, ease of processing, long lengths, and lack of interference with electromagnetic fields [1].

The transmission characteristics of optical fiber are very much influenced in radiation environment due to generation of radiation-induced defect centers by ionization and atomic displacement within the molecular bonding network of silica (SiO_2) glass. The generated defect centers cause absorption in UV, VIS or near IR region and are responsible for the radiation sensitivity of the fiber. The radiation induced loss in optical fiber depends largely on core-clad composition, dopant concentration, fiber design along with different radiation parameters like radiation source, dose rate and operating parameters like temperature, transmission wavelength etc. [2]. Several studies have been performed to improve their resistance by adjusting the chloride (Cl) and hydroxil (OH) contents of the silica glass. The exact influence of the OH concentration on the waveguide is more application-dependent and actually the two types of pure-silica-core fibers (high- and low-OH) are still studied for potential application in the international thermonuclear experimental reactor for plasma diagnostics [3].

In the present experiment, to aid the development of a new radiation dosimeter, two types of single mode fibers were exposed to an electron beam provided by the ALIN-10 linear accelerator of the Laboratory of Electron Accelerators, National Institute for Research and Development for Laser, Plasma and Radiation. This optical fiber was manufactured and supplied by Thorlabs [4], Germany.

2. MATERIALS AND EXPERIMENTAL SETUP

The single mode fibers used in the experiment were irradiated in a electron beam at the ALIN-10 linear accelerator of the Electron Accelerator Laboratory, INFLPR [5]. Irradiation was performed at a distance of 100 cm from the exit window of the accelerator. They used two types of single mode optical fiber: ultra-high numerical aperture single-mode fiber (ultra-high NA single mode fiber) and photosensitive single mode fiber.

Irradiation of the two types of optic fibers consisted of two stages, each performed in different days and containing several steps of irradiation. Each step consisted of fibers with different irradiation doses and different times. Monitoring environmental conditions was performed using OPUS 10 TPR thermobarometer from the STARDOOR laboratory.

2.1. ULTRA-HIGH NUMERICAL APERTURE SINGLE MODE FIBER

Manufactured by the company Thorlabs, Germany, this type of optical fiber is characterized by nominal operating wavelength range 1100 – 1600 nm, the numerical aperture is 0.28 and the nominal attenuation less than 20 dB typical / km [4]. The core of such a fiber is made of silicon oxide (SiO_2 / GeO_2) having a diameter of 2.5 μm, the cladding is made of fluorine-doped silica having a diameter of 125 ± 1.5 μm, and the coating is made of a double layer of acrylate having a diameter of 250 ± 20 μm. Operating temperature of this type of fiber is from –55 ^{o}C to 85 ^{o}C [4].

The structure of this type of fiber is given in Fig. 2.1.

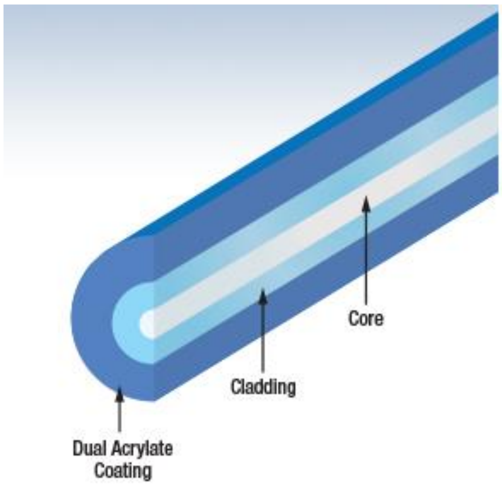

Fig. 2.1 – Structure of ultra-high NA single-mode fiber [4].

For the experiments, it was proposed to use a length of about 45 m of ultra-high NA single-mode fiber of which 15 m were installed in a spiral with an inner diameter of 10.5 cm and an outer diameter of 11.5 cm, the remaining 30 m of fiber is used to connect to the OTDR M200 reflectometer to gain a better distinction of the OTDR's noise floor that affects the measurements.

The applied radiation dose rate was measured with a Roos TN 34001 series 1017 ionization chamber, specific dosage and flow measuring absorbed dose in electron beam. The ionization chamber, belonging to the Secondary Standard Dosimetry Laboratory of High Energies – STARDOOR – of INFLPR, was connected to the UNIDOS T10005 series 50406 dosimeter and placed in the center of the spiral, perpendicular to the direction of the electron beam at a distance of 100 cm from the exit window of the accelerator. Uncertainty of measuring absorbed dose was 3.13%. Measurement method complies with IAEA TRS 398 [6, 7].

Before the start of irradiation attenuation measurements at 1310 nm and 1550 nm wavelengths were carried out for the two single mode optical fiber. The measured values were used to calculate the actual attenuation of the optical fiber depending on the dose absorbed during irradiation and after irradiation. Uncertainty of measurement of attenuation in optical fiber was 8.15% and the wavelength of 1550 nm and 5.33% for a wavelength of 1550 nm.

In the second stage of irradiation temperature values ranged from 19.5 ° C to 23.5 °C and atmospheric pressure values ranged between 1005.1 hPa and 1015.7 hPa.

2.2. PHOTOSENSITIVE SINGLE MODE FIBER

The single mode photosensitive optical fiber is characterized through a nominal operating wavelength range 1500 – 1600 nm, a numerical aperture of 0.13 and a nominal attenuation 20 dB / km. The core of such a fiber has a diameter of 9.0 μm and is made of silicon and the cladding with a diameter of 125 ± 1.5 μm is also made of silicon. The coating is made from acrylic and has a diameter of 250 ± 20 μm [4]. The structure of this type of fiber is given in Fig. 2.2:

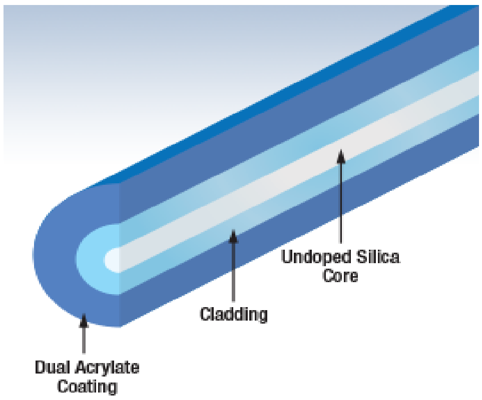

Fig. 2.2 – Structure of photosensitive single mode optical fiber [4].

The measurements were done on 50 m of photosensitive single mode optical fiber out of which 20 m were installed in a spiral with a diameter of 10.5 cm, 15 m were used to be connected to the OTDR M200 reflectometer and the remaining 15 m is used to have a better distinction of areas where noise affect's OTDR measurements. Before performing the actual measurements, attenuation was measured with an uncertainty of measurement of 14% for the 1310 nm wavelength and 5% for a wavelength of 1550 nm.

In the first step of the irradiation temperature ranged around 22.4°C and a pressure of 1002.9 hPa, while in the second irradiation step the temperature was 22.1 °C and a pressure of 1002.0 hPa.

3. EXPERIMENTAL MEASUREMENTS RESULTS

3.1. RESULTS EXPERIMENTAL OF ULTRA-HIGH NA SINGLE MODE OPTICAL FIBER

Attenuation measurement results during electron beam irradiation of the ultra high numerical aperture optical fiber depending on the dose applied in the first stage are given in Fig. 3.1.1. From the figure it can be seen that the attenuation measured in this type of optical fiber depends linearly on the applied dose for each step, from a value of around 4 kGy up to a value of about 22 kGy.

The increase of attenuation function of the irradiation dose applied is due to the interaction of the electron beam with the optic fiber at electron level, to the creation of intrinsic and extrinsic absorptions of luminescent radiation and also because of scattering of that luminescent radiation, such as Rayleigh scattering, in the fiber core. Such absorptions lead to the generation of faults in the germanium-doped oxide matrix with the main consequence of increasing the light propagation attenuation (non-ionizing radiation) into the fiber. A higher sensitivity to radiation can be seen at a wavelength of 1550 nm.

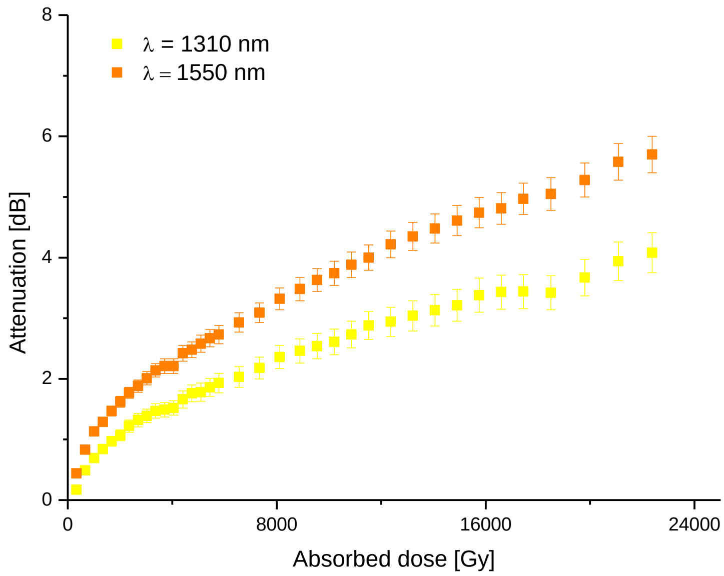

Fig. 3.1.1 – Optical fiber attenuation during exposure to high energy electron beam.

The behavior of ultra high numerical aperture single mode fiber after ceasing the irradiation with electron beams, for the first stage, is shown in Fig. 3.1.2. Once you stop irradiation, attenuation in the optic fiber is expected to decline, as it was observed in multimode optical fiber [8], but for a certain period of time after irradiation has stopped attenuation was found to increase. This increase of the attenuation is probably due to the fact that dispersion centers are still generated by the excited states present in the material even after irradiation with electron beams has stopped.

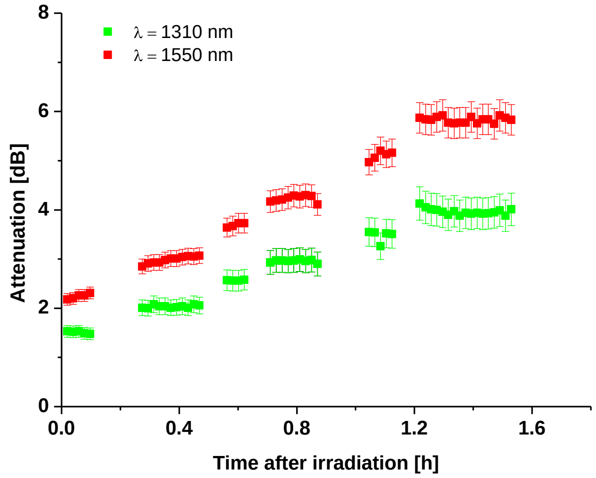

Fig. 3.1.2 – Optical fiber attenuation after an elapsed time in ultra-high NA single-mode fiber.

The behavior of ultra-high NA single mode optical fiber during electron beam exposure and after irradiation is shown in Fig. 3.1.3.

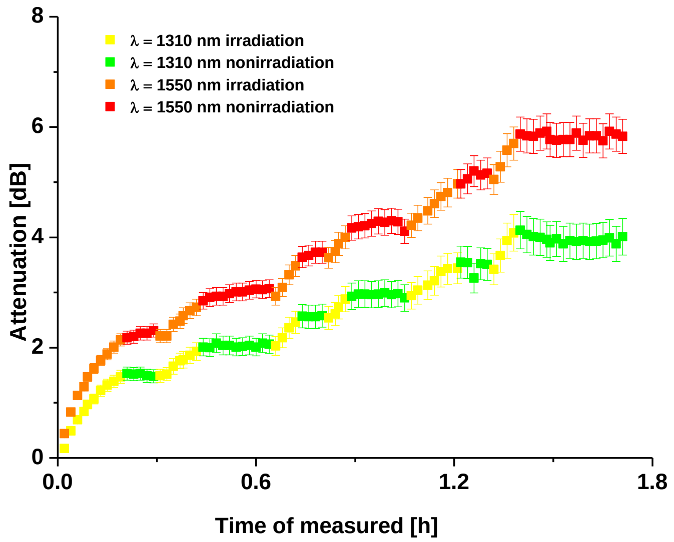

Fig. 3.1.3 – Optical fiber attenuation during exposure to high energy electron beam and after.

After being irradiated the fiber was allowed to recover for a longer time (hundreds of hours). Measurements of the attenuation values were made during the recovery time (Fig. 3.1.4). From the figure we can see that the attenuation decreases slowly for approximately 126 hours from the time after irradiation, and then begins to decrease faster. The slow decrease is due to the fact that the optical fiber was kept in the dark. It was subsequently observed that if kept in direct solar light, its behavior depends on solar radiation.

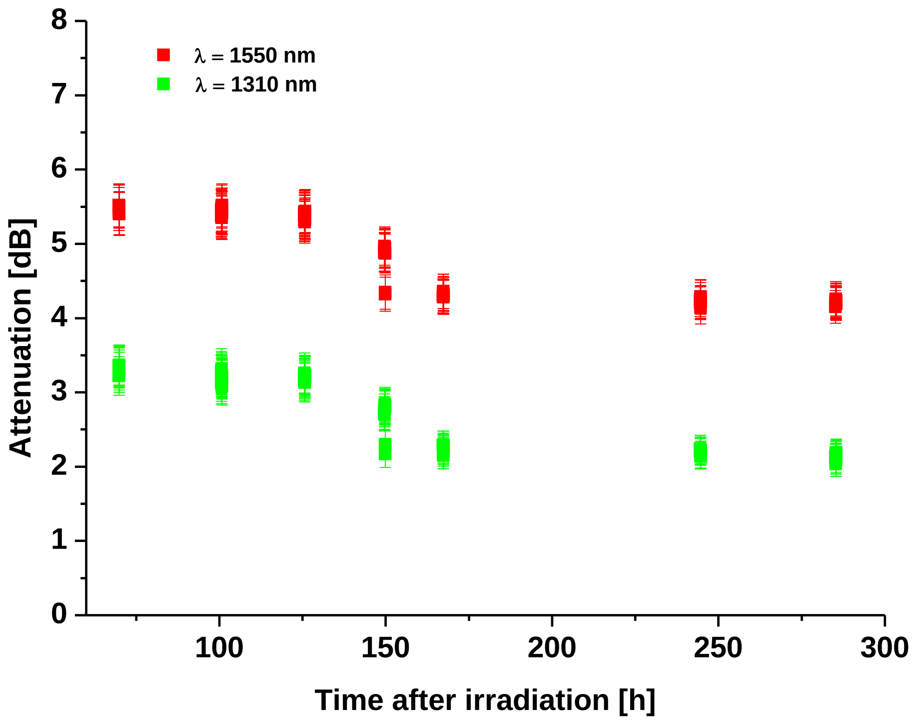

Fig. 3.1.4 – Optical fiber attenuation after an elapsed time of recovery.

The accumulated absorbed dose that was applied in the second period of irradiation was about 41.5 kGy. The behavior of the optical fiber was similar to the one in the first step, but in this phase, after a certain received dose the measured attenuation reached saturation. This means that no matter how long the fiber was irradiated and no matter how large the dose of radiation is received after this phenomena is observed, the attenuation values measured in the optical fiber will still be the same. Saturation occurred at such high dose due to the fact that the fiber has a core of silica (SiO_2 / GeO_2) and the cladding is made of fluorine doped silica. The doping substance increases the resistance to high doses of radiation.

3.2. EXPERIMENTAL RESULTS OF PHOTOSENSITIVE OPTICAL FIBER

After irradiation of the photosensitive single mode optical fiber with electron beams it was observed that the attenuation values in the optical fiber show a linear dependence to the applied dose up to a value of about 1 kGy. After this dose value the saturation phenomenon occurs [9]. Dose applied in the first measurement period was about 2 kGy, while in the second period is about 1 kGy. There was a higher sensitivity to radiation at a wavelength of 1310 nm.

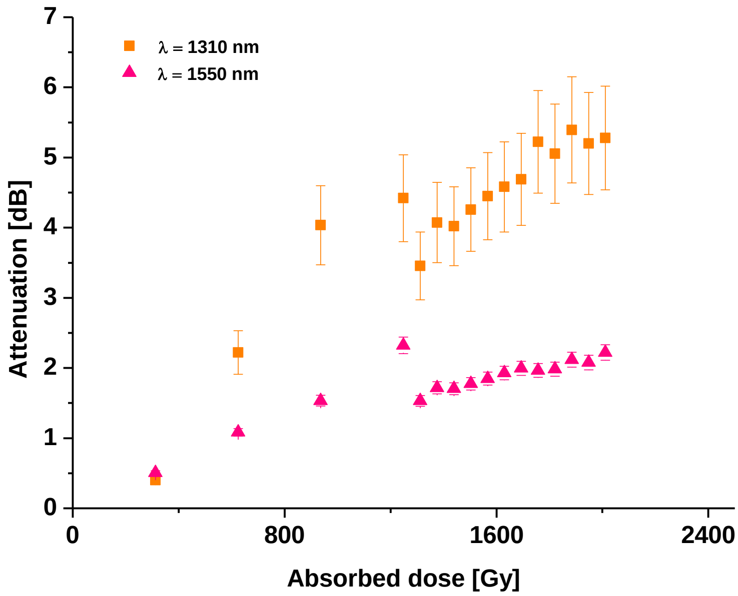

Fig. 3.2.1 – Optical fiber attenuation during exposure to radiation.

After the irradiation session was finished it was decided to leave the fiber for some time to recover. The attenuation was measured during this period (Fig. 3.2.2). During these measurements it was observed that the values of attenuation decrease within a short time (of the order of minutes). A few hours after cessation of irradiation (about 21 hours) the attenuation in the fiber shows a value close to the one before irradiation and thus decided to conduct the second period of irradiation.

Figure 3.2.3 shows the behavior of photosensitive single mode optical fiber during electron beam irradiation and after irradiation in the first stage.

In the second stage of irradiation, as in the first stage, it was observed that the attenuation in the fiber has a linear dependence to the dose applied up to a value of 1 kGy. After this dose is cumulated saturation occurs in the fiber.

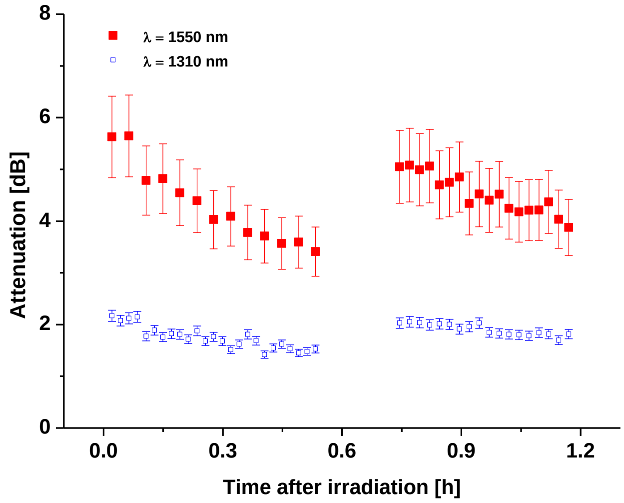

Fig. 3.2.2 – Optical fiber attenuation after an elapsed time.

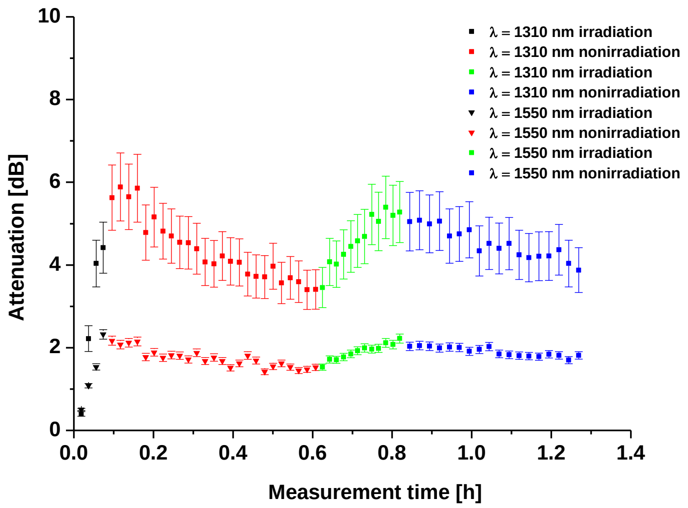

Fig. 3.2.2 – Optical fiber attenuation during exposure to high energy electron beams and after.

3. CONCLUSION

The measurements for radiation exposure ultra-high NA single mode fiber and photosensitive single mode fiber showed a linear increase of the attenuation depending on the exposure dose in both cases for each measurement step, up to a certain value of the applied dose. After this fiber type specific dose limit is reached, saturation is observable in the fibers. This phenomenon means that no matter how long the fibers are irradiated and however great the irradiation dose is the attenuation in the fibers will almost be the same value if the irradiation is continued after the specific dose limit. Attenuation in the optical fiber is, in essence a consequence of the blackening of the fiber. A higher sensitivity was observed at a wavelength of 1550 nm for the ultra-high NA single mode fiber and 1310 nm in the case of photosensitive single mode optical fiber.

The ultra high numerical aperture single mode optical fiber withstands high doses of radiation (exceeding 40 kGy) providing a linear behavior up to those dose values for both wavelengths used for monitoring. The photosensitive single mode optical fiber is resistant to low doses radiation (about 1 kGy). The ultra-high NA single-mode fiber shows a very slow recovery of the attenuation values (up to several months) which makes them suitable for use as solid state detector for long term monitoring of radiation sources in areas such as medicine, chemical industry food industry, mining, research, radiation protection for personal environment, radioactive waste treatment plants, nuclear power plants, sterilization of medical and pharmaceutical products, etc [10]. The photosensitive single-mode optical fiber provides a rapid return to pre-irradiation attenuation values (of the order of minutes) and can be reused which makes it appropriate for use as a possible solid state detector for monitoring short-term irradiation events in areas such as: medicine, chemical industry food industry, mining, research, radiation protection for personal environment, radioactive waste treatment plants, etc. [10].

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