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Evaluation of UV Optical Fibers Behavior under Neutron Irradiation

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ABSTRACT

Degradation of UV transmitting optical fibers under nuclear reactor neutron exposure is reported. Four type of optical fibers (solarization resistant, H_2-loaded; UV transmission standard OH; UV enhanced transmission, high OH, H_2-loaded; high OH, deep UV enhanced) were exposed to neutron fluences up to 4 x 10^{17} n/cm^2. The optical transmission was measured off-line over the 200 nm – 900 nm spectral range and the build-up of color centers was monitored.

Keywords: Irradiation Effects; Neutron; Optical Attenuation; UV Optical Fibers

1. Introduction

In the last 30 years optical fibers were extensively studied in order to assess their possible use in radiation environments for communications, sensing, remote control, light guides, robotics etc. [1-3]. Optical fibers and, by extension, optical fiber-based systems have a great potential for such applications considering their advantages such as: capabilities to work under strong electromagnetic fields; possibility to carry multiplexed signals (time, wavelength multiplexing); small size and low mass; ability to handle multi-parameter measurements in distributed configuration; possibility to monitor sites far away from the controller; their availability to be incorporated into the monitored structure; wide bandwidth for communication applications. In addition, these systems are free of hazards such as fire, explosion, and contamination. All these facts recommend them for space or terrestrial applications (spacecraft on board instrumentation, nuclear facilities, future fusion installations, medical treatment and diagnostics premises, medical equipment sterilization), embedded into various all-fiber or hybrid sensors or as light-guides for control and diagnostics. In these implementations optical fiber systems accept real-time interrogation capabilities, provide spatially resolved answers (the capability to build array detectors), make possible on-line/ real time investigations [4].

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Different types of optical fibers (silica-based, plastic, sapphire) and glass types were investigated under various irradiation conditions: gamma-ray, X-ray, electron beam, neutron, proton, alpha particles [4-7]. Exposed to ionizing radiation, silica optical fibers exhibit effects such as: radiation induced absorption (RIA), radiation induced luminescence (RIL), increase of the optical radiation scattering as it propagates over the fiber length, thermo-luminescence, change of the waveguide refractive index. Attempts were made to reformulate the problem and to use these effects as a measure of the dose rate/total dose of the radiation to which the optical fiber is exposed [4,8]. A special situation appears in the case of multimode optical fibers projected for UV-visible transmission, when the degradation of the optical transmission is more evident [9-11].

The present paper reports for the first time, according to our knowledge, the evaluation of UV optical fibers degradation under neutron irradiation, exposed in a research nuclear reactor.

2. Experiment

The optical fiber samples we investigated fall into four different categories: solarization resistant, H_2-loaded; UV transmission standard OH; UV enhanced transmission, high OH, H_2-loaded; high OH, deep UV enhanced. They are all commercially available products, from two manufactures. In **Table 1** the characteristics of the irradiated optical fiber samples are specified.

The optical transmission of optical fibers samples was measured in the Laser Metrology Laboratory, at the National Institute for Laser, Plasma and Radiation Physics (NILPRP), before the irradiation process.

Neutron irradiation was performed at TRIGA SSR research reactor, operated by the Institute for Nuclear Research. In this investigation channel J7 belonging to the beryllium reflector of the reactor was used. The TRIGA-SSR reactor is a nuclear reactor whose active area is supplied with LEU fuel in zirconium hydride matrix type.

This fuel feeds stainless steel bars, these bars being grouped in boxes of 5 x 5 pins. The total length of fuel pellets is 57.5 cm. In the active zone the axial flux distribution is not uniform, and can be represented by a cosine function. This distribution is maintained outside the active area, so it follows the neutron source distribution. For this reason, it is necessary to know this flux distribution. The irradiation process run in two phases, for the neutron flux of $3x10^{13}$ n·cm^{-2}s^{-1} calculated for the lower end of the optical fibers, and a neutron flux of $7x10^{13}$ n· cm^{-2}s^{-1}

calculated for the upper end of the optical fibers, and different exposure times were employed (from 60 s to 4 h) to obtain different fluences (10^{15} n/cm^2, and respectively 10^{17} n/cm^2).

The characterization of the neutron irradiation channel was done by neutron activation analysis applied to a set of activation foil detectors, followed by the deconvolution of the neutron spectrum deduced from the measured reaction rates. This characterization was performed by measuring the neutron flux density and the spatial distribution, relative to the information provided by the monitoring system. The axial profile of the J-7 channel as resulted from the above mentioned characterization is given in **Figure 1**.

To characterize the J-7 neutron channel, was developed a set of flux monitors consisting of: An5%-Al-Al Dy5%, Lu5%-Al-Al Mn1%, In100%, Fe100% Al100% Ni100%, Mg100%. The set was completed with two additionally irradiated monitors coated by a 1mm thick cadmium layer: Au5%-Al-Al and Mn1%, in order to evaluate the contribution of intermediate neutrons at the respective monitors' resonances. The irradiation time for each flux monitor was selected to obtain a sufficient activity level to enable the measurements precisely without extra handling precautions. **Figure 2** illustrates the integral spectrum obtained for channel J-7 at the end the measurements.

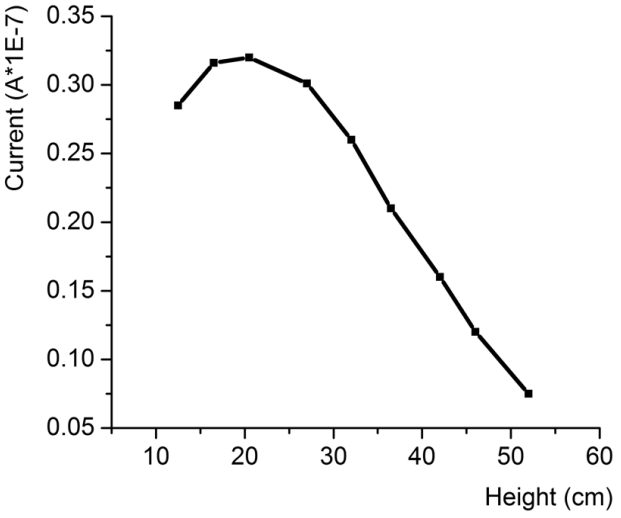

Figure 1. The axial profile corresponding to the irradiation channel used

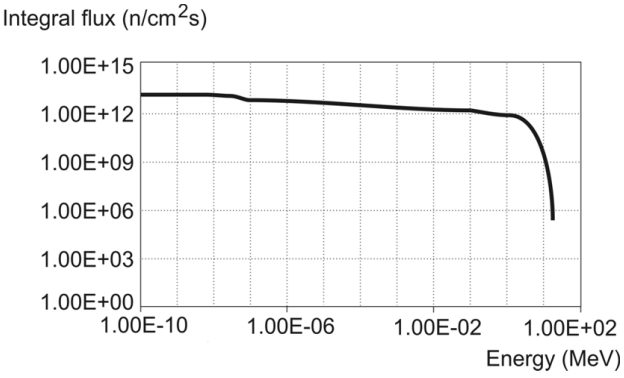

Figure 2. The integral spectrum of neutrons corresponding to the irradiation channel used.

After the radiation exposure, the irradiated optical fibers were transferred and stored in Post Irradiation Examination Laboratory for "cooling"/ disintegration of the radioactive products, to allow handling and safe transfer to NILPRP for further investigations. At this stage, the samples were subjected to gamma spectrometry measurements for all isotopes emitting gamma radiation with energy of 60 keV and 2.5 MeV, with gamma-ray line intensity greater than 4% range for the determination of activation products. Measurements were performed using a chain of high-resolution gamma spectrometry calibrated in efficiency for different distances and consisting of an HPGe detector and a multichannel analyzer with 8192 channels, coupled to the data acquisition system. Following gamma spectrometry measurements some gamma radioactive impurities were found: 124 Sb, Sc 46, Zn 65, I 152 and 137 Cs. The general set-up for the off-line optical absorbance measurements is similar to that we used previously [10, 11] but, for the purpose of this investigation, it has a better S/N ratio (1,000:1 full signal), 16 bits A/D conversion resolution, a dynamic range of 25,000:1, a greater quantum efficiency in the UV range (65 % at 250 nm), spectral resolution 1.2 nm, a sensitivity of 0.065 counts/e-, and a minimum OD detection level of 0.4 [4].

For the optical set-up used (this value is determined by two factors: first, the core of the connecting optical fibers and the core of the samples are different, and second, the sample optical fibers have no fixed connectors, hence, a biasing level which limits the set-up lowest detectable OD). Such a detecting scheme makes possible a better tracking of the color centre development in the UV spectral range and enables a higher range of absorption levels to be detected (O.D. of 4.4). For the reported optical absorption curves, the signal was averaged over three detected acquisitions with a value of 2 for the box car parameter. Irradiation and off-line measurements were carried out at room temperature.

3. Results

Figures 3 to **6** represent the results of the spectral optical absorption measurements for the tested optical fibers after they were irradiated with neutrons in a research reactor. For comparison the curves corresponding to the non-irradiated case and for two fluencies (1.8 x 10^{15} and 4.3 x 10^{17} n/cm^2) are superposed. According to data from the literature [12,13], we were interested to observe the change of the optical transmission at specific wavelengths, corresponding to expected color centers:

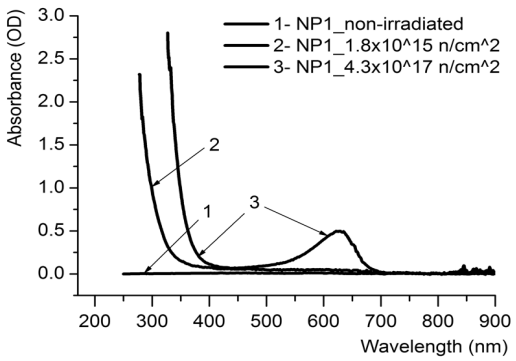

Figure 3. The optical spectral absorption for sample NP 1.

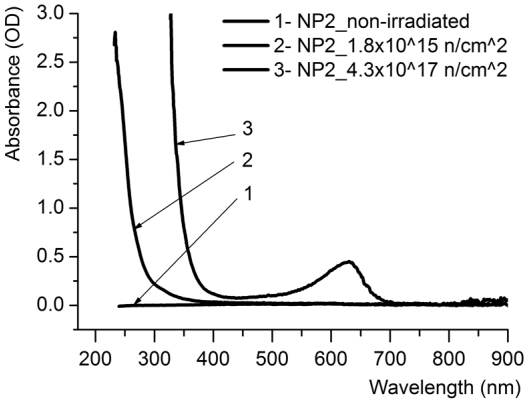

Figure 4. The optical spectral absorption for sample NP 2.

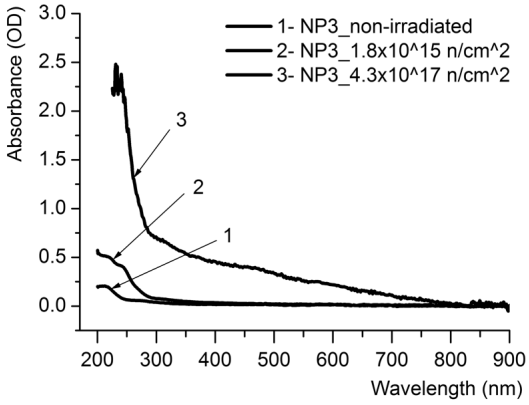

Figure 5. The optical spectral absorption for sample NP 3.

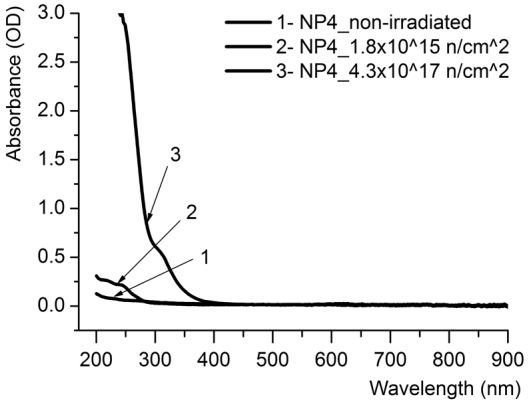

Figure 6. The optical spectral absorption for sample NP 4.

a) λ = 248 nm, ODC(II) twofold coordinated silicon (or according to some authors an oxygen deficiency center),

$$O_3{\equiv}Si-Si{\equiv}O_3$$

b) λ = 265 nm, non bridging-oxygen hole color center,

$$O_3{\equiv}Si-O^{-}$$

c) λ = 320 nm, bound chlorine center,

$$O_3{\equiv}Si-Cl-Cl-Si{\equiv}O_3$$

d) λ = 330 nm, molecular chlorine center,

$$Cl-Cl$$

or peroxy linkage,

$$O_3{\equiv}Si-O-O-Si{\equiv}O_3$$

e) λ = 630 nm, non bridging-oxygen hole color center,

$$O_3{\equiv}Si-O^{-}$$

Based on the available post irradiation information, two of the optical fibers (samples NP 1 and NP 2) exhibit a degradation of the optical transmission at λ = 630 nm, for the high neutron flux. At a low flux value this phenomenon is not present.

For sample NP 3 the influence of the chlorine related color center can explain the increase of the optical absorption in the 300 nm – 600 nm spectral range, may be combined with the effect due to the non bridging-oxygen hole color center.

The molecular chlorine center (λ = 330 nm) is less present in sample NP 4, at higher neutron flux. At the lower neutron flux, samples NP 1 and NP 2 proved to be more sensitive to neutron irradiation for ODC(II) and non bridging-oxygen hole color center (λ = 248 nm and λ = 265 nm).

The presence of the non bridging-oxygen hole color center is confirmed by the degradation of the optical transmission at the two characteristic wavelengths (λ = 265 nm and λ = 630 nm).

Less vulnerable at shorter wavelengths seems to be the optical fiber NP 3, as the optical absorption is lower in this case, at the highest neutron flux.

It is known that high neutron fluxes induce mechanical degradation of the irradiated glass. In order to check this assuption electron microscopy investigations were carried out on optical fiber samples before and after irardiation. **Figure 7** illustrates the deffects induced in the glass as this was subjected to neutrons.

4. Conclusions

The study of the UV optical fibers exposed to high neutron fluxes from a nuclear reactor is reported for the first time. The effect of this irradiation on the formation of color center in the UV spectral range was studied along with the mechanical degradation of the optical fibers samples.

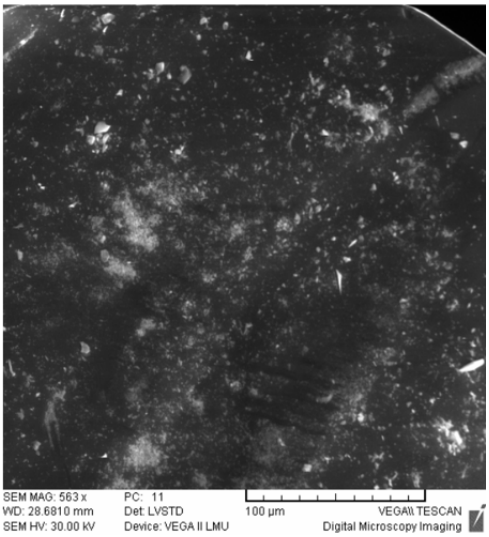

Figure 7. Electron microscopy image of an irradiated optical fiber sample.

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