Detection of X-Rays Radiation Effect on Radiation Sensors Based on Optical Fiber Technology

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Abstract. This study aims to investigate the characteristics of optical fiber sensors under X-rays radiation. The Radiation-Induced Absorption (RIA) and Radiation-Induced Refractive-Index Change (RIRIC) in the UV-VIS domain were investigated. Single and multi-mode optical fibers (SMFs & MMFs) have been used for this purpose. The outer diameters of these fibers were reduced from (125 to 50 and 55µm for SMF and MMF respectively) via chemical etching process then dipped into (3 wt % concentration) of germanium (Ge) solution to produce the sensing part of the fibers. Due to the applied X-rays radiation, an attenuation of the spectrum and a redshift in peak wavelength were achieved. Both sensors show good responsivity to the applied radiation and the MMFs sensors showed higher wavelength shifting as compared to SMFs sensors.

Keywords: X-rays, optical fiber radiation sensors, Radiation-induced Absorption; Radiation-Induced Refractive-Index Change; Germanium doped optical fibers.

1. Introduction

Most types of radiation are dangerous for living beings when exposed to them. For this reason, real-time remote dose measurements have great necessity. Radiation dosimeters have been applied in wide fields such as nuclear facilities, industrial process controls (X- or e- beam polymerization), nuclear medicine, and radiotherapy. The usage of traditional electronic dosimeters has some problems like using high power energy, uncertain measurement under radiation due to degradation and changing of measured sensitivity. Furthermore, it is difficult access to very hazardous areas, such as hot cells, high active source storage areas [1]. On the other hand, optical fibers sensors (OFS) present the key feature to be used as radiation detection dosimeters in different fields including space military, industry etc. This is because they have a number of advantages regarding the traditional forms of the data link [2]. The high spatial resolution (parts of millimetres), accuracy, large dynamic range, the cost-effectiveness, sufficient sensitivity, acceptable fading, response linearity, reproducibility, dose rate independence, and immune to electromagnetic radiation. All these characteristics made OFS very suitable choice for radiation detection applications [3]. Two types of OFS’s structures can be used as radiation sensors; the first one is the intrinsic sensor which is used as a radiation sensitive material, and a guide for an optical signal passing through it to the detector [4]. This type is frequently used for monitoring the radiation dose of the radioactive waste container[5]. The second type is the extrinsic sensor that only acts as a waveguide to deliver the optical signal from transmitter to receiver and the sensing part is spliced or coupled to the waveguide [6]. These types of sensors mostly used in vivo monitoring during radiotherapy [7]. The interaction between fiber material and the applied radiation causes the existence of point defects in fiber core and cladding. Also, this interaction leads to three
macroscopic effects; Radiation-Induced Attenuation (RIA) which increases the attenuation of the signal, Radiation-Induced Emission (RIE) which is responsible for the emission of light and originates from the luminescence of point defects or Cerenkov emission, and finally, Radiation-Induced Refractive Index Change (RIRIC) which is caused by changing the density in the glass or by the RIA via the Kramers-Kronig relations [8][9]. The sensitivity of multimode or single-mode optical fibers exposed to different types of radiations was described in many research. Gerard et al. [2] studied the sensitivity of SMFs under gamma and pulsed x-rays radiation in the IR wavelength range. The tested samples were doped with P (Phosphor), N (Nitrogen), and Ge (Germanium) dopants. A demonstration of the actual ability of a silica-based optical fiber doped with Ge to be used as a thermally stimulated luminescence-mode dosimeter and to confirm its applicability. These fibers have been irradiated with different types of radiation photons, x and gamma rays within a dose range higher than 10 krad, with different dose rates[10].The Thermo-luminescence response of Ge-doped silica-based optical fiber to electron, x-rays and gamma rays had been presented by Entezam et al. [11] they found that the Ge-doped optical fiber with higher core size has a higher sensitivity. Ladaci et al [12] investigated the Ytterbium and Erbium energy level lifetimes versus doses of various radiation types (40 KeV X-rays, 480 MeV protons, 1.2 MeV γ-rays and 6 MeV electrons). Also, they added Cerium ions Erbium-doped fiber to improve its tolerance on RIA effects. The RIA of different doped optical fibers under X-rays at three different temperatures had been studied by Vecchi et al. [8]. They found that the irradiation of both gamma rays and x-rays leads to the same levels of RIA. This result confirmed that these types of optical fiber sensors could be used in dosimetry fields.

In this work, the behaviour and performance of SMFs and MMFs optical fiber sensors with modified cladding under x-ray radiation at different exposure times will be observed and studied.

2. Materials and Methods

Commercially available SMFs and MMFs were utilized as radiation sensors in the measurements technique. The core diameter of the SMF sensor was 10 μm and the cladding diameter was 125 μm, while the MMF has a core diameter of 50 μm and a cladding diameter of 125 μm. The fabrication process of the radiation sensors took place as follows; first, the middle region of these fibers were stripped and cleaned very well with the suitable solution (the length of the stripped region is about 3 cm). After that, the fibers’ diameters were reduced via the chemical etching process by immersing them into hydrofluoric acid (HF) diluted with distilled water. The concentration of HF acid was 42 %, this concentration had been diluted by adding distilled water with percentage (1(HF):2 (water)) ml for 45 and 30 min for SMF and MMF respectively. Then the fibers removed from HF solution and dipped into water for three stages to remove any remaining HF solution from the fiber surface. Fibers have been removed from the water and measure the diameter of the fibers after etching. For accurate measurement, the etching procedure is done at room temperature (around 25 °C). The obtained diameters were (50 and 55) μm for SMF and MMF respectively. Finally, the etched region of the fibers was dipped in (3wt. %) of Ge solution to generate the sensing part of the sensor. The germanium is a colloidal solution; it was prepared by dissolving Ge powder in toluene liquid. Due to etching process the cladding surface of silica optical fiber becomes rough and contains pores and what is called dangling bonds; these bonds capture Ge nanoparticles and make them settle down inside the pores. Since the stripped part of the fiber is immersed in the solution with caution then the etching process will be equal all over cladding surface, therefore, Ge nanoparticles will adhere equally on the cladding surface. According to these steps, the modified cladding fiber sensors were manufactured and submitted as clarified in Figure 1.
Figure 1. The manufacturing steps of the modified cladding optical fiber sensor.

Figure 2 illustrates the schematic diagram of the experiment to investigate the x-rays irradiation effect on the properties of the transmitted signal. It is worthy to mention that the transmitted signal in the UV-VIS range changes due to the absorption process of the x-rays radiation.

The sensing parts of SMFs and MMFs samples placed on a glass slide then inserted inside an isolated armed chamber of the X-ray radiation source (XRD-6000 SHIMADZU) device. This device is located at the material research directorate, ministry of science and technology, Iraq. The exposure angle was (90°) to ensure that all the sensing area exposed to radiation. The distance between the fiber sensor and the radiation source head was (10 cm). The other parts of optical fibers were located outside the chamber and the two ends of each fiber considered as the sensor terminals. The first terminal was connected to the UV-VIS light source (DH-2000 Ocean optics) with range (200-1100) nm as a transmitting signal passing through the sensors. While the other terminal was connected to the spectrometer (Ocean Optics USB-2000) to record the spectrum online during the irradiation process (real-time measurement). The X-rays were emitted from a Cu tube with the following specifications; (X-rays tube target Cu with Broad Focus (BF 2.7 KW type), the maximum voltage of 60KV, maximum current of 80 mA, and average maximum power of 3 KW). The resulted spectrum of each sample was recorded as (3) measurements within (3) minutes (one measurement each minute) to test the responsivity of designed sensors to low radiation doses.
3. Results and Discussions

As mentioned, earlier the transmitted spectra of both investigated optical fibers sensors were measured and recorded at different x-rays dose rates. The following figures illustrate the output data revealed from this work. Figure (3a, and b) shows the spectral dependence of the measured spectra for the SMF and MMF sensors respectively due to x-rays irradiation.

Figure 3. The spectral shape of (a) SMF sensor, (b) MMF sensor.

The above figures show that RIA in both investigated fibers has similar spectral character. For SMF’s sensors we can notice that in the VIS spectral region, there is a local sensitivity maximum at around 655 nm from which the induced RIA drops rapidly towards IR wavelengths. Besides, there is another peak with a local minimum around 570 nm as is clear in Figure 3 (a). The same behaviour founds when using MMF’s sensors except a new peak found in the range of 255 nm as it shown in Figure 3 (b). The transmitted intensity for all samples decreases due to radiation application attenuation in transmitted intensity increases with the dose rate which is 3 minutes.

Figure (4a, and b ) shows the intensity values (intensity attenuation)as a function of radiation exposure time for both SMF and MMF sensors. The RIA sensitivity for SMF sensor was measured through the linear fitting relation between the intensity and exposure time for each peak. The values were (-) 23.1 count/ min and (-)11 count /min for the peaks 650nm and 570 nm respectively with good reliability of 0.93 and 0.99 respectively. While for the MMF sensor the sensitivity values were (-) 6.8 count /min, (- ) 8.3 count /min, and (-) 8.7 count /min with reliability values of 0.98, 0.99, and 0.95 for the peaks 650 nm, 570 nm, and 255 nm respectively. The transmitted intensity for all samples decreases due to the attenuation phenomenon that appears in optical fibers due to X-rays irradiation.
One of the most important and effective parameters for any radiation sensor is its wavelength sensitivity. The wavelength sensitivity was measured through the linear fitting relationship. In this work, sensitivity was measured for both modified cladding SMF and MMF sensors. SMF sensor shows a wavelength sensitivity of 8.1 pm/min and 25 pm/min with good reliability 0.96 and 0.95 for the peaks 650 nm and 570 nm respectively. On the other hand, MMF sensor showed a very high sensitivity of 112 pm/min and 50 pm/min with good reliability 0.95 and 0.96 for the peaks 650 nm and 570 nm respectively. The third peak that appeared in the output spectra of the MMF sensor at 255 nm suffered from a blue shift due to radiation application, and the sensitivity for this peak was (-) 10060 pm/min with a reliability of 0.95.

According to these results, SMF sensors have higher intensity sensitivity than MMF sensors. This could be explained as follows; for MMF sensors with their large core, the effects of the light-guiding on changing signal intensity are small, while the changing in wavelength due to radiation application was higher for them as compared to SMF sensors. Investigating the behaviour and performance of SMF and MMF sensors with smaller diameters decreased by the chemical etching process was achieved. However, this procedure resulted in leaking some of the transmitted light signals outside the cladding known as an evanescent wave. These leaked waveforms act as a field around the cladding material and interacts with the dipping material (germanium) lead to generation of point defects that change fiber structure, and thus change its refractive index. Ge nanoparticles plays very important role in sensing.
process since Ge and Si are isoelectronic elements having therefore the same number of electrons. Therefore, Ge-related point defects have a similar structure as those related to Si, but replacing Si with Ge atoms. In Ge-doped fibers, Ge-related defects are dominant over Si-related defects because they are generated in a more efficient way. In Ge-doped fibers, the RIA has been found to monotonously increase with dose (D) before reaching a saturation level. It is worthy to mention that the submitted optical fibers sensors have different layers and compositions (silica and germanium) and therefore they are subjected to different stresses. Hence, due to what mentioned earlier, the structural modification, defects generation, and layers stress, all these factors can have spatial distribution and in return modify the guiding properties of the optical fibers. The changing in wavelength due to radiation application was higher for MMF sensors. This is because the interaction between the incident radiation and fiber materials lead to inelastic scattering. The origin of scattering is due to the interaction of light with the excitation of the medium. According to quantum theory approach, the interaction is between the quanta of light (photons) and quanta of medium excitation which are phonons. This is true for the low light intensity levels, but for the strong excitation of the medium due to the high intensity of light, the semi-classical wave theory turns to be more appropriate to describe the scattering process. For an inhomogeneous medium, the scattering process removes some photons of the incident light and produces scattered photons that might be shifted in direction, phase and frequency in this work the shifting was in frequency (wavelength). The incident photons give or receive energy to or from the medium, leading to scattered photons shifted in frequency by definition, the components of the scattered light which are shifted to lower frequencies are known as Stokes components while those components which are shifted to higher frequencies are known as anti-Stokes components. This scattering leads to produce new photons with new phase and frequency. This could be the reason behind we get two different shifting red and blue in MMF sensors.

4. Conclusions

This work is aim to perform an initial assessment of the possibility to utilize optical fibers as radiation sensors; modified cladding SMFs and MMFs had been used for this purpose. X-rays source with an exposure time of 3 minutes source was employed as the radiation source. Both fibers exhibited a similar spectral character of decreasing the transmitted light and shifting in peak wavelength due to radiation. In spite of small exposure radiation time (due to Lab protocols) but both sensors exhibited good response. The SMF sensors showed a higher intensity sensitivity, while the MMF sensors showed a higher wavelength sensitivity. The presented sensors could be very useful in medical applications like monitor low doses of ionising radiation, radiation dose real-time measurements, and radiotherapy applications.

Acknowledgment

Funding of this work was provided by L’Oréal Foundation, where Aseel Mahmood and her scientific group win the L’Oréal- UNESCO for Women in Science Levant Program Fellowship 2018.

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