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Real-time Ultraviolet Radiation Sensor Based on Modified Cladding Optical Fibers Technology

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Abstract

In this work, the performance of single-mode optical fibers (SMFs) for ultraviolet (UV) radiation monitoring and dosimetry applications is presented. In particular, this work will focus on the Radiation-Induced Absorption (RIA) phenomena in the Near-Infrared domain (NIR). Such phenomena play a very important role in the sensing mechanism for SMF. Single mode fibers with a diameter of 50 µm were used for this purpose. These fibers were dipped into germanium (Ge) solution with different concentrations (1, 3, and 5 wt%) to produce the sensing part of the sensor. For all optical fiber sensors under investigation, the results indicated the dependence of the RIA on the applied UV radiation energy. Also, a redshift in peak wavelength was obtained. The influence of Ge concentration on sensing efficiency was studied and the best results were obtained with 3 wt% concentration as compared to 1 wt % and 5 wt % concentrations. The presented sensor shows good sensitivity to UV radiation which makes it possible to be applied in medical applications.

Keywords: Germanium doped optical fibers; Radiation-induced Absorption Optical fiber dosimeters; Optical fibers sensors; UV radiation.

متحسس الاشعة فوق البنفسجية في الوقت الحقيقي بالاعتماد على تقنية الالياف البصرية

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الخلاصة

في هذا العمل تم تقييم اداء متحسسات الالياف البصرية للأشعة فوق البنفسجية لتطبيقات مراقبة الاشعاع ومقاييس الجرع. عمليا سيتم التركيز على ظاهرة الامتصاص المحتث بالإشعاع ضمن منطقة الاشعة تحت الحمراء. حيث تلعب هذه الظاهرة دورا مهما في داء متحسسات الالياف البصرية ذات النمط المفرد. في هذا العمل سيتم استخدام ليف بصري احادي النمط ذو قطر 50 مايكرومتر . تم غمر هذه الالياف البصرية بمحلول الجيرمانيوم بتراكيز مختلفة (1,3,5) نسبة وزنية مئوية لتكوين منطقة التحسس في المتحسس .لكل متحسسات الالياف البصرية المختبرة اظهرت النتائج اعتمادية الامتصاص المحتث بالإشعاع على طاقة الاشعة

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فوق البنفسجية المطبقة. وكذلك اظهرت النتائج زحزحة في الطول الموجي لقمم الامتصاص نحو الاطوال الموجية الحمراء . تم اختبار تأثير تركيز نسبة الجرمانيوم على اداء المتحسسات واظهرت النتائج ان المتحسسات المغمورة بنسبة الجيرمانيوم 3 نسبة وزنية مئوية افضل تحسسية مقارنه بالتراكيز الاخرى. المتحسسات المقدمة اظهرت عموما استجابة جيدة للأشعة فوق البنفسجية والتي يمكن ان تكون مفيدة في التطبيقات الطبية

1. Introduction

Dosimeters are devices that are utilized for radiation monitoring and measuring. Different information could be collected through them due to the radiation nature and characteristics [1]. Optical Fiber Dosimeter Sensors (OFDS) have impressive characteristics that render them very important devices in detecting radiation compared to other ones [2]. Their immunity to electromagnetic radiation, ability to monitor the doses remotely in harsh environments and water resistance, small size, and cheap price, in addition to their availability in the commercial markets, are considered as the most unique characteristics of OFDS [3]. The OFDS have many applications, especially in the medical fields, like cancer treatment by measuring the radiation dose under different conditions through radiation therapy [4]. These treatments must be very accurate to give the desired dose in the desired location without affecting the surrounding healthy tissue [5].

Monitoring of Radiation-Induced Attenuation (RIA) of a fiber is perhaps the most straightforward OFDS technique. Radiation damages the material of the fiber which, in turn, degrades the fiber's transmission properties. The corresponding attenuation increase can then be measured optically and correlated to the total dose that the fiber has been subjected to [6].

The RIA can be calculated through the Beer-Lambert Principle. The attenuation which is caused by radiation is given by Eq. (1) [7].

$$RIA(dB) = -\frac{10}{L - L_o} log\left\{\frac{P_T(\lambda, t)}{P_T^0(\lambda)}\right\} \tag{1}$$

where L is the irradiated length of the fiber, L_o is the length of the reference fiber, $P_T(\lambda, t)$ is the measured optical power in the irradiated fiber, and $P_T^0(\lambda)$ is the optical power of the reference fiber. The applied radiation can change the glass structure, leading to pure or doped silica compaction and refractive index (RI) changes. These effects are largely affected when the fiber is used as a point or distributed sensor, relying on the glass response to temperature or strain [3]. The optical properties of the optical fiber are influenced by the nature of the dopant elements. These dopants must be easy to liquefy and to vitrify with silica, which renders their thermal expansion coefficient equal to that of silica and provides them with stability [8]. The most common material used as a dopant material is Ge, which is used in telecommunication optical fibers to adjust the refractive index. The doped fibers are more sensitive in comparison to non-doped ones. Germanium doped fibers have been widely used in medical applications because most standard telecommunication optical fibers were made from germanium, in addition to their high radiation sensitivity [9,10].

Many studies have been presented in the field of UV radiation; U-shaped optical fibers dipped with a UV marker to detect the UV radiation were presented by Joža *et al.* [11]. Chen *et al.* conclude that the intensity of UV radiation decays approximately inversely proportionally to the sensor distance from the UV source [10]. They presented a UV sensor based on photochromic optical microfiber which enhances the sensitivity to 3.13 nW/cm2 compared to traditional electrical devices. A UV optical fiber sensor based on the scintillating material La2O2S: Eu was presented in 2018 [12]. These materials were very sensitive to UV light intensity even in presence of strong electromagnetic interference. The introduced sensor showed very good accuracy and linearity. Investigation of RIA of modified cladding multimode fibers with different diameters in the UV-VIS region was achieved by Mahmood *et al*. The s sensor has a very good response to low-level UV radiation [13].

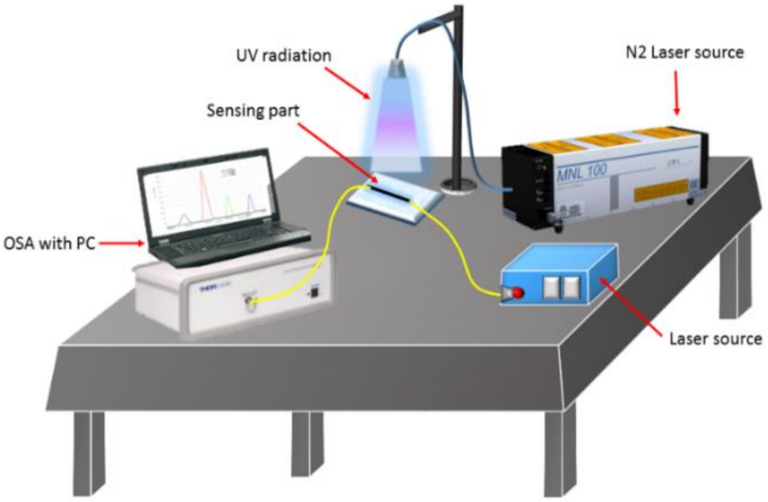
The aim of this work is to evaluate the response of the modified cladding SMF (which is dipped with germanium) to UV radiation under different energies and to study the effect of the germanium concentration on sensor's characteristics.

2. Materials and Methods

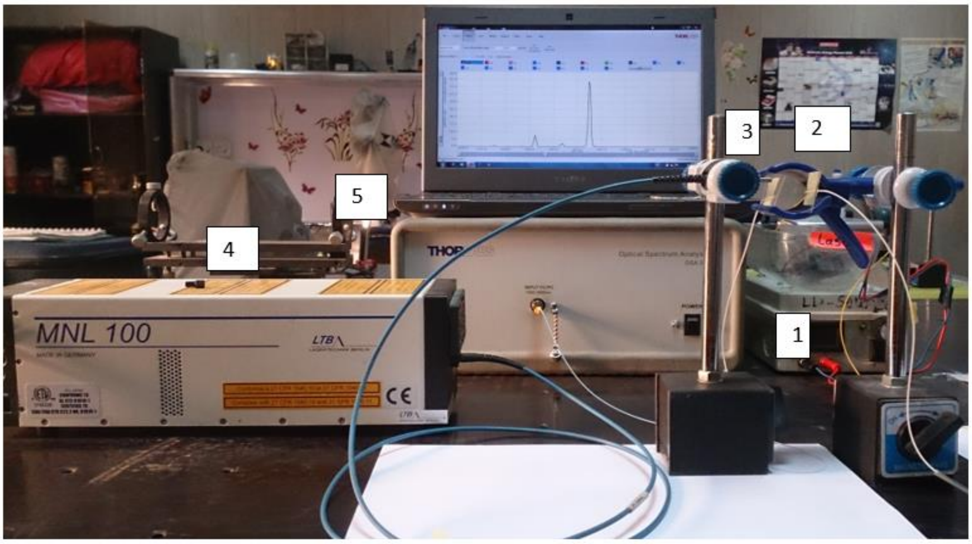
The operation principle of the submitted sensor is based on detecting the changes in transmission signal (of the known spectrum NIR in this work)due to absorption of the UV radiation. A modified cladding optical fiber sensor was manufactured in this work through the following steps. First, ~3 cm length of the middle region of commercially available SMF with a core diameter of about 10 µm and a cladding diameter of 125 µm was stripped and cleaned very well. The outer diameter of the stripped region was reduced using the chemical etching process by immersing the stripped region in diluted hydrofluoric acid (HF) for 30 minutes. The obtained SMF diameter was 50 µm. Then the etched region was dipped into Ge nanoparticle solution from Sky Spring Nanomaterials Inc., USA, with different concentrations (1, 3, 5 wt.%). The germanium colloidal solution was prepared by dissolving Ge powder in toluene liquid.

The immersion step is considered as very important, as it provides a modified cladding fiber which is regarded as the sensing part of the submitted sensor.

The experimental steps of the measurement set-up were achieved by attaching one side of the fiber sensor to a 1550 nm laser source (Thorlabs-United States) coupled with fiber as a transmitting signal through SMF. The end side was connected to Optical Spectrum Analyzer (OSA-THORLABS 203- United States) for recording the spectrum online during the irradiation process. Figure 1 (a & b) shows the schematic diagram and the photographic image of the experimental setup.



(a)



(b)

Figure 1– **(a)** Schematic diagram, and **(b)** photographic image of the experimental setup of the optical fiber UV radiation sensor, where (1) laser source, (2) sensor fiber, (3) UV probe, (4) N_2 laser, and (5) OSA with PC.

The sensing parts of the different prepared sensor samples were exposed to UV radiation. The distance between the sensor head and UV radiation source probe is about 2 cm. The UV radiation source used in this work is an N_2 laser source (MNL-100- Germany) with a wavelength of 337.1 nm, repetition rate of 60 Hz, duration time of 2.5 ns for every pulse, and varying pulse energy spectra (0–40 µJ) . The transmission spectra were recorded online by OSA for different UV radiation energies.

3. Results and Discussion

The optical properties of the transmission spectra for the presented sensors were studied. These sensors were irradiated with a UV radiation energy range of 0-40 µJ. The transmission spectra were monitored and recorded online for different optical fiber sensors dipped with different Ge concentrations (1, 3, 5 wt%). Figure 2 shows selective transmission spectra to sensors dipped in Ge with the concentration of 3%wt.

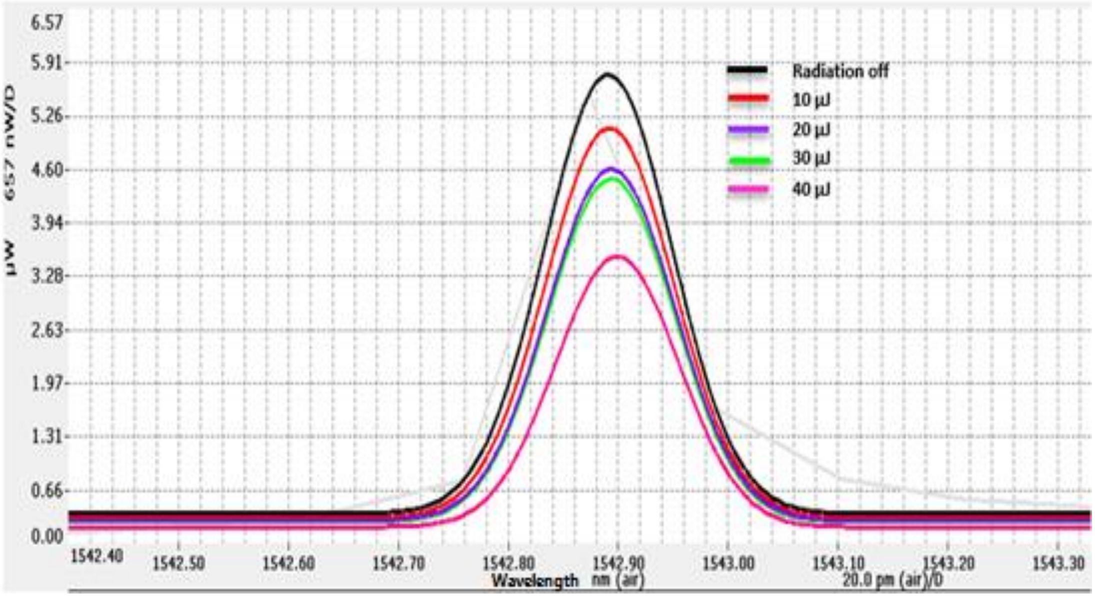


Figure 2- Selected transmission spectra of modified cladding SMF sensor dipped with Ge solution of concentration 3wt %.

From Figure 2, it can be noticed that the optical power was attenuated due to the applied radiation. Also, a slight shift of peak wavelength towards longer wavelengths was obtained. Figure 3 shows the relation between irradiation energy and attenuation in power for the submitted sensors. The power sensitivity was calculated from the linear fitting relation of curves shown in Figure 3.

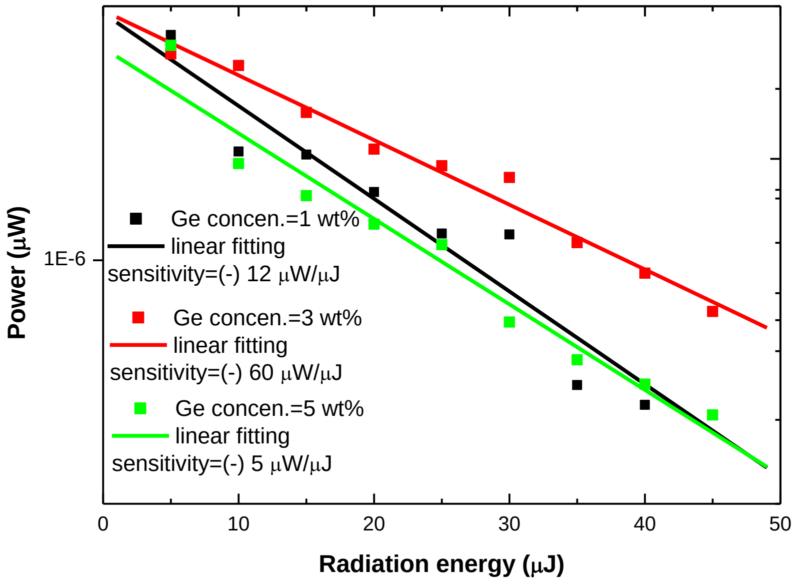


Figure 3- The relationship between the applied radiation energy and transmission power for different Ge concentrations (1, 3, 5 wt %).

The calculated values of power sensitivity were -12, - 60, and – 5 µw /µJ for Ge concentrations of 1, 3, and 5 wt %, respectively. Also, the peak spectrum wavelength exhibited a slight shift towards the red region, as shown in Figure 4.

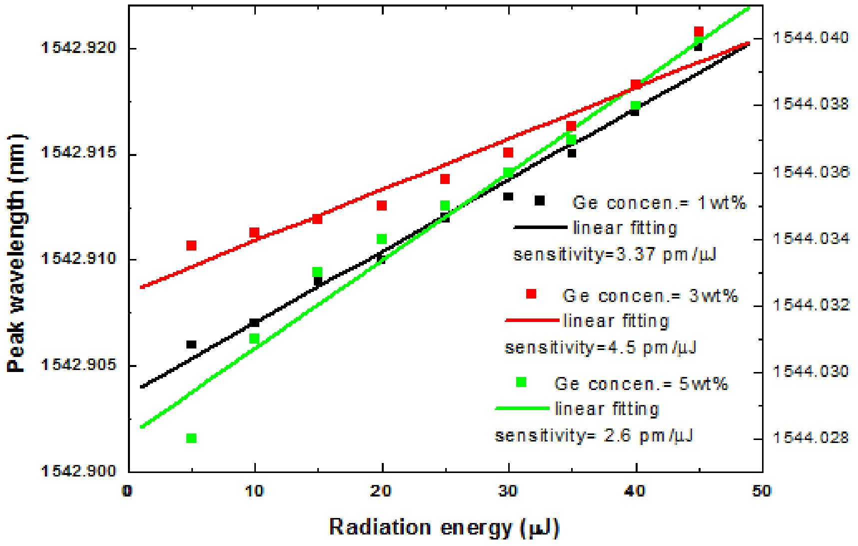


Figure 4 -The relationship between the radiation power and peak wavelength for different Ge concentrations.

The wavelength sensitivity was calculated from the linear fitting relation of curves in Figure 4, where the values were equal to 3.37, 4.5, and 2.6 pm/µJ for Ge concentrations of 1, 3, and 5 wt %, respectively.

The RIA causes an increase in fiber attenuation when exposed to radiation. RIA levels depend on many parameters, including the irradiation characteristics, operating wavelength, fiber intrinsic characteristics such as the composition of its core and cladding, manufacturing process, opto-geometric parameters, and light guiding properties. In this work, the fiber characteristics were modified to be sensitive to the applied radiation by making a modification to the cladding part. The guided modes of SMFs at an optical window 1550 nm between 15% and 40% of the propagated light could be guided in the cladding. Here, the diameter of the cladding was decreased to 50 µm. In this way, more leakage modes could be propagated close to the fiber's outer surface which is dipped with the radiation-sensitive material.

This modification aimed to design the fiber refractive index profile which controls the guided modes and the confinement factor and, thus, the sensing properties. It is very complicated to evaluate the contribution of a specific defect to the change in refractive index which leads to wavelength shift in the transmission spectra, because it is difficult to infer if one or more species of color centers are the unique origin of this change. Due to the above reasons and lack of publications related to that subject, we could not find appropriate explanations to discuss our results related to germanium concentration effects. We found a study submitted by Kobayashi *et al*. [14] who studied the influence of Ge-Co doping on P- RIA in doped fibers. They used concentration percentage range of 0-6.7 wt% and found that RIA decreased with the increase in Ge concentration due to the application of gamma radiation. Also, Girard *et al*. [15] studied the response of core doped optical fibers to different radiation sources. They used germanium core doping ratios that varied between about 3 and 15 wt% in these fibers. The different cladding co-dopants used were pure silica, Ge–F, F, P–F, Ge–P–F and Ge–P. However, they did not report which concentration had the best results.

4. Conclusions

The RIA patterns for different radiation-sensitive single-mode optical fiber sensors were characterized under UV radiation in the NIR region. These sensors were prepared by chemically-etched SMF to 50 µm, then dipped in germanium solution with different concentration. We investigated the influence of the concentration of dipping material on sensor characteristics. All the presented sensors proved good sensitivity to optical power and wavelength. The best results were obtained for the samples dipped in 3 wt% Ge concentration. The radiation can change the glass structure, leading to dipped silica compaction and refractive index changes. Also, the interaction between the incident radiation and fiber materials has led to inelastic scattering. The origin of this scattering is the interaction of the incident light with the excitation of the medium (which is UV radiation). According to the quantum theory approach, the interaction occurs between the quanta of light (photons) and quanta of medium excitation (phonons). 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. The incident photons give or receive energy to or from the medium, leading to scattered photons shifted in frequency. The components of the scattered light which are shifted to lower frequencies are known as Stokes components, while those shifted to higher frequencies are known as anti-Stokes components. Ultraviolet sensors have many applications, like industrial manufacturing, biochemical research, light sources, and environmental and structural health monitoring.

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