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Simple and Low-Cost Fiber-Optic Sensors for Detection of UV Radiation

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***Abstract* — In this paper two simple and low-cost fiber-optic sensors for detection of UV radiation are presented. A U-shaped sensor covered with an UV marker for UV radiation detection and a fiber-optic sensor with one end covered with powder from a mercury lamp are produced and described in details. Both sensors are made of large-core PMMA plastic optical fibers. As UV sources, a solar simulator and four different UV lamps are used. The light spectrum on the fiber output is measured by using an USB spectrometer. Dependence of output light intensity on the distance of end-type sensor with powder from a mercury lamp from UV lamp is investigated as well. On the output of the sensor covered with powder from a mercury lamp are obtained peaks of fluorescent emission at approximately 616 nm and 620 nm wavelengths.**

***Keywords* — Fiber-optic, powder from mercury lamp, U-shaped, UV marker, UV sensor.**

I. Introduction

NOWADAYS, measurement of UV radiation becomes very significant because of its numerous negative effects on human health. Ultraviolet radiation has genotoxic, mutagenic, cancerogenic and imunotoxic properties, which make ultraviolet radiation a serious threat to human health. In order to prevent dangerous influence of UV radiation, different methods for UV detection are developed. One example is UV detection with nanowires based on monitoring the current–voltage or the electrical conductance variation when exposed to UV radiation [1]. An ultraviolet sensor based on ferroelectric-semiconductor thin film structures is proposed in [2]. A wireless UV sensor based on photocapacitive effect in GaN (upon illumination of oscillator with ultraviolet light an oscillator frequency decreases due to the photocapacitive effect) is reported in [3]. These are relatively complex methods of measuring ultraviolet radiation. The need for simpler solutions has led to the fiber-optic sensors.

Fiber-optic sensors have many advantages over conventional optical sensors [4]. Fiber-optic sensors are small in size, light, electrically safe and immune to electromagnetic interference. Immunity to electromagnetic interference is especially important during measurements near an UV lamp due to intense electromagnetic fields encountered in its vicinity [5]. Also, fiber-optic sensors offer the possibility of distributed and localized measurements along the whole sensor length, ensuring in that way power measurements over an interval and in a point.

Plastic optical fibers (POFs) are used for the fabrication of the sensor because they are cheap, robust and easy to handle [6]. Also, POF is very suitable for the realization of the sensor because it has a large core diameter.

Glass optical fibers can also be used and they have further advantages over the plastic type such as sensitivity and lower attenuation but they are costly, fragile and difficult to handle. As POF has a higher numeric aperture than glass optical fibers our system also benefits from a wider acceptance angle which provides better light collecting conditions.

A fiber-optic UV sensor based on cladding luminescence with sections of its cladding stripped and replaced with a mixture of epoxy and phosphor is presented in [7]. A similar fiber-optic UV sensor covered with azobenzene dye-doped polycarbonate is reported in [8].

In this paper, two UV sensors based on the fluorescence phenomenon, which are implemented by using a plastic optical fiber covered with UV sensitive compounds, are proposed.

The paper is organized in five chapters. This introduction section is chapter one. In the second chapter is briefly described the principle of operation of UV sensors proposed in this paper. In the third chapter are shown experimental setups for two UV sensors, while the measurement results are given in the fourth chapter. The fifth chapter is conclusion.

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II. Principle of Operation

The principle of operation of UV sensors presented in this paper is based on the fluorescence phenomenon. Fluorescence is a form of photoluminescence phenomena, i.e. luminescent phenomena caused by absorption of light [9]. It is determined that the intensity of photoluminescent emission decreases exponentially with time:

$$I_t = I_0 \cdot e^{-\frac{t}{\tau}} \quad (1)$$

where I_0 and I_t are emission intensities when t=0 and t=t. τ denotes the mean lifetime and represents a time in which the intensity of photoluminescent emission decays to 1/e of its initial value.

Absorption of UV radiation by a molecule excites it from a vibrational level in the electronic ground state to one of the many vibrational levels in the electronic excited state. A molecule in a high vibrational level of the excited state will quickly fall to the lowest vibrational level of this state by losing energy to other molecules through collision. Fluorescence occurs when the molecule returns to the electronic ground state by emission of a photon hν. Fluorescence stops immediately when the source of excitation is removed, i.e. the emission occurs immediately after the absorption. The mean lifetime has values from 10^{-8} to 10^{-6} s.

The main characteristic of fluorescent emission is lower frequency (lower energy) than the frequency of absorbed radiation, i.e. a longer wavelength of fluorescent emission than the wavelength of absorbed radiation. Therefore, by exposing some UV sensitive material to UV radiation, fluorescent emission is expected in the visible range of wavelengths.

It is assumed that fluorescence phenomena could be noticed when some UV sensitive compound (e.g. a UV marker or powder from a mercury lamp) is deposited on an optical fiber.

III. Experimental Setup

Different methods of UV detection implemented by combining optical fiber and UV sensitive compounds were tested. The best results were achieved with two sensor types, which will be described below in more details.

A. U-Shaped Sensor

The principle of U-shaped sensor operation is based on detecting known radiation spectrum changes due to absorption of the same in the presence of UV radiation. The block diagram of experimental setup used in experiments with the proposed U-shaped fiber-optic UV radiation sensor is shown in Fig. 1.

The schematic structure and the photograph of the proposed sensor are given in Fig. 2. U-shaped sensor is fabricated by polishing cladding and partially core on a strongly bent (U) part of 1 mm diameter PMMA (poly(methyl methacrylate)) plastic optical fiber. The diameter of bent part of a fiber is 3.5 mm and polishing depth is 0.3 mm. On the polished fiber part is then applied a UV marker in a thin film. On the sensor input is placed a white LED of a known spectrum, while the output of plastic optical fiber is connected to a spectrometer

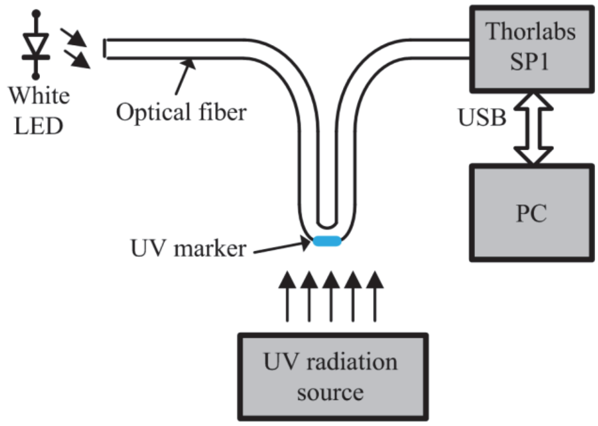

Fig. 1. The block diagram of experimental setup for fiber-optic UV radiation sensor based on U-shaped optical fiber.

(Thorlabs SP1). As a UV source, a solar simulator with variable output intensity is used.

The solar simulator used for this purpose is Sun 2000 Solar Simulator produced by *Abet Technologies, Inc.*, which has maximum irradiance of 1.3 suns.

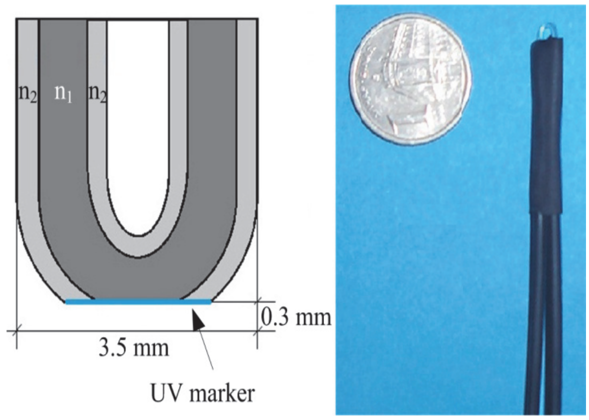

Fig. 2. U-shaped sensor.

B. End-Type Sensor with Powder from Mercury Lamp

The second implemented sensor is based on the detection of fluorescent emission due to UV radiation. The block diagram of experimental setup for measurements with the proposed end-type fiber-optic UV radiation sensor is shown in Fig. 3.

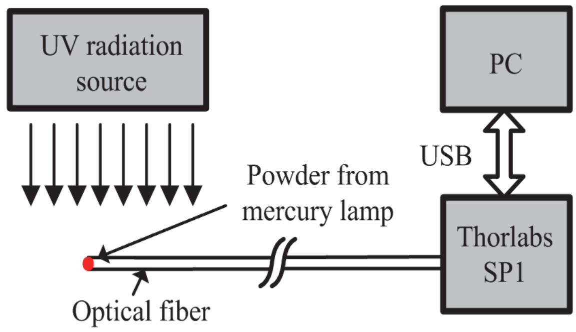

Fig. 3. The block diagram of experimental setup for end-type fiber-optic UV radiation sensor.

This sensor is also produced by using an 1 mm diameter PMMA plastic optical fiber. The ends of optical fiber are firstly polished and then on one fiber end is applied a mixture of index matching gel and powder from a mercury lamp. Index matching gel is used to achieve better optical coupling between the emitted fluorescent radiation and the optical fiber input as its main purpose in this sensor configuration is to bind powder from a mercury lamp onto optical fiber tip. Index matching gel also has approximately the same refractive index as the plastic optical fiber core. In Fig. 4 a photograph of the produced end-type sensor with powder from a mercury lamp for UV detection is given.

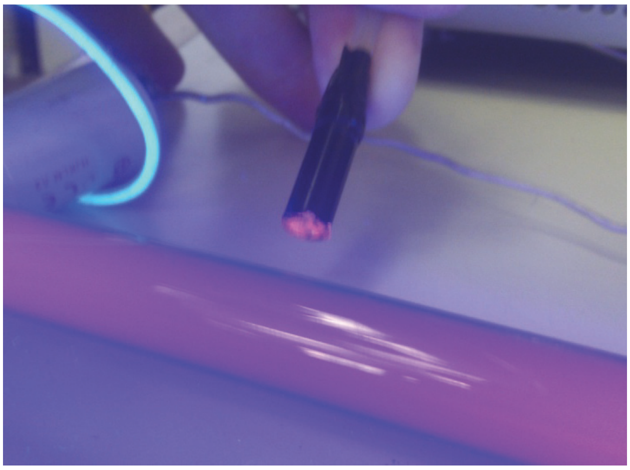

Fig. 4. End-type sensor with powder from mercury lamp.

In order to measure the dependence of fluorescent emission on the intensity of UV radiation, the end-type sensor is mounted on the precise micrometer positioner (produced by *Oriel Inc*) and its output was observed for distances 0 mm, 2.5 mm, 5 mm, 7.5 mm, 10 mm, 12.5 mm and 15 mm from the UV lamp. Distance 0 mm means that the sensor was pressed against the UV lamp. It is assumed that the intensity of UV radiation decays inversely proportionally to the distance as a UV lamp represents a line source of ultraviolet light. As a UV source is used a UV lamp and fluorescent emission spectrum on the fiber output is measured using a spectrometer. Measurement of fluorescent emission (measured with end-type fiber-optic sensor with powder from a mercury lamp) in dependence on sensor distance from UV lamp is shown in Fig. 5.

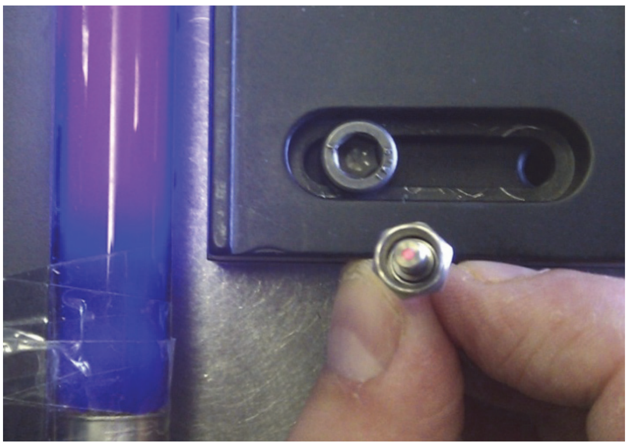

Fig. 5. Measurement of fluorescent emission (measured with end-type sensor with powder from mercury lamp) in dependence on sensor distance from UV lamp.

From Fig. 5 it can be noticed that spectrum on the fiber output is shifted to the range of red wavelengths (it can be seen that red light comes from the optical fiber), which will be graphically shown as well in the next chapter.

Spectrum characteristics of UV sources were measured by using the OCEAN OPTICS (200-400 nm) spectrometer in 2048 points. The output characteristics of fiber-optic UV sensors were measured using the THORLABS SP1 USB 2.0 spectrometer (400-800nm) in 3000 points.

IV. Results and Discussion

In Figs. 6-11 are given the results of measuring the spectra of UV sources, as well as measured light spectra on the sensor output. In Fig. 6 the measured UV spectrum of solar simulator is given. The solar UV spectrum consists of UV-C (100-280 nm), UV-B (280-315 nm) and UV-A (315-400 nm) bands [10]. UV-C radiation is the UV radiation of the highest energy and the most destructive, but it cannot reach the earth's surface as it is almost completely absorbed by the ozone, molecular oxygen and water vapor in the upper atmosphere. Thus, UV-C light does not represent a threat for the biosphere. The main part of UV light that reaches the earth's surface is UV-A radiation (only 2% of total UV radiation that reaches Earth is UV-B radiation). This radiation penetrates deeper into the skin than UV-B radiation, but the effects it causes are weaker and act cumulatively. Hence, the consequences of this radiation can be discovered only when changes are seriously developed.

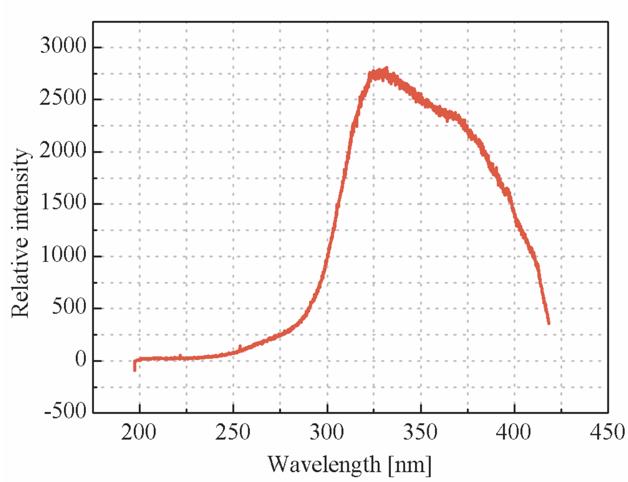

Fig. 6. UV spectrum of solar simulator.

In Fig. 7 one can see the relation between spectra on the U-shaped sensor output for cases with and without a UV marker applied on the polished part of the fiber.

From Fig. 7 one can clearly notice changes in the spectrum on the optical fiber output due to UV radiation in the presence of UV marker. Part of the spectrum of white LED 400–550 nm is subjected to lower absorption in comparison with the part of the spectrum 550-700 nm.

Spectra of four UV lamps used for measurements of UV radiation with end-type fiber-optic sensor with powder from a mercury lamp are given in Fig. 8. All four UV lamps emit in UV-A band.

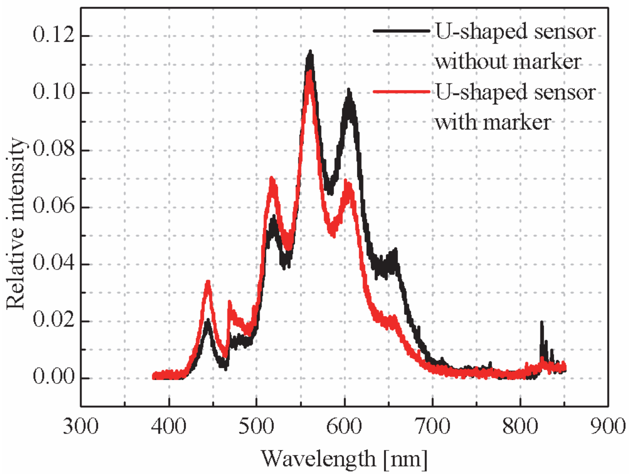

Fig. 7. Comparison of light spectra measured on the output of U-shaped sensor for cases with and without applied UV marker.

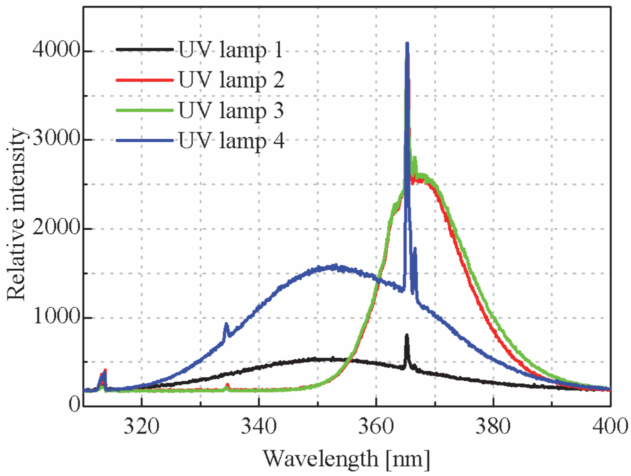

Fig. 8. Spectra of UV lamps used in experiments.

In Fig. 8 it is important to notice that the spectra of UV lamps 1 and 4 have identical shape, as well as the spectra of UV lamps 2 and 3. When the end-type sensor was exposed to radiation from UV lamps 2 and 3, no changes in the spectrum were detected on the sensor output. However, when end-type sensor was exposed to UV radiation from UV lamps 1 and 4, on the output of optical fiber there was detected a fluorescent emission in the range of red wavelengths, with peak values of 616 nm and 620 nm. The peaks of fluorescent emission are shown in Fig. 9. From these measurement results it can be concluded that the part of the spectrum 330-350 nm has the biggest influence on the appearance of fluorescent emission in the range of red wavelengths.

Measured spectra on the output of the end-type fiber-optic sensor with powder from a mercury lamp in dependence on sensor distance from UV lamp 1 are compared in Fig. 10. On the basis of Fig. 10, it can be concluded that as the sensor distance from UV lamp increases the shape of the spectra on the sensor output remains the same, only its intensity changes. This characteristic gives us the opportunity to think about future work and directions and also, commercialization of the proposed sensor by its price reduction. Price reduction is possible by replacing expensive spectrometers used in

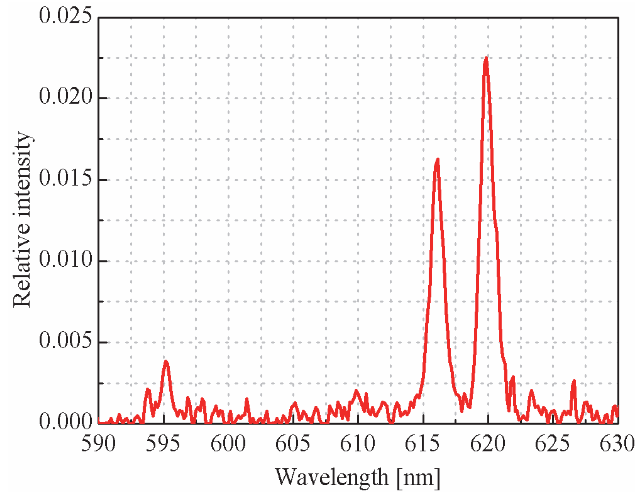

Fig. 9. Spectrum of fluorescent emission on the output of the fiber-optic sensor with powder from mercury lamp.

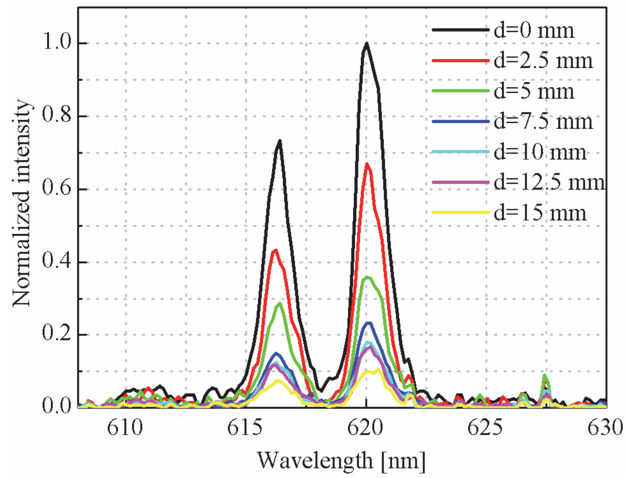

Fig. 10. Comparison of spectra on the output of the fiber-optic sensor with powder from mercury lamp in dependence on sensor distance from UV lamp 1.

experiments with a low-cost photodetector and optical filter in the wavelength range of interest.

The change in intensity depending on sensor distance from UV lamp 1 is shown in Fig. 11, from which it can be clearly noted that this dependence is approximately $1/d$, where d is the distance in mm. It is assumed that the cause of this non-ideal $\sim 1/d$ dependence is the non-uniform thickness of the film made of a mixture of index matching gel and powder from a mercury lamp.

V. Conclusion

Fiber-optic sensors presented in this paper allow detection of UV-A radiation in the visible range of wavelengths. Based on the measurements with described sensors, it is concluded that the intensity of UV radiation decays approximately inversely proportionally to the sensor distance from the UV source.

After testing both sensors it is concluded that the end-type sensor with a mixture of powder from a mercury lamp and index matching gel shows better characteristics for potential commercialization. A U-shaped sensor with a UV marker needs double length of plastic optical fiber in comparison with the end-type sensor. This feature is very

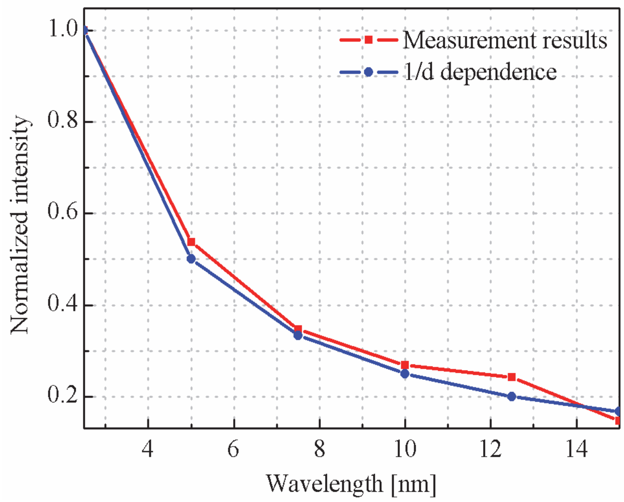

Fig. 11. Dependence of intensity of fluorescent emission on the output of fiber-optic sensor with powder from mercury lamp on sensor distance from UV lamp 1.

important in case of long distance measurements. Also, the sensor with powder from a mercury lamp does not require a light source in contrast to U-shaped sensor, where a white light LED is used. However, it has been noticed that the U-shaped UV sensor represents a potentially better solution for UV sensitive materials, which are less sensitive to UV radiation, such as a UV marker. A UV marker is also tested with an end-type sensor configuration, but no results were obtained.

The logical extension of this work is employment of some PMMA material as a binding material instead of index matching gel. This is expected to enable better connection of powder from a mercury lamp with a plastic optical fiber.

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