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Fluorescein filled photonic crystal fiber sensor for simultaneous ultraviolet light and temperature monitoring

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ABSTRACT

We present a novel structure composed of a photonic crystal fiber filled with fluorescein dissolved in water spliced between two conventional multimode fibers. Based on unique features of the fluorescein luminescence it is possible to adjust its emission spectrum to required spectral region. With increasing value of the fluorescein solvent pH factor, the peak wavelength of the emission spectrum is shifting to longer wavelength values. Since the excitation spectrum of fluorescein is relatively wide, this optical fiber sensor could be used for an efficient ultraviolet light monitoring. The detection limit at the level 0.24 mW with 490 nm excitation wavelength is presented. Moreover the emission spectrum is temperature sensitive what provides possibility of simultaneous ultraviolet light and temperature monitoring. Also the temperature sensitivity of the structure based on intermodal interference investigation for a compensation purposes and structure usage as spectrum enlarger are outlined.

1. Introduction

The use of an optical fiber for various sensing purposes has been reported [1]. Especially the photonic crystal fibers (PCF) as a new development of optical fibers attract an interest of many fields of optical studies [2]. The geometry of photonic crystal fibers which could be customized according to the application demands is generally composed of an array of air holes running all along the fiber. Owing to the existence of holes, these fibers could be filled by various substances. In that case, there is a direct interaction between the guided light and filling substance, usually evanescent. This causes the variation of original waveguide and could provide a wide range of interesting features of propagating light. Many types of filling substances have been already reported as liquid crystals [3], gases [4], polymers, metals [5,6].

Changing the structure and material of waveguide was always an attractive manner to reach new features of optical fibers. One of them is to create the luminescence optical fiber. For that purpose the optical fibers are very commonly doped by various compounds such as rare metals [7] or fluorescent dyes [8]. Radial irradiating or axial light confined in such a composite optical fiber with the light of excitation wavelength of dopant results in emission of new optical frequencies. This principle is then used in many biological, chemical, physical and medicine [9–11] sensoric applications.

In this paper we present the combination of the solid core photonic crystal fiber and synthetic organic compound fluorescein dissolved in water for sensoric applications. The PCF holey structure is filled by in water dissolved fluorescein and spliced in-line with conventional multimode optical fibers. The properties such as ultraviolet sensitivity and enhanced temperature sensitivity of the structure are presented.

2. Fabrication parameters and characterization

The component is made using silica PCF with GeO_2 doped core as well as commercially available 125 μm silica multimode (MM) optical fibers. The PCF design is described by parameters such as the outer diameter 82.7 μm, a pitch $\Lambda = 4.2$ μm, diameter of the cladding formed by an array of air holes 42.8 μm and GeO_2 doped core diameter 4.1 μm. The PCF was chosen due to "core" diameter fit to the core of MM fiber and also the diameter of the holes is suitable for a filling process. PCF is filled by a liquid compound of fluorescein dissolved in the water and then cut to 2 cm long sample (all holes are filled equally without any air gaps) and spliced between input and output MM optical fibers (Fig. 1). The fluorescein is an organic compound, dark red/orange powder slightly soluble in water or ethanol. For an experiment the water has been chosen, because the heat of vaporization of ethanol is too low for its preservation in a liquid state during a filling and splicing

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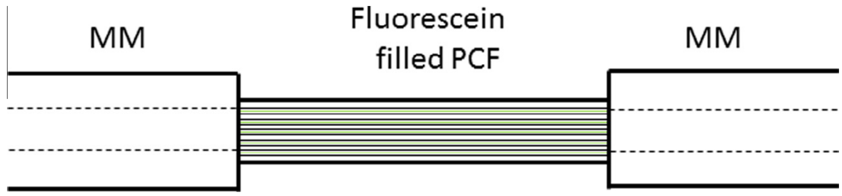

Fig. 1. Schematic figure of the MM-PCF-MM structure.

process. Fluorescein is a fluorophore commonly used in microscopy, dye lasers, sensors and widely in medicine as tracking dye. One of the most significant feature of fluorescein is that excitation and emission maximum and their spectral overlap are strongly dependent on a pH factor of the solvent [12]. This feature provides a possibility of adjustment of emission spectrum in suitable region, based on the application demands. In the case of water (pH ≈ 7) the excitation maximum is at 494 nm what overlaps the spectral line of argon-ion laser. The emission maximum is at 521 nm with the negligible excitation spectrum overlap. Another advantage of this substance is that the excitation spectrum is relatively wide and it can be excited by light even lower values of the wavelengths. The filling process was performed using the capillary forces. After the filling, the PCF fiber was cut and spliced to a MM fiber using the manual fusion splicer (with manual setting of alignment, place of splicing, fusing time, autofeed and fusing current) (Corning Siecor M 91). During the splicing process of MM and PCF fibers an amount of water was evaporated (hundreds microns in length) from the solution in the splice region and the microstructure of PCF was partially collapsed. This fact perfectly ensured the confinement of the water-fluorescein compound in the fiber.

The multimode fiber was used due to its 50 μm core, which covers most of filled microstructure of the PCF and potentiates equally the absorption of excitation light from input fiber as well as the effective confinement of emitted light to output fiber connected to the spectrometer. The facet capture of filled PCF fiber and the emission near the splice are depicted in Fig. 2.

3. Experimental results

In our experiment we investigated the prepared MM-PCF-MM structure for two possible options of in-PCF fluorescein excitation – radial (PCF irradiated perpendicular to the axis of the fiber) and axial (in-line excitation through the confined light from MM fiber). For a purpose of water-fluorescein compound excitation the Fiber-Coupled High Power LED source with nominal wavelength of 490 nm, typical power open output 7 mW and full width half maximum 23 nm was used. The output MM fiber was connected to Ocean Optics USB2000+ spectrometer with resolution ∼1 nm.

At first the excitation LED diode spectrum and the water-fluorescein compound emission spectrum for a different values of solvent pH factor was measured (Fig. 3). These characteristics were acquired directly from prepared water-fluorescein compounds specimen's LED irradiation without using the photonic crystal optical fiber. As obvious from Fig. 3, the emission spectrum peak is shifting to longer wavelength values with increasing pH factor of fluorescein solvent. Also the emitted light power level is increasing due to rising pH factor. For our experiment the neutral pH ≈ 7 was chosen. The spectral peak separation of excitation and emission spectrum (pH ≈ 7) is approximately 37 nm what provides a sufficient detection capability even with mutual spectrum overlap at the level of 36% of the emission maxima. The overlap level at this value is caused by a fact that all irradiate light was not absorbed and used for an excitation process.

Radial excitation of filled PCF was performed using the same LED source oriented perpendicular to the axis of the PCF fiber. To investigate the sensitivity of filled PCF on incident radiation the LED source was gradually placed in different distances from the fiber what corresponds to different levels of incident light, measured using the power meter (Ophir, Orion-TH). The spectral responses for a various values of incident optical power are shown in Fig. 4.

The measured detection limit of prepared structure was at the level of 0.24 mW of incident irradiation. So in the case of radial irradiation the emission spectrum of the water-fluorescein compound could be detected even for a very low power level of incident light. This is mainly due to uniform excitation of fluorescein. Although the excitation spectrum of fluorescein has its maxima around at 490 nm, there is a relatively wide range of the wavelengths, which can cause the effective excitation (approximately from 200 nm to 500 nm). Therefore this structure can be considered as a very efficient ultraviolet light sensor. All the measurements were performed at a constant room temperature 24 °C. Since the refractive indices of the used materials, silica and water are changing with the temperature the influence of the varying temperature on emission of the water-fluorescein compound was

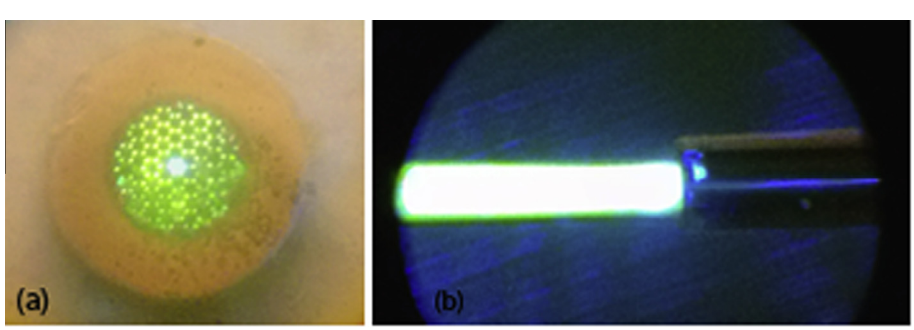

Fig. 2. (a) Facet of the prepared PCF fiber. (b) The splice region of in-line excited water-fluorescein compound. The UV-light is guided through the core of MM fiber (from right to left side) and the emission of the green light in the PCF can be observed.