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High sensitivity photonic crystal fiber-based refractive index microbiosensor

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ABSTRACT

We design a simple photonic crystal fiber-based refractive index biosensor (PCF-RIBS) and analyze its sensing performances using the finite element method. We analyze the loss spectra of PCF-RIBS for a wide range of wavelengths from visible to near infrared (0.4–2 µm). Besides, we extend the sensing performances in terms of loss spectra for three sets of refractive indices of analyte, n_a. From the detailed study, we find that the PCF-RIBS exhibits a highest spectral sensitivity of 12,000 nm/RIU with a corresponding resolution of 8.33×10^{-6} RIU and amplitude sensitivity of 11,412 RIU^{-1} with a resolution of 8.76×10^{-8} RIU when the refractive index is varied from 1.44 to 1.45. Finally, we also examine the robustness of the proposed sensor by perturbing some of the structural parameters, namely, thickness of the metal layer and diameter of the air-holes.

1. Introduction

It is well known that intensive care, monitoring, diagnosing and detecting the disease, drug testing, food safety and environmental field monitoring are considered to be the fore-most concerns in the world. In order to fulfil the above necessities, various fiber optic sensors are reported [1–5]. Of various sensing techniques, the surface plasmon resonance (SPR) based fiber optic biosensors have gained a considerable attention as they possess the rapid real-time sensing performances [6–8].

The SPR optical phenomenon has been widely used in various fields, i.e., to study the conformational changes of protein molecules, in the study of biomolecular interactions and in the detection of pesticides [9–11]. The SPR sensing method employs traditional Kretschmann configuration to excite surface plasmonic waves under a polarized light radiation parallel to the plane of incidence [12]. In a fiber optic SPR sensor probe, a small portion of the cladding is removed in an optical fiber and the unclad portion is coated with a thin metal layer [13]. The outstanding characteristics of SPR optical fiber sensors are admirable sensitivity to the refractive indices of the surrounding dielectric mediums. Generally, the SPR optical fiber sensors have been established in terms of angle modulation in prism-based setup and the wavelength modulation in optical fibers [14]. In recent years, the new class of fiber called photonic crystal fiber (PCF) overcomes the drawbacks posed by the conventional SPR optical sensors. Thus, with the PCF based sensor, one can have the miniaturization of the device, compatibility and portable, rapid and multi-sample testing with sensing performances, etc. [15]. Most importantly, an important condition for optical sensing is so-called phase matching which can be easily achieved in the PCF based SPR sensor by engineering the effective refractive index of the core-guided mode and the plasmonic mode. Recently, a great interest in engineering the geometrical and material properties of the PCF-SPR sensors are numerically investigated with different biological samples to monitor the medical conditions [16].

Diabetes mellitus is a chronic disease which frightens the health and economy of the globe in various developing countries [17]. The consumption of insulin and the role of diet allow the patients to endure a normal life. Nonetheless, a concern of maintaining the glucose levels is essential to control the abiding complications concerned with diabetes. Thus, it is highly essential to regulate the glucose concentration for clinical analysts [18]. In 2009, a glucose fiber optic sensor accordant with changes in the concentration of the liquid for the refractive index variation from 1.3322 to 1.3617 has been reported [19]. An ultra-sensitive microfluidic refractive index based photonic crystal fiber sensor with the sensitivity of 30,100 nm/RIU for the refractive index of 1.5 has been reported [20]. A highly sensitive refractometric sensor based on the long period grating in a PCF has exhibited the sensitivity of 1500 nm/RIU for the refractive index of 1.33 [21]. A PCF based refractive index sensor was established with a linear response of 262.28 nm/RIU to analyze the glucose solutions for various refractive index ranges from 1.337 to 1.395 [22]. A long period fiber grating based refractive index sensor has been successfully demonstrated with a maximum sensitivity of 193.42 nm/RIU in the concentrations of glucose-water and glycerol water [23]. A 2D photonic crystal-based

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biological sensor has been numerically investigated for the detection of glucose concentration from urine with the refractive index range from 1.335 to 1.347 [24]. A photonic crystal with a multi-layered structure has been fabricated for sensing the glucose of various refractive indices with a sensitivity of ~50.23 nm/RIU and a lower signal-to-noise ratio of ~0.46 [25]. Recently, the surface plasmon resonance-based D-shaped PCF coated with Indium Tin Oxide at the near-infrared wavelength with high sensitivity of ~6000 nm/RIU has been reported [26]. By using finite element method, the sensing performance of a D-shaped PCF based refractive index sensor has achieved a high sensitivity of 7700 nm/RIU in the analyte refractive index ranges from 1.43 to 1.46 [27]. In this line, the characteristics of a D-shaped PCF optic sensor was studied with various polishing depths with achieving a sensitivity of 7381.0 nm/RIU in the refractive index range of 1.40–1.42 [28]. Yong Wang et al., have experimentally realized a surface plasmon resonance biosensor based on gold-coated multimode fiber-PCF-multimode fiber obtaining the sensitivity of range from 1060.78 nm/RIU to 4613.73 nm/RIU in the analyte refractive index range of 1.3330–1.3904 [29]. In 2018, a surface plasmon resonance based D-shaped photonic crystal fiber sensor has been reported with a sensitivity of 3340 nm/RIU in the analyte refractive index 1.36–1.38 [30].

In the present study, we report the sensing properties of the PCF based surface plasmon resonance (SPR) refractive index sensor for the application of biomolecular detection. The paper is laid out as follows. In Section 2, we model the proposed PCF based SPR sensor by using the finite element method and analyze the metal influence in the proposed sensor by the Drude-Lorenz model [31]. The metal thickness is varied from 20 to 60 nm and the sensor-balance performance holds good for the thickness of 40 nm. Besides, the metal thickness has been followed as 40 nm for analysing the wavelength and amplitude sensitivities. We report the sensing properties in Section 3. We achieve a maximum wavelength sensitivity of 12,000 nm/RIU with a resolution of 8.33×10^{-5} RIU and amplitude sensitivity of 11,412 RIU^{-1} with a resolution of 8.76×10^{-8} RIU by varying the refractive index of the analyte. The sensing performances of the proposed device are investigated in terms of sensitivity and detection accuracy. The influence of the geometry parameters of the sensor such as air-hole diameter and metal-layer thickness are investigated in detail in Section 4. Finally, Section 5 concludes the work.

2. Simulation model and principle

The cross-section and schematic set-up of the PCF based SPR sensor are shown in Figs. 1 and 2. The thickness of the gold layer is varied from 20 to 60 nm. The diameter of the air-holes is 2 µm and pitch is 3 µm. Perfectly matched layer (PML) boundaries are used to calculate the complex propagation constant of the core guided modes. The refractive index of the analyte is varied from 1.31 to 1.45. The analyte refractive index is filled in between the gold layer and PML with a support in four sides. The refractive indices of silica-cladding are calculated from the Sellmeier equation for each corresponding wavelength [32]. The proposed sensor can be fabricated by the stack and draw technique [33]. The light from the source transmits into the proposed PCF-SPR sensor through the single mode fiber (SMF) and modulated by the different values of refractive index of an analyte in the analyte zone. The modulated signal is further collected by the oscilloscope spectrometer analyzer and then the spectral data are processed by a computer through a USB channel.

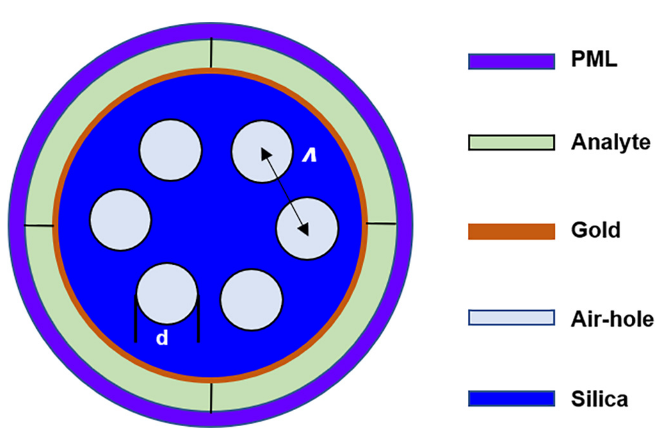

Fig. 1. Geometrical structure of the proposed PCF-RIBS.

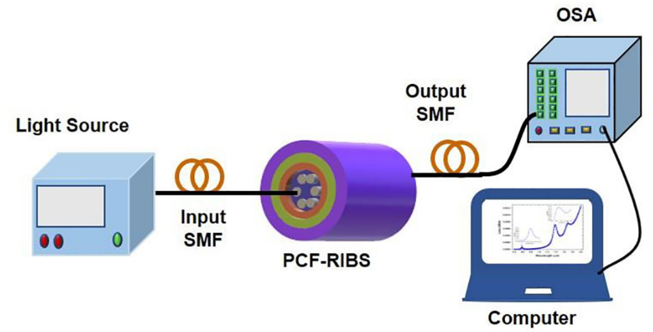

Fig. 2. Schematic set-up of the proposed PCF-RIBS.

3. PCF-RIBS based on SPR

In this section, we numerically investigate the sensing properties of the proposed sensor by using the finite element method. Initially, we calculate the real and imaginary parts of the effective refractive index (n_{eff}) as a function of wavelength. Using the imaginary part of n_{eff} values, we calculate the confinement loss, α, as shown in Fig. 3 by using the following expression,

$$\alpha\left(\frac{dB}{cm}\right) = \frac{40\pi Im(n_{eff})}{\ln(10)\lambda} \times 10^4. \tag{1}$$

In Eq. (1), $Im(n_{eff})$ denotes the imaginary part of the core-guided mode for the corresponding wavelength, λ in µm. The phase-matching condition of the proposed PCF based SPR refractive index sensor is shown in Fig. 3.

The numerical results of the proposed PCF based SPR refractive index sensor for a microfludic environment which explains the resonance condition i.e., the SPR peak appears at the crossing point of the

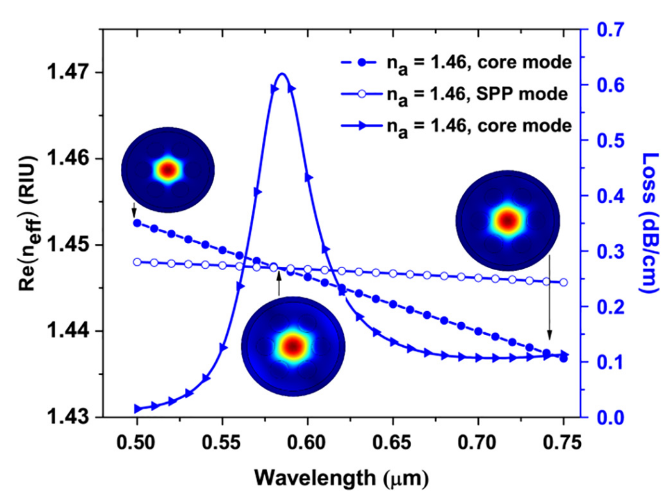

Fig. 3. Phase-matching principle of the proposed PCF based SPR refractive index sensor. The inset shows the mode field distribution in different wavelength of the proposed PCF-RIBS.