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A surface plasmon resonance sensor based on concave-shaped photonic crystal fiber for low refractive index detection

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ABSTRACT

A concave-shaped photonic crystal fiber (PCF) combined with square-channel using indium tin oxide (ITO) for surface plasmon resonance (SPR) sensing is proposed. By means of finite element method (FEM) to multiple parameter optimization of structure, the operation wavelength spans from 1270 nm to 1692 nm covering low-loss communication band when a dynamic refractive index (RI) in a range of 1.19 to 1.29, and meanwhile the sensor displays the maximum wavelength sensitivity of 1700–10700 nm/RIU. This is so far the minimum RI detection sensor in the known reported D-shaped PCF-SPR sensors. It reveals the remarkable ability of our sensor to detect the 10^{-6} scaled smallest RI changes in solutions of medical oxygen, liquid CO_2, and fluorine-containing organics, which extremely expands the application of existing PCF-SPR sensors for medical testing, unknown biomolecules and organic chemistry detections.

1. Introduction

Over the past decades, surface plasmon resonance (SPR) technologies have attracted considerable attention because of their high sensitivity, fast response, free-labeling detection and other unique features, therefore they offer high potential for physical, chemical and biological sensing [1]. SPR is strong collective oscillations of charge efficiently excited by the incident polarized light at the metal–dielectric interface, where the surface plasmon polaritons (SPP) are extremely sensitive to changes in the refractive index (RI) of the analyte to be measured [2]. This characteristic forms the theoretical basis of many SPR sensors [3–8].

Traditional SPR sensors which based on the prism sheet [3], optical waveguides [4] and standard single/multi-mode fibers [5,6] are either too bulky or too complex to operate in actual occasion, as well as existing low-sensitivity and phase-matching issues. Photonic crystal fiber (PCF) offers the sensors a solution of phase-matching and encapsulation inherited from the attractive advantages of small size, flexible design, special porous structure and guided mode mechanism [7]. Thus, PCF has been emerging as a promising candidate for assembling compact and ultra-sensitive SPR sensors with fast, sustainable and real-time monitoring, which can be effectively applied in biotechnology, drug screening, environmental monitoring, food safety and other fields [7–9].

To date, numerous attempts have been made to enhance the sensing performance of PCF-SPR sensors [8]. Owing to the great efforts from many research experts and teams related to this field, a considerable variety of PCF-SPR structures have been reported. They are mainly divided into two categories, internal metal-coated structures using selectively coating or nanowires filled, and external metal-coated structures such as D-shaped, slotted and exposed core PCFs. [9]. Among them, D-shaped PCF has gained particular interests compared with other PCF structures, as it can perfectly solve the key issues of difficulties in uniform coating and filling analytes to Nano-size holes or circular surface, and also achieve high sensitivity when detecting low refractive index analytes [10,11]. In 2017, Tiesheng Wu experimental demonstrated a SPR RI sensor based on D-shaped single mode PCF, which exhibits a good agreement between simulation and experiment [12].

Aside from that, by choosing distinct plasmonic materials as SPR sensing layer and controlling the coating thickness, various characteristics of PCF-SPR sensors have been discussed [13–17]. Generally, metals e.g. gold, silver, copper and aluminum are the most commonly used SPR exciting materials [18]. Recently, indium tin oxide (ITO), as a novel plasmonic material, was proposed and has gained special attention. Especially, it opened up new opportunities for SPR sensing at the second and third telecommunication windows in infrared region (IR) of spectrum [13]. In contrast with the noble metal like gold and

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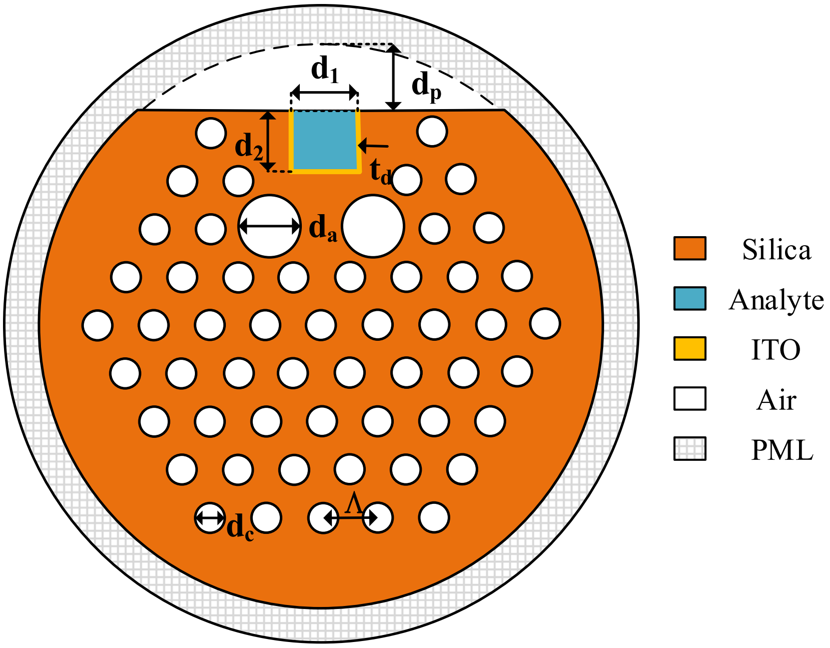

Fig. 1. Cross section of the PCF-SPR sensor.

silver, ITO has extra superior properties due to its lower bulk plasma frequency (less than 3 eV), no band-to-band transitions or the tendency towards island formation, and relatively low cost. Thus, ITO has become a promising material for production and study of SPR [14,15]. In most PCF-SPR researches, only several works have studied low RI sensors with the detection range RI < 1.30. For instance, Chi Zhou et al. presented a PCF sensor with one gold-coated analyte channel for SPR sensing which can achieve a broad RI detection of analyte from 1.25 to 1.45 [17]. Tianye Huang proposed an ITO-based D-shaped PCF-SPR sensor showing average wavelength sensitivity of 6000 nm/RIU in the sensing RI of 1.28–1.34 [16]. Chao Liu et al. reported a mid-infrared PCF-SPR sensor to detect low RI between 1.23 and 1.29 with average spectral sensitivity of 5500 nm/RIU [19]. Nevertheless, these sensors provide little or no capability to detect analyte with RI < 1.25, which is caused by fairly low sensitivity. This crucial issue extremely limits the performance of PCF-SPR sensors for the detection of various samples having low refractive index between 1.20 and 1.30, for example, medical oxygen, liquid CO_2, and fluorine-containing organics [20]. Hence, it is essential for us to develop a high sensitivity low RI sensor.

Here, we propose a SPR sensor based on side-polished PCF combined with an ITO coated square-groove. The usage of square ITO-coated open-groove can help to effectively adjust both the SPR wavelength and refractive index measurement range. The side-polished depth can be flexibly designed, too. Our sensor displays the maximum wavelength of 1700–10700 nm/RIU over a dynamic refractive index range of 1.19 to 1.29. Overall, the objective of this work is to achieve high sensitivity and wide measurement range for the detection of substances with refractive index lower than 1.30 such as medical oxygen, liquid CO_2, and fluorine-containing organics.

2. Theoretical model

In this work, the COMSOL Multiphysics software based on FEM theory has been used to investigate the mode characteristics of light waves propagating in the PCF. The cross-section of the proposed structure is mainly composed of four hexagonal air-holes rings surrounding the center air hole as shown in Fig. 1. As illustrated in this figure, the pitch of the air holes has been fixed at $\Lambda = 2$ μm, the refractive index of air is $n_{air} = 1$, and the diameter of the air holes is $d_c = 0.6 \times \Lambda$. We design the core situated in the second ring, under the bottom of square-groove so that the SPR sensing layer can be placed extremely close to the core. Moreover, the two symmetrical air holes on both sides of core have been replaced by larger-diameter holes with $d_a = \Lambda$, which are responsible for enhancing the mode birefringence effect and effectively reducing the effective index of the core mode to increase the sensitivity when detecting low RI analyte [10]. The total PCF diameter is 20 μm, which can be fabricated by the most versatile stack-and-draw method [21] and side-polishing technology [22]. First, we insert solid rods to create air holes, use thick or thin wall capillaries for air holes with different diameters, and create rectangle channel via rectangle capillary. Then, the fabricated canes will be drawn to the desired fiber size, which containing a rectangle-shape hole with 2.5 μm width (d1) and > 2.75 μm depth (d2), two symmetrical larger-diameter holes with da = Λ and other small air holes with dc = 0.6 × Λ. Final, one side of the PCF can been polished to D-shaped surface with a depth of dp = 2.2 μm. The depth of square-groove (d_2) can be adjusted to 2.75 μm during the polishing process. Briefly, these steps above-mentioned are for dramatically facilitating the strong interaction with the sample and promoting more core energy leakage into the SPR sensing layer. The plasmonic material ITO having a thickness of $t_g = 100$ nm is uniformly deposited on the open-groove surface. The relative dielectric constant of ITO can be demonstrated by Drude–Lorentz model, which is expressed as follows [14]:

$$\varepsilon_{ITO} = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma} \tag{1}$$

where $\varepsilon_{\infty} = 3.9$ is the high frequency limit of ITO, $\Gamma = 0.111$ eV denotes the charge carrier collision rate, the plasma resonance frequency ω_p can be given by:

$$\omega_p = \sqrt{\frac{ne^2}{\mu\varepsilon_0}} \tag{2}$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the vacuum dielectric constant, the effective mass $\mu = 0.3\ m_e$, $m_e = 9.1 \times 10^{-31}$ kg is free electron mass, and e is the elementary charge. Via adjusting the thin film preparative condition, changing the doping concentration of metal atom and oxygen content, variable charge carrier concentration n can be obtained [15]. Here we fix n to the value of 1.8×10^{21} cm^{-3}, calculating that $\omega_p = 2.39$ eV [16].