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# Hollow-core silver coated photonic crystal fiber plasmonic sensor

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ABSTRACT

We propose a simple hollow-core circular lattice photonic crystal fiber (PCF) based surface plasmon resonance (SPR) refractive index sensor. The sensing performance is investigated by using the finite element method (FEM). Silver is used as the plasmonic material for this design, which is placed on the outer surface of the PCF to facilitate the fabrication. The proposed sensor shows a maximum wavelength sensitivity of 4200 nm/RIU with a sensor resolution of $2.38 \times 10^{-5}$ RIU. Besides, a maximum amplitude sensitivity of 300 $RIU^{-1}$ and a resolution of $3.33 \times 10^{-5}$ RIU is reported for an analyte refractive index of 1.37. Moreover, the effect of varying structural parameters on the sensing performance such as pitch, air hole diameter and silver layer thickness are also discussed thoroughly. Sensitivity analysis of the proposed sensor is performed in order to investigate the impact on loss depth and amplitude sensitivity. Thanks to high sensitivity and linearity characteristics, the proposed sensor can be potentially employed in practical bio-sensing and chemical sensing applications.



## 1. Introduction

Over the last three decades, surface plasmon resonance (SPR) phenomenon has been highlighted as a powerful optical detection technique due to its highly sensitive behavior, and capability for label-free sensing [1,2]. SPR sensors have revealed impressive progress in bio-sensing applications including biological analytes detection, medical diagnosis, bio-imagining, antibody-antigen interaction, organic chemical sensing, water testing, and environmental safety [3–7]. Due to ongoing development of SPR technology, it has been also employed in optoelectronic devices such as film thickness monitoring [8,9], optical tunable filters [10,11], SPR imaging [12,13], and optical modulators [14,15]. Additionally, SPR technology permits integration of nanoelectronic and nanophotonic components with the aim of obtaining ultra-compact optoelectronic devices [16,17].

Recently, photonic crystal fiber (PCF) based SPR sensors have been extensively studied due to their unusual and appealing optical characteristics over the conventional optical fibers [18]. Due to controllable birefringence and confinement loss, PCF SPR sensors have shown an improved performance in bio-sensing applications. For instance, by changing the structural parameters such as pitch, air hole dimension, and number of air hole rings, it is possible to operate the PCF sensor at the optimum condition. In contrast to conventional optical sensors, PCF-based SPR sensors permit better control of the evanescent field by varying the structural parameters. Moreover, the size of the PCF SPR sensors is small, making them suitable for nanosensors and remote sensing applications [19].

Over the last few years, several PCF SPR sensors have been explored in order to improve the sensitivity, detection accuracy and dynamic range of detection. PCF SPR sensors are classified into two categories. First, internally metal-coated PCF sensors where plasmonic material is selectively deposited inside the PCF and liquid analyte is selectively infiltrated into the air hole(s). Second, externally metal-coated PCF sensors where plasmonic materials are deposited on the outer surface of the PCF. Very recently, a diamond ring fiber (DRF) based SPR sensor has been proposed [20] showing maximum wavelength sensitivity of 6000 nm/RIU and sensing resolution of $1.67 \times 10^{-5}$ RIU in the sensing range between 1.33 and 1.39. The open-ring channel-based sensor proposed by Liu et al. [21] can be used to detect low refractive index (RI) analyte between 1.23 and 1.29. The proposed design shows average wavelength sensitivity of 5500 nm/RIU and maximum amplitude sensitivity of 333.8 $RIU^{-1}$.

Based on internal metal coating, few potential PCF SPR sensors have been reported in Refs. [22–25]. In practice, deposition of metal on several air holes while maintaining uniform thickness is unfeasible from the fabrication point of view. Moreover, selective

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infiltration of air holes with analyte is complex and time consuming. It potentially limits widespread applications in practical sensing applications. Recently, nanowire-based PCF SPR sensors have been reported in order to eliminate the issues of selective infiltration [26,27]. Very recently, a hollow-core silver nanowire-based PCF SPR sensor [28] has been proposed having large detection range from 1.33 to 1.50. The proposed sensor shows maximum wavelength sensitivity of 1800 nm/RIU when analyte index is varied from 1.33 to 1.34. Recently, externally-metal-coated PCF SPR sensors have gained increased attention because of their straightforward detection and ease of fabrication. The PCF based SPR sensor proposed by Hassani et al. was used for the detection of biolayer thickness [29]. Plasmonic gold and biolayer were deposited outside the PCF surface. The proposed bimetallic SPR sensor shows maximum wavelength sensitivity of 4750 nm/RIU and 4300 nm/RIU for quasi TM and TM fundamental core modes, respectively. Recently, a multichannel PCF-based sensor has been proposed by Hameed et al. [30], where plasmonic silver is coated by the gold. The proposed bimetallic SPR sensor shows maximum wavelength sensitivity of 4750 nm/RIU and 4300 nm/RIU for quasi TM and TM fundamental core modes, respectively. The PCF SPR sensor proposed by Otupiri et al. consists of elliptical air holes and four microfluidic channels [31], which can detect multi-analytes having different refractive indices. It is reported that maximum wavelength sensitivity of 4600 nm/RIU and amplitude sensitivity of 425 $RIU^{-1}$ can be achieved for a gold layer thickness of 50 nm. A single-ring hexagonal PCF SPR sensor with four microfluidic channels has been demonstrated, where four modes are separately studied for multi-analyte detections [32]. The proposed sensor shows maximum wavelength sensitivity of 2400 nm/RIU in *y*-polarized $HE_{11}$ mode. Although multichannel SPR sensors are useful for multi-analyte detections, obtaining such microfluidic channels is difficult from a fabrication point of view.

In D-shaped PCF sensors, the top of the cladding is etched out in order to obtain a flat surface. The plasmonic material and analyte sample are both placed on that flat surface. Most of the internally and externally metal-coated PCF sensors are based on the metal coating on the circular surface. In general, obtaining a uniform circular surface is difficult since it associates with unwanted surface roughness. Taking advantage from the flat surface, D-shaped PCF sensors provide possibilities for homogeneous coating with minimal surface roughness [33]. Very recently, a D-shaped PCF sensor has been proposed using gold as the plasmonic material and titanium di-oxide ($TiO_2$) for shifting the resonance wavelength from visible to near infrared [34]. In the sensing range between 1.33 and 1.43, the D-shaped sensor shows maximum amplitude sensitivity of 1086 RIU-1 with sensing resolution of $9.2 \times 10^{-6}$ RIU. Although D-shaped PCF sensors provide high sensitivity and eliminate the issue of uniform thickness, they require accurate polishing of the predefined section. Very recently, a quasi D-shaped PCF SPR sensor has been proposed by An et al. [35] using graphene and indium tin oxide (ITO) layers operating in the near-infrared wavelengths. Another D-shaped PCF sensor has been reported having rectangular lattice air-holes [36]. Two larger air holes are placed near the core of the PCF to create birefringence, which yields a higher figure-of-merit (FOM) of about 478.3 $RIU^{-1}$.

In this paper, a hollow-core PCF SPR sensor with circular lattice air holes is proposed. A thin layer of silver is used in the outer surface of the PCF structure, which simplifies the detection mechanism. The performance of the sensor is investigated in terms of amplitude sensitivity, wavelength sensitivity, sensor resolution, and linearity. Compared to other designs in the literature, the proposed sensor exhibits lower confinement loss. Due to such low confinement loss, the length of the sensor can be extended to centimeter scale. We also discuss the fabrication tolerance in order to investigate how sensing performance varies due to fluctuations of the fiber design parameters.

## 2. Structural design and plasmonic materials

Cross-section view of the proposed circular lattice PCF sensor is shown in Fig. 1. There are two air-hole rings with four missing air holes in the second ring. The size of the air holes in the second ring is larger than first ring for obtaining better light confinement in the desired direction [37]. In the first ring, air holes are arranged at 60° anticlockwise progressive rotations and in second ring air holes are arranged at 30° anticlockwise rotations. In the second ring, four air holes are missing, which accumulates the evanescent electromagnetic field at the four sides of the PCF, and it can easily move towards the metal surface. Here, $\Lambda$ is the center-to-center distance between two adjacent air holes, $d$ is the diameter of air holes in the first ring and $d_1$ is the diameter of air holes in the second ring. The thickness of silver layer is $t_s$. Outside of silver layer an analyte layer is placed, which acts as the dielectric medium (sensing medium). In the proposed sensor, we used fused silica as the background material. The RI of fused silica can be obtained by using the Sellmeier equation [38]. The complex RI of silver can be obtained from the Palik [39]. Finite element method (FEM) with circularly perfectly matched layer (PML) boundary condition has been used to simulate the proposed structure. We used finer element meshing, which took 64,475 elements to represent the full structure. The PML thickness and analyte layer thickness were 2.5 μm and 3.5 μm, respectively. The RI of analyte ($n_a$) is varied from 1.33 to 1.37.

The sensing performance of a SPR sensor greatly depends on the plasmonic material employed in the design. Current plasmonic sensors mostly use gold because of several advantageous properties. Gold is chemically inert, long-term stable, and easy to structure [19]. However, it has higher optical damping and has wider resonance wavelength peak leading to false positive analyte detections [33]. Copper is another potential plasmonic material having almost the same optical damping and interband transition as gold. Compared to gold and copper, aluminum has not attracted much attention due to its high optical damping, and high interband transition loss [19]. From the optical point of view, silver can be regarded as one of the potential candidates for plasmonic material. The positive attributes of silver are no interband transition in the visible wavelength spectrum, low optical damping, narrow

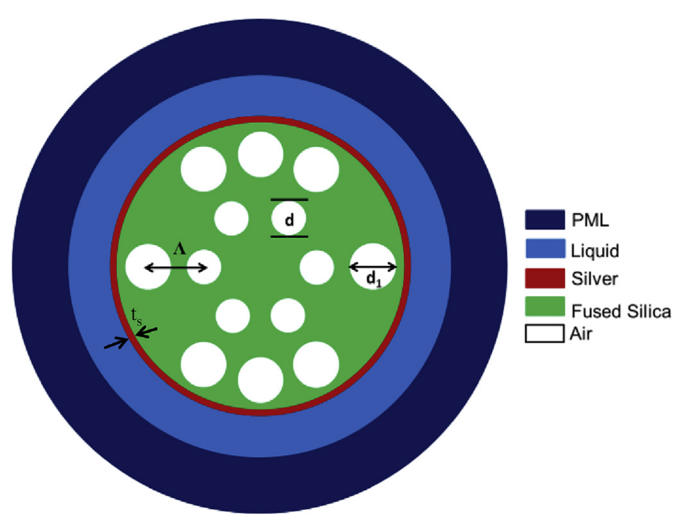


**Fig. 1.** Cross-section view of the proposed circular lattice PCF sensor with $\Lambda = 2$ μm, $d = 0.57\Lambda$, $d_1 = 0.78\Lambda$ and $t_s = 30$ nm.