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Simulation analysis of a temperature sensor based on photonic crystal fiber filled with different shapes of nanowires

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ABSTRACT

We propose a photonic crystal fiber (PCF)-based surface plasmons resonance (SPR) temperature sensor in this paper, and using the dual function of PCF filled with different shapes of nanowires and analyte to realize temperature sensing and have designed an experimental setup. Different shapes of nanowires with the mixed liquid are filled into the proposed octagon PCF. The simulation results indicate that not only structure parameters of PCF but also the shapes of filled nanowires play a key role to the sensing. A blue-shift in the SPR resonant peak is shown with the temperature increases. Different loss spectra present that a higher confinement loss for low temperature and the octagon PCF filled with elliptical nanowires shows a more obvious peak shift and higher sensitivity, which is about 500 pm/°C and the corresponding sensor resolution is 2.0×10^{-2} °C. This PCF sensing system has great practical value and significance for its advantage of high sensitivity.

1. Introduction

Development of optical fiber sensing technology like chemical and biological sensing, based on excitation of surface plasmons with metallic films coated on the surface of optical fiber, has provided a better platform for optical fiber applications and has been extensively reported [1,2]. Fiber SPR sensors have received considerable attention due to their characteristics such as low cost fabrication, simple measurement system, and capability of remote sensing [3–5]. SPR is a kind of physical optics phenomenon, which can be excited by light when the phase matching condition is met between the exciting light and the surface plasmons [6,7]. About the improvement of SPR sensors, the polarization requirements can be significantly relaxed with the metallic nanowires instead of the metallic films [8]. Moreover, surface plasmons (SPs) can be excited by propagating light and generate resonance. A strong light absorption to the metallic nanowires will be presented with the resonant excitation [9]. And the resonant light absorption by metal-dielectric nano-materials can be well estimated by Mie theory for the spherical nanowires and the finite difference time domain (FDTD) method or discrete dipole approximation (DDA) method for the non-spherical nanowires. This resonance excitation, in principle, depends on the metallic nanowires shape, size, dielectric constant, dimension and the dielectric constant of the material surrounding the nanowires [10]. The resonant wavelength will change with the above related factors, especially the shape and the material surrounding the nanowires, so based on the features various optical fiber supporting SPR sensors have been investigated [11,12].

The development of PCF applying is contributed to its features like that the PCF can be used either as transmission media or in optical functional devices and PCFs have so many other unique characteristics like endless single-mode characteristic, high birefringence coefficient, controllable dispersion, high nonlinear coefficient, etc. that are superior to conventional fibers when applied to sensing applications. Many studies attempted to confine the plasmonic modes within the PCF through incorporating metallic layers or metallic nano-materials into it [13–15]. And various PCF designs have been proposed to control different transmission properties, such as hexagonal PCFs, square PCFs and octagonal PCFs [16–18]. Additionally, the polarization properties of various PCFs can be manipulated by filling the air holes with polymer [19], oil [20], gas [21], liquid [22], or liquid crystal [23]. In recent years, PCF-based SPR sensors have been investigated by many researchers. Florous et al. [24] numerically analyzed a cryogenic temperature sensor based on localized SPR with gold nanoparticles into PCF. The rigorous study result had shown that the PCF-based temperature sensor could be used for remote monitoring of temperature in different media and obtained a fairly fine resolution. Yu et al. [25]

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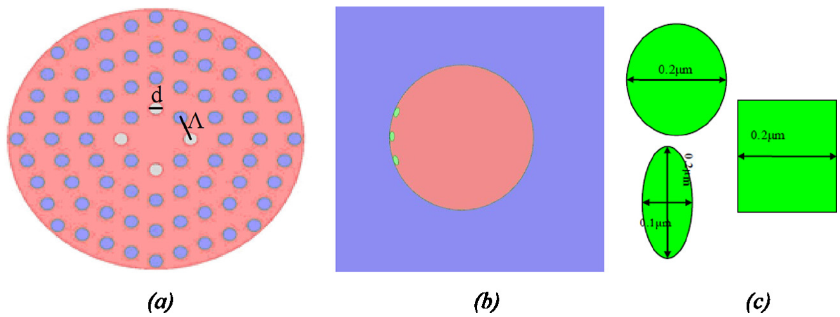

Fig. 1. (a) The schematic geometry of the cross section of the octagon PCF-based SPR temperature sensor. (b) The cross section of analyte channel filled with nanowires. (c) The cross section of different shapes of silver nanowires, which are circle, ellipse and square. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

introduced a PCF temperature sensor, which is based on intensity modulation and liquid ethanol filling of air holes, and made some experiments and simulations to study the temperature sensitivity of transmission.

In this paper, we numerically study the sensing properties of a SPR temperature sensor based on octagon PCF filled with different shapes of nanowires through full-vectorial finite element method (FEM). This sensor is based on intensity modulation, and mixed liquid medium (chloroform and ethanol) that has a large thermo-optic coefficient selectively is filled into air holes of the index-guiding PCF. This structure of selective filling can reduce the material absorption loss and the coupling between the plasmonic modes at non-resonant wavelength, and enhance the coupling efficiency between the plasmonic mode and the core-guide mode. Furthermore, it is different with other reports, octagonal PCF is used in temperature sensing that can possess the advantages of a wider wavelength range operating in single mode region, more circular-like field distribution, and significantly lower confinement loss [18]. More than ever, the influence of structures of the filled nanowires on temperature sensing has been investigated. According to the influence of the nanowires shapes, we simulate the sensing properties of octagonal PCF-based sensor filled with nanowires of circle, ellipse and square [26–28] with the changes of refractive indices (RI) of the background material and the liquid analyte depending on temperature.

2. Structure design and simulated modeling

In this work, we introduce a SPR temperature sensor design utilizing the octagon PCF, and present a comprehensive numerical analysis of the mode distributions, sensing properties, and the influence of some parameters based on the FEM with triangular elements. The schematic geometry of the cross section of the SPR temperature sensor based on octagon PCF in this paper is shown in Fig. 1(a). The index-guiding PCF is consisted of four layers of air holes arranged in an octagonal way, which can realize the difference among various modes loss and obtain little bend loss comparing to the hexagonal way. The air holes are arranged in an isosceles triangle lattice with a vertex angle of 45°. The pitch of the underlying octagonal lattice is $\Lambda = 15\,\mu$m, the diameters of air holes are $d = 6\,\mu$m, and the diameter of the solid core dc = 18 μm. Surface plasmons can be excited by propagating light, and when the phase matching condition is met between the exciting light and the surface plasmons, a strong resonant absorption to the metallic nanowires will be presented with the resonant excitation between the plasmonic mode and core-guided modes and sensing can be realized. Attempts are made to enhance the coupling between a plasmonic mode and a core-guide mode and reduce the plasmonic to plasmonic mode coupling. Just like that in order to effectively avoid the interaction of adjacent liquid channels, the designed octagon PCF only alternate holes (the white holes) of the first layer are filled with nanowires and mixed liquid and other holes (the blue holes) are filled with air. The analyte channels feature symmetry to guarantee a polarization independent propagation characteristic. And the interference among the adjacent analyte channels can be eliminated effectively. Theoretically, phase matching requires equating the propagation constants of the plasmonic mode and core-guide mode, implying that the effective indices of the two modes have to be close [29]. In this sensor, the fused silica, silver nanowires and the analyte influence the effective RI of the fundamental mode. The core-guide mode RI is close to the core material that is approximately 1.45 for fused silica and the precise material dispersion is taken to be the refractive index of fused silica Sellmeier equation [19]. For each analyte channel, where mixed liquid with large thermo-optic coefficient and lower RI is filled to guarantee the total index-guiding mechanism and the corresponding reflection condition. And every analyte channel (the white air holes) surrounded the solid core is filled with metallic nanowires, whose diameters are around 200 nm. And the nanowires are made of silver and the dielectric constant is defined by the Drude model [6]. One of the structures of the cross section of analyte channel filled with nanowires is shown in Fig. 1 (b), in which elliptical silver nanowires (the green ellipse) are filled. The sizes of the Ag nanowires are shown in Fig. 1(c), and the diameter is about 0.2 μm.

The analyte channels are filled with mixed thermo-optic liquid. The refractive index of thermo-optic liquid (n_x) as the sensing medium can be evaluated by

$$n_x = n_0 \left| T_0 + \frac{dn}{dT}(T - T_0) \right. \quad (1)$$

And the refractive index of the mixed liquid can be defined as

$$n = x\% \times [\, n_{\text{ethanol}}|_{T=293\text{K}} + d_{\text{nethanol}}/dT \times (T-293)] + (100-x)\% \times [\, n_{\text{chloroform}}|_{T=293\text{K}} + dn_{\text{chloroform}}/dT \times (T-293)] \quad (2)$$

where x% is the ratio of ethanol and $(100 - x)$ % is the ration of chloroform, and the thermo-optic coefficient of chloroform and ethanol are -6.328×10^{-4} (K^{-1}) and -4×10^{-4} (K^{-1}) respectively, n and n_0 are the refractive indices at temperature T and T_0, respectively.

About the refractive index of n_{ethanol} and $n_{\text{chloroform}}$ are defined as (T = 20 °C) follows respectively [30].

$$\begin{aligned} n_{\text{ethanol}} &= 1.35265 + 0.00306\lambda^{-2} + 0.00002\lambda^{-4} \\ n_{\text{chloroform}} &= 1.431364 + 0.00563241\lambda^{-2} - 2.0805 \times 10^{-4}\lambda^{-4} \end{aligned} \quad (3)$$

In order to make the refractive index lower than the core's and guarantee total internal reflection sensing mechanism of the PCF-based temperature sensor, the ratio of chloroform and ethanol is defined as 7:3. The relationship of mixed liquid and the background material of PCF with the increase of temperature are shown in