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A highly temperature-sensitive photonic crystal fiber based on surface plasmon resonance

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ABSTRACT

A novel temperature sensor comprising a photonic crystal fiber (PCF) is investigated based on surface plasmon resonance (SPR). The finite element method (FEM) is used to determine the temperature sensitivity of the PCF consisting of different concentrations of the analyte. Coating the sensor with a gold layer on the wall of the liquid channel not only overcomes experimental challenges, but also enhances the temperature sensitivity. The simulation results show that the SPR spectra blue-shift with increasing temperature and the resonance wavelength and confinement loss depend on the thickness of the gold layer. The sensor exhibits remarkable temperature sensitivity up to 3080 pm/°C with a corresponding resolution of 0.01325 °C.

1. Introduction

Surface plasmon resonance (SPR) is widely adopted in optical sensing due to its extremely high sensitivity to variations in the refractive index of the surrounding dielectrics and has tremendous potential in the fields of environmental monitoring, biotechnology, medical diagnostics, and food safety [1]. Since the demonstration of an SPR sensor with optical fibers in 1993 [2], many optical fiber SPR sensors with diverse structures such as D-shape, cladding, FBG-based, and PCF have been proposed and investigated experimentally and theoretically [3–5]. For instance, Hassani et al. [6–8] have proposed two different SPR sensors based on PCF and thoroughly analyzed the design principles of sensors with metallic coatings applicable to biosensing. The numerical results reveal a refractive-index resolution up to 10^{-4} RIU in the structure. Moreover, the loss spectrum analysis derived from the coupled mode theory has been used to numerically analyze PCF-SPR sensors.

In general, PCF-SPR sensors have a number of advantages over existing sensors, for instance, flexibility in structure design, high sensitivity, and being free from electromagnetic interference and are promising in conductive, corrosive, dangerous, or harsh environments. Many studies have been conducted to investigate SPR temperature sensors based on PCF. Temperature sensing can be achieved by adding a thermosensitive liquid into the air holes and sensitive metal layer. Yu et al. [7] have studied a total internal reflection (TIR) PCF temperature sensor filled with ethanol. Based on the bandgap-like effect, the temperature sensor proposed and numerically investigated by Peng et al. exhibits a temperature sensitivity of 720 pm/°C [9,10]. Herein, we present and investigate a temperature sensor based on SPR supported by PCF. The proposed structure not only facilitates energy coupling between the plasmon mode and core-guided mode as a result of the large contact area between the sample and metal film, but also possesses an interface close to the core. The temperature sensing properties are investigated by COMSOL Multiphysics software. The spectra are shown to blue-shift with temperature and the resonance wavelength and confinement loss are influenced by the gold layer thickness. The temperature sensitivity and resolution are calculated to be 3080 pm/°C and 0.01325 °C, respectively.

2. Theoretical modeling of a PCF-SPR sensor

The schematic cross-section of the PCF-SPR temperature sensor is presented in Fig. 1(a). The main purpose of the design is to

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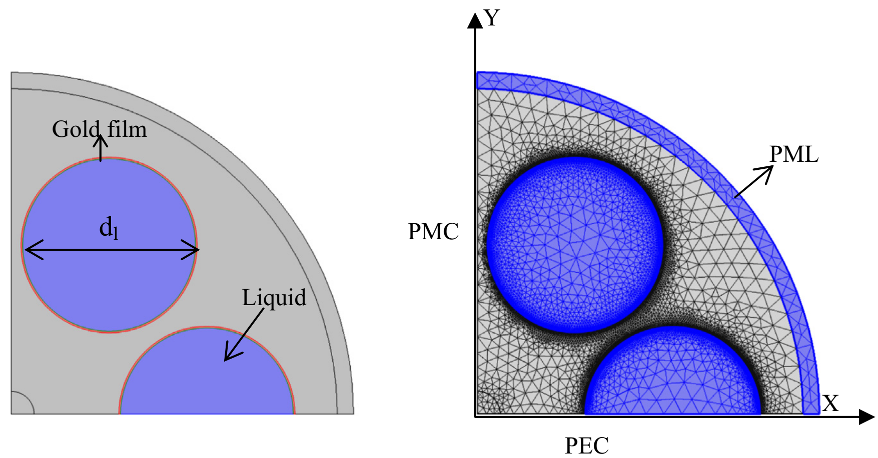

Fig. 1. (a) Cross-section of the PCF-SPR temperature sensor. (b) Example FEM mesh and boundary conditions.

improve the phase-matching between the core-guided mode and plasmonic mode. The structure of the PCF-SPR temperature sensor contains a central air hole and six large liquid-filled holes coated with a thin gold layer to form a hexagonal structure. The central air hole can effectively reduce the effective refractive index of the core-guided mode and match the effective refractive index of the plasmonic mode. In order to produce SPR, gold thin films with different thickness are produced as the sensitive layers on the wall of the liquid channel. As shown in Fig. 1(a), $\Lambda=2$ μm, $d_1=2.7\Lambda$ μm, and $d_c=0.7\Lambda$ μm representing the pitch of the air holes, diameter of the liquid-filled holes, and diameter of the central hole, respectively.

As the refractive indices of the components vary with temperature, the phase-matching wavelength between the core-guided mode and plasmonic mode changes [9]. Accordingly, the absorption peak in the loss spectrum shifts with temperature of the sensor components including the silica, sensing liquid, and gold coating. Here, the relationship between the temperature and properties of the sensor constituents is discussed from the theoretical perspective. PCF is considered to be made of fused silica and he temperature dependence on the dielectric constant of fused silica [11] is given by the Ghosh's model as follows:

$$n^2_{silica}(\lambda, T) = 1.31552 + \left(0.690754 \times 10^{-5}\right)T + \frac{\left(0.788404 + 0.235835 \times 10^{-4}T\right)\lambda^2}{\lambda^2 - \left(0.0110199 + 0.584758 \times 10^{-6}T\right)} + \frac{\left(0.91316 + 0.548368 \times 10^{-6}T\right)\lambda^2}{\lambda^2 - 100} \quad (1)$$

where λ represents the wavelength of the incident light in vacuum and T represents the temperature in degrees Celsius. A dielectric material with a thermo-optic coefficient (dn/dT) is used in the liquid-filled holes to enhance the sensitivity in temperature sensing [12]. The refractive index of the sensing liquid is expressed by

$$n = n_{liquid} + (dn/dT)\left(T - T_0\right), \quad (2)$$

here $dn/dT = -4 \times 10^{-4}(°C^{-1})$, dispersion of the liquid is ignored, and $n_{liquid} = 1.35$ is selected to be the refractive index of the liquid at the reference temperature $T_0=25$ °C [12].

The dielectric constant of gold is described by the Drude model [3] as follows:

$$\varepsilon(\omega) = \varepsilon_1 + i\varepsilon_2 = \varepsilon_\infty - \frac{\omega_p^2}{\omega\left(\omega + i\omega_c\right)}, \quad (3)$$

where, $\varepsilon_\infty = 9.75$ is the dielectric constant of gold at high frequencies, $\omega_p = 1.36 \times 10^{16}$ is the plasma frequency of the metal, and $\omega_c = 1.45 \times 10^{14}$ is the scattering frequency of electrons [13]. The plasma frequency changes with temperature due to thermal expansion and can be expressed as [14]

$$\omega_p = \omega_{p0} \times \left(-\frac{T - T_0}{2}\right) \times \alpha_V\left(T_0\right) \quad (4)$$

where T_0 is the room temperature (298.15 K, 25 °C), ω_{p0} is the plasma frequency at T_0, and $a_V = 4.26 \times 10^{-5}(K^{-1})$ is the volumetric thermal expansion coefficient of gold. The scattering frequency ω_c is mainly determined by the phonon–electron scattering and electron–electron scattering as follows:

$$\omega_c = \omega_{cp} + \omega_{ce}, \quad (5)$$

where ω_{ce} is given by the Lawrence's electron–electron scattering model [15] as

$$\omega_{ce}(T) = \frac{1}{6}\pi^4\frac{\Gamma\Delta}{hE_F}\left[\left(k_BT\right)^2 + \left(\frac{h\omega}{4\pi^2}\right)^2\right], \quad (6)$$

where $E_F=5.51$ eV is the Fermi energy of the metal electrons, h is Planck's constant, and $k_B=1.38 \times 10^{-23}$ J/K is Boltzmann constant. $\Gamma=0.55$ and $\Delta=0.77$ are defined in Ref. [15]. ω_{cp} is obtained by Holstein's phonon–electron scattering model [16]

$$\omega_{cp}(T) = \omega_p\left(T_0\right)\left[\frac{2}{5} + 4\left(\frac{T}{T_D}\right)^5\int_0^{T_D/T}\frac{z^4\,dz}{e^z - 1}\right], \quad (7)$$

where $T_D=185$ K is the Debye temperature and T is temperature in degrees Kelvin. The plasma frequency can be obtained by

$$\omega_p(T) = \sqrt{\frac{4\pi N(T)e^2}{m^*(T)}}, \quad (8)$$

where $N(T)$ and $m^*(T)$ are the density and effective mass of electrons, respectively [17].

Apart from the temperature-dependence of the permittivity, the thermal expansion of the metal thin film is significant as well. The temperature dependence of the metal film thickness can be evaluated using $d = d_0[1 + \alpha'_L(T - T_0)]$ with the corrected thermal expansion coefficient α'_L, which is given by [18]

$$\alpha'_L = \alpha_L\frac{1 + \mu}{1 - \mu}. \quad (9)$$

Here $\mu = 0.44$ is the Poisson ratio of the metal. According to Ref. [19], the attenuation constant α_{loss} is proportional to the imaginary part of the effective index and can be defined as