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Ex-centric core photonic crystal fiber sensor with gold nanowires based on surface plasmon resonance

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ABSTRACT

An ex-centric core photonic crystal fiber sensor with gold nanowires based on surface plasmon resonance is designed and analyzed by the finite element method (FEM). The influence of the structural parameters of the sensor on the spectral sensitivity and resonance wavelength is studied for analyte refractive indexes (n a) between 1.33 and 1.4. The guided mode in the ex-centric core passes the three states of intersection, anti-intersection, non-intersection successively. The average spectral sensitivity and maximum spectral sensitivity are 7428 nm/RIU and 14,200 nm/RIU, respectively, and the refractive index resolution is 7.04 × 10⁻⁶ RIU. A quality factor of 140 is achieved indicating great potential for application to biochemistry and other fields.

1. Introduction

Surface plasmon resonance (SPR) refers to the collective oscillation of conductance band electrons excited by a transverse magnetic wave (TM) or p polarized light at the metal-dielectric interface [1–3]. SPR that is highly sensitive to variations in the refractive indexes of the surrounding medium possesses advantages such as label-free, high resolution, and real-time detection and has many potential applications in biology, chemistry, light absorption, environmental monitoring, as well as surface enhancement Raman scattering [4–8].

SPR is a unique optical absorption phenomenon and has become one of significant sensing technologies since Kretschmann and Reather proposed the prism-type structures based on attenuated total reflection (ATR) in 1968. A large amount of light energy is transferred from the incident light to the surface plasmon wave under the condition of phase matching. Compared with the prism-type angle modulation SPR sensors, optical fiber SPR sensors offer more convenience in device miniaturization by depositing sensitive metal thin films on the fiber core instead of the prism [9]. Compact and integrated platforms of optical fibers overcome the drawbacks of traditional prism-type SPR sensors and provide distinct features for flexible optical design, remote sensing capability, continuous analysis, and in situ detection [10,11]. Recently, the design of miniaturized SPR sensors has been extended to photonic crystal fibers (PCFs) and photonic quasic-crystal fibers (PQFs) composed of a series of air holes in the direction of light propagation [12,13]. The air holes make it possible to manipulate the effective refractive index of the cladding thereby offering many new features including high nonlinearity [14,15], near-zero flattened dispersion [16], high birefringence [17,18], ultra-low confinement loss and large effective
mode area [17], no-cutoff single mode [19] and controllable dispersion [20]. Therefore, microstructured optical fibers including PCFs and PQFs constitute an excellent platform of SPR excitation because of easy phase matching between core-guided mode and surface plasmon polaritons (SPPs) mode [21–23] due to the controllable refractive index.

So far, much efforts have been made to improve the sensing sensitivity, broaden the refractive index detection range, and tune the resonance wavelength region of PCF based SPR sensors by optimizing the air holes and structure. For example, Xin et al. designed a gold-filled liquid-core PCF with a spectral sensitivity of about 4100 nm/RIU [24]. Yang et al. proposed a SPR with two open-ring channels based on a PCF [25] with an average spectral sensitivity of 5500 nm/RIU and maximum resolution of \(7.69 \times 10^{-6}\) RIU for refractive indexes between 1.23 and 1.29. Su et al. presented a novel SPR sensor based on two parallel PCFs with a D-shape structure [26] and the maximum spectral sensitivity of 13,500 nm/RIU was attained in the refractive index range between 1.27 and 1.32 with a corresponding resolution of \(7.41 \times 10^{-6}\) RIU. In these D-type PCF sensors [27,28], the ultimate goal of structural design was to make the fiber core close to the D-shape edge coated with metal layers to produce the core-guided mode coupled with the plasmonic mode. However, it is a big practical challenge to fabricate D-type PCFs by removing the cladding. So far, existing PCF-SPR sensors with the fiber cores centered in the cladding have been common. Owing to the importance of the position of the fiber core, it is interesting to move the fiber core to the outside and fabricate ex-centric core PCF-SPR sensors with gold nanowires on the cladding.

Here in, an ex-centric core PCF-SPR sensor with gold nanowires coated on the cladding surface is designed. This structure has two advantages. Firstly, it is a simple design with engineering feasibility. Since there is no need to deposit a metal thin film on the inner wall of the air holes, gold nanowires can be attached directly onto the cladding surface. Secondly, the ex-centric core is close to the external surface of the cladding without removing the cladding to form a D-type structure consequently improving the coupling between the core-guided mode and plasmonic mode. As a result, the novel sensor boasts a maximum spectral sensitivity of 14,200 nm/RIU and refractive index resolution up to \(7.04 \times 10^{-6}\) RIU.

### 2. Numerical model

The COMSOL Multiphysics software based on the finite element method (FEM) is used to calculate two-dimensional mode characteristics of the ex-centric core PCF with gold nanowires as shown in Fig. 1. The green part is the analyte and orange part is the gold nanowire. Here, \(r = 4 \mu m, r_1 = 0.4 \mu m, r_2 = 0.4 \mu m\) represent the radius of the silica glass, air holes, and gold nanowire, respectively. \(L_1 = 2 \mu m\) is the vertical distance, \(L_2 = 2^{0.5} \cdot 0.5 \mu m\), and \(L_3 = 1.3 \mu m\) is the cross distance. The refractive indexes of the analyte range from 1.33 to 1.4. The dark blue background material is pure silica and an array of air holes (air refractive index \(n_{air} = 1\)) is introduced to the edge of silica glass to lower the average refractive index of the edge. This proposed PCF structure can be fabricated by drawing the preforms formed by stacking [29]. And the high-pressure chemical deposition techniques can be used to deposit the gold layers on the inner surface of the fiber holes [30].

The refraction index of silica can be expressed by Sellmeier equation. The relative dielectric constant of the gold nanowire in the near-infrared region is given by Drude model [31]:

\[
\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\omega_c)}
\]

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, \(\omega_c = 1.45 \times 10^{14}\) is the scattering frequency of electrons, and \(\omega\) is the angular frequency of the incident light. The computational region comprises a mesh with 8480 elements. A perfectly matched layer (PML) is considered as the boundary condition with 592 elements at the edge of the numerical calculation area. The number of vertex unit is 79, in addition, the minimum unit mass is \(8.83 \times 10^{-6}\) kg. The perfect matching layer (PML) is a boundary condition artificially introduced in order to fully absorb the radiation energy, the perfect magnetic conductors (PMC) and perfect electric conductors (PEC) are also used at the boundaries of the structure.

The performance of the sensor is usually represented by confinement losses is defined as [32]:

\[
\alpha_{loss} = 8.686 \times \frac{2\pi}{\lambda} \text{Im}(n_{eff}) \times 10^4 (\text{dB/cm}),
\]

Fig. 1. Cross section of the ex-centric core PCF-SPR sensor with gold nanowires.
where λ stands for the wavelength of the incident light in vacuum with a unit of micrometer (μm) and Im(\textit{n}_{\text{eff}}) is the imaginary part of the effective refractive index of the core-guide mode.

3. Results and discussion

Fig. 2 presents the confinement loss spectra of the sensor for the x-polarized and y-polarized modes at 1.35 and 1.37. The x polarization loss is higher and the resonance peak is sharper than that of the y polarization mode. It can be explained by that the contact area between the analyte and gold nanowire is larger in the x direction than the y direction. In addition, the resonance wavelength red-shifts and resonance intensity increases with increasing refractive indexes. Therefore, the subsequent simulation and calculation are carried out for x polarization.

Fig. 3 shows the loss spectrum and dispersion relation between the x polarization fundamental mode and SPPs mode. The black curve describes the confinement loss of the x polarization fundamental mode, the blue curve represents the real effective refractive index of the x fundamental mode, and the red curve reveals the real effective refractive index of the SPPs mode. The effective refractive indexes of the x fundamental mode and SPPs mode decrease with increasing wavelengths. An intersection point exists between the two curves at 823 nm and a loss peak is present at 823 nm in the black loss curve. Therefore, the phase matching condition is fulfilled at the intersection point of 823 nm. Although the phase matching conditions are satisfied at the intersection point between the real part of the effective refractive index and SPP mode, it does not mean that the incident light energy is transferred entirely to the SPP mode [33]. As demonstrated in Fig. 3(b), there is no intersection point for the imaginary part of the fundamental mode and SPP mode, a condition called incomplete coupling in which the energy of the fundamental mode is not completely transferred to the SPPs mode [34].

Fig. 4 shows the dispersion curves of the fundamental and SPPs modes for an analyte refractive index of 1.38. Fig. 4(a) shows that there is no interaction between the real parts of the fundamental mode and SPP mode, whereas the imaginary parts of the fundamental mode with an upward peak and SPP mode with a downward peak coincide at 0.957 μm. This intersection point is called the
anti-intersection point and the energy of the fundamental mode is completely coupled with the SPP mode [34]. However, the real and imaginary parts of the fundamental mode and SPPs mode do not intersect when the refractive index of the analyte is 1.4 corresponding to incomplete coupling.

Fig. 5 displays the loss spectra of the sensor coated with gold and silver nanowires as the sensitive materials for different analyte refractive indexes. The resonance wavelengths of the sensors coated with gold and silver nanowires red-shift with increasing refractive indexes. The loss of the sensor coated with gold nanowires is larger than that of the sensor coated with silver nanowires. Moreover, the resonance intensity of the sensor coated with silver nanowires is much weaker when the analyte refractive index is less than 1.35, indicating poor sensitivity to smaller refractive indexes. Therefore, gold nanowires are chosen in lieu of silver nanowires in subsequent simulation.

From the perspective of device manufacturing, a consistent air hole size in the PCF is important to the design of optical fibers. Fig. 6 shows the loss spectra of the sensors with different air hole radii for an analyte refractive index of 1.36. The resonance wavelength red-shifts with increasing the air hole radius but when the air hole radius is less than 0.3 μm, the core-guided mode is not properly confined in the ex-centric core. However, when the air hole radius is larger than 0.6 μm, it exceeds the radius of the silica glass cladding. When the air hole radius is 0.4 μm, the resonance peak has a relatively narrower full-width at half-maximum compared with other radius, thus an air hole radius of 0.4 μm is selected in the following simulations.

The loss spectra of the sensor with gold nanowires is shown in Fig. 7(a) for an analyte refractive index of 1.36. The radius of gold nanowires ranges from 0.1 μm to 0.7 μm. The resonance wavelengths red-shift for gold nanowire radii from 0.1 μm to 0.3 μm and blue-shift for radii between 0.3 μm and 0.7 μm. Furthermore, the loss peak intensity decreases gradually with increasing gold nanowire radii because the larger the gold nanowire radius, the more difficult it is for the evanescent wave to penetrate consequently leading to weak SPR coupling. The spectral sensitivity is expressed as [32]:

$$S_i = \frac{\Delta \lambda_{\text{peak}}}{\Delta n_a} \text{ (nm/RIU)},$$

where $\Delta \lambda_{\text{peak}}$ is the change of peak wavelength of loss and $\Delta n_a$ is the change of analyte refractive index.

Fig. 8 displays the dependence of the spectral sensitivity on $r_1$. The maximum spectral sensitivities of 9200 nm/RIU and 6000 nm/
RIU are obtained for analyte refractive indexes of 1.33–1.39 and 1.36–1.39 when \( r_1 \) is 0.4 \( \mu \)m. Therefore, 0.4 \( \mu \)m is the optimal radius \( (r_1) \) for gold nanowires.

**Fig. 6.** Loss spectrum of different air hole radius for an analyte refractive index of 1.36. \( (n_{\text{air}} = 1, r_1 = 0.4 \mu \text{m}, r = 4 \mu \text{m}, L_1 = 2 \mu \text{m}, L_2 = 3^{0.5 - 0.5} \mu \text{m}, L_3 = 1.3 \mu \text{m}).\)

**Fig. 7.** Confinement loss spectra of gold nanowires with different radii. \( (n_{\text{air}} = 1, r_2 = 0.4 \mu \text{m}, r = 4 \mu \text{m}, L_1 = 2 \mu \text{m}, L_2 = 3^{0.5 - 0.5} \mu \text{m}, L_3 = 1.3 \mu \text{m}).\)

**Fig. 8.** Dependence of spectral sensitivity on the radius \( (r_1) \) of gold nanowires. \( (S(\lambda)1: \text{for } 1.33-1.39, S(\lambda)2: \text{for } 1.36-1.39,n_{\text{air}} = 1, r_2 = 0.4 \mu \text{m}, r = 4 \mu \text{m}, L_1 = 2 \mu \text{m}, L_2 = 3^{0.5 - 0.5} \mu \text{m}, L_3 = 1.3 \mu \text{m}).\)

RIU are obtained for analyte refractive indexes of 1.33–1.39 and 1.36–1.39 when \( r_1 \) is 0.4 \( \mu \)m. Therefore, 0.4 \( \mu \)m is the optimal radius \( (r_1) \) for gold nanowires.

**Fig. 9** shows the confinement loss spectra of the sensor for analyte refractive indexes ranging from 1.33 to 1.40. The optimal gold nanowire and air hole radius is both 0.4 \( \mu \)m and the confinement loss curves red-shift with increasing refractive indexes. An average
spectral sensitivity of 7428 nm/RIU is obtained for refractive indexes between 1.33 and 1.4 and the maximum spectral sensitivity is 14,200 nm/RIU.

Fig. 10 presents the fitted polynomial curve of the resonance wavelength versus analyte refractive index. The polynomial fitting equation can be expressed as:

$$y = -2980.187 + 6536.538x - 4894.642x^2 + 1222.2212x^3$$

The adjusted $R^2$ is 0.99782 indicating excellent fitting. The refractive index resolution (R) is defined as [35]:

$$R = \frac{\Delta n_a \Delta \lambda_{min}}{\Delta \lambda_{peak}}$$

$\Delta \lambda_{min} = 0.1$ nm represents the minimum spectral resolution. $\Delta \lambda_{peak}$ is the wavelength change of loss peaks and $\Delta n_a$ is the change of analyte refractive index. The average refractive index resolution of $1.72 \times 10^{-5}$ RIU is obtained and the highest resolution is up to $7.04 \times 10^{-6}$ RIU.

The spectral width and signal-to-noise ratio are two significant parameters to evaluate the sensing performance and are described by the factor of merit (FOM) as shown in the Eq. (6) [36,37]:

$$FOM = \frac{S(\mu m/RIU)}{FWHM(\mu m)}$$

where $S$ is the slope of the fitted curve at each refractive index position in Fig. 10 and the FWHM is the half-peak width of the loss spectrum. Fig. 11 shows the dependence of the FOM on different refractive indexes. The FOM increases initially and then decreases. The maximum value of 141 is observed for an index of 1.38, indicating that the effect is optimal when the refractive index is 1.38.
References