Asymmetrical photonic crystal fiber based on the surface plasmon resonance sensor and analysis by the lower-birefringence peak method

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ABSTRACT

A lower-birefringence peak method is used to investigate a new birefringence photonic crystal fiber (PCF) based on the surface plasmon resonance (SPR) sensor with an asymmetrical configuration. The novel method can determine the resonance wavelength and resonance intensity by the appearance of the lower peak and overcome deficiencies of the reported zero-birefringence point method. Upper and lower gaps are designed in the air holes to enhance the birefringence of the sensor as well as coupling efficiency between the plasmonic mode and core-guided mode. The dependence of the sensing performance on the structure parameters is discussed considering the depth of penetration of the evanescent wave and location of light confinement analysis. A maximum spectral sensitivity of 16,700 nm/RIU can be obtained in a broad refractive index (RI) detection range from 1.33 to 1.42 and the corresponding RI resolution is 5.99×10⁻⁶ RIU.

1. Introduction

The surface plasmon wave is generated from charge density oscillation on a metal layer and the evanescent wave is a kind of electromagnetic wave arising from incident p-polarized light or TM (transverse magnetic) wave [1–3]. Surface plasmon resonance (SPR) can be achieved at the metal-dielectric interface by coupling the evanescent wave with the surface plasmon wave [4,5]. The SPR sensing technology has drawn a great deal of attention due to advantages of being label-free, highly sensitive, and real-time [6–9] and thus has great application potentials in the fields of biomedicine, biomaterials, and chemical sensing. SPR has become a versatile tool in monitoring refractive indexes (RI) of analytes, filtering light at certain frequencies and detecting the formation of nanoscale biofilms [6–9,10–15].

Many types of operating platforms such as the prism and optical fiber have been developed for SPR excitation. Although the prism-based SPR sensor was proposed as early as 1982 to detect chemicals with good sensitivity and high resolution [16], it suffers from the bulky configuration. In 1993, Jorgenson et al. [17] presented the first optical fiber SPR sensing configuration without the required light-coupling prism. The proposed fiber sensor allows for a small sample volume and miniaturizes the sensing element.
However, the SPR sensors employing conventional fibers have limited sensitivity due to the single configuration. Recently, the photonic crystal fiber (PCF) and photonic quasi-crystal fiber (PQF) have attracted much research interest due to their distinctive microstructures and excellent optical properties, including near-zero flattened dispersion [18], high birefringence [19,20], ultra-low confinement loss and large effective mode area [21] as well as large cutoff ratio for endlessly single-mode propagation [22]. The PCF comprising metallized holes provides a novel platform for SPR excitation and is a great breakthrough in the SPR sensing field as a result of unique properties and flexibility of the microstructure design [8,23–25]. The PCF-based SPR (PCF-SPR) sensor not only overcomes the bulky size and low sensitivity drawbacks of the prism-based and conventional optical fiber-based SPR sensors, but also possesses very high sensitivity and resolution in refractive index detection. Typically, refractive indexes between 1.33 and 1.42 constitute the important detection range for various analytes. An et al. [26] studied the quasi-D-shaped PCF-SPR sensor for RI detection range of 1.33–1.42 and achieved a maximum spectral sensitivity of 3877 nm/RIU. Rifat et al. [27] proposed a highly sensitive PCF-SPR sensor with a selectively coated metal layer and the maximum spectral sensitivity reached 11,000 nm/RIU for the RI detection range of 1.33–1.42. Yang et al. [23] investigated a grapefruit PCF-SPR sensor with an exposed core to detect analyte RI of 1.33–1.42 and the maximum spectral sensitivity was 13,500 nm/RIU. For the RI detection range of 1.33–1.42, the maximum spectral sensitivity of PCF-SPR sensors available is still lower than 15,000 nm/RIU. Besides, the resonance properties of most of the reported PCF-SPR sensors have been calculated by the conventional confinement loss method. For instance, Yu et al. [28] used a zero-birefringence point method to determine the resonance wavelength of the asymmetrical PCF-SPR sensor. Nevertheless, this method is incapable of determining the resonance intensity and cannot be applied to some asymmetrical sensors because of the non-existent zero-birefringence point.

Herein, we describe an asymmetrical birefringent PCF-SPR sensor for the RI detection range of 1.33–1.42 and a novel lower-birefringence peak method to study the resonance characteristics of the sensor. The lower peak is caused by the irregular change in the real part curve of the effective index of the y-polarized mode. A maximum spectral sensitivity of 16,700 nm/RIU is achieved when the analyte RI is varied from 1.41 to 1.42 and the corresponding RI resolution is 5.99 × 10^{-6} RIU. Our results reveal that the lower-birefringence peak method can overcome the two limitations of indescribable resonance intensity and non-existent zero-birefringence point compared to the reported zero-birefringence point method.

2. Theoretical model

This study focuses on 2D simulation of the novel birefringent PCF sensor based on SPR and the sensing characteristics are investigated by the COMSOL Multiphysics software based on the finite element method (FEM). The software has prominent advantages in both the computational efficiency and memory utilization. Fig. 1 depicts the schematic diagram of the birefringent PCF-SPR sensor. The proposed PCF can be achieved by using a stack and draw method [27] and a thin metallic coating can be deposited onto the surface of the PCF by using a physical vapor deposition or wet chemical method [29]. Pure silica glass is used as the background materials and the RI of silica glass is calculated by the Sellmeier dispersion relation [30,31]:

\[
n^2 - 1 = \frac{0.6961663 \lambda^2}{\Lambda^2 - (0.0684043)^2} + \frac{0.4079426 \lambda^2}{\Lambda^2 - (0.1162414)^2} + \frac{0.897479 \lambda^2}{\Lambda^2 - (9.896161)^2},
\]

where \(n\) and \(\lambda\) are the RI of silica glass and wavelength of the incident light, respectively. At the edge of the fiber, an array of circular air holes with the same radius of \(r_1 = 0.6 \mu m\) are introduced to lower the average RI of the edge. The RI of air (RI_{air}) is fixed to be 1. \(d_1 = 2 \sin(\pi/16)\) is the distance between adjacent air holes. These air holes are positive for confining the light into the fiber core. It is noteworthy that there are no air holes at the upper and lower edges, thus enhancing the birefringence of the sensor as well as coupling efficiency between the plasmonic mode and core-guided mode. \(d_2 = 2 \sin(\pi/8)\) is the size of opening. Additionally, there is a big central air hole with a radius of \(r_2 = 4 \mu m\). The distance between the edge air holes and central air hole is \(\Lambda = 11 \mu m\). An active plasmonic silver layer is deposited outside the fiber structure, which is beneficial to PCF fabrication compared to the silver layer deposited on the inner surface of the fiber hole. The thickness of the silver layer is \(t_{Ag} = 45 \text{ nm}\) and the relative permittivity of silver

Fig. 1. Cross-section of the birefringent PCF-SPR sensor.
The permittivity ($\varepsilon_r$) between 188 nm and 2066 nm is defined by the L4 model (extended Drude model) [32]:

$$
\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\sigma / \varepsilon_0}{i\omega} + \sum_{p=1}^{4} \frac{C_p}{\omega^2 + A_p \omega + B_p}.
$$

(2)

The parameters for Eq. (2) are listed in Table 1. The entire sensor is surrounded by the analyte with RI ($n_{ana}$) varying from 1.33 to 1.42 and an artificial and perfectly matched layer (PML) is used as the boundary condition to absorbing the radiation energy [33]. The other two boundary conditions, the perfect electric conductor and perfect magnetic conductor, are added to the outer boundaries of the theoretical model.

<table>
<thead>
<tr>
<th>$p$</th>
<th>$A_p$ (eV)</th>
<th>$B_p$ (eV$^2$)</th>
<th>$C_p$ (eV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-1.160 \times 10^3$</td>
<td>$-3050$</td>
<td>$3.634 \times 10^8$</td>
</tr>
<tr>
<td>2</td>
<td>$-4.252$</td>
<td>$-0.8385$</td>
<td>$112.2$</td>
</tr>
<tr>
<td>3</td>
<td>$-0.4960$</td>
<td>$-13.85$</td>
<td>$1.815$</td>
</tr>
<tr>
<td>4</td>
<td>$-2.118$</td>
<td>$-10.23$</td>
<td>$14.31$</td>
</tr>
</tbody>
</table>

Table 1 Parameters of the L4 model of Ag permittivity.

The other two boundary conditions, the perfect electric conductor and perfect magnetic conductor, are added to the outer boundaries of the theoretical model.

Fig. 2. Mode field distributions of the core-guided modes: (a) y-polarized mode; (b) x-polarized mode.

Fig. 3. Electric field intensity distribution along the y-axis ($\lambda = 1096$ nm, $n_{ana} = 1.42$, $r_1 = 0.6 \mu$m, $r_2 = 4 \mu$m, $\Lambda = 11 \mu$m, and $t_{Ag} = 45$ nm).
3. Results and discussion

Fig. 2 shows the mode field distributions of the core-guided modes and the black arrows represent the direction of the electric fields. Figs. 2(a) and (b) display the mode distribution in the y-polarized direction (y-polarized mode) and mode distribution in the x-polarized direction (x-polarized mode), respectively. The coupling efficiency between the plasmonic mode and core-guided mode is clearly stronger in the y-polarized mode than the x-polarized mode. With regard to the designed asymmetrical PCF structure, the real part of the effective index of the y-polarized mode is different from that of the x-polarized mode. The birefringence ($B$) is determined by the difference between the real parts of the effective indexes of two orthogonal polarized modes [20]:

$$B = |\text{Re}(n_{eff}^y) - \text{Re}(n_{eff}^x)|,$$

where $n_{eff}^y$ and $n_{eff}^x$ are the effective indices of the y- and x-polarized modes, respectively.
where $\text{Re}(n_{\text{eff}}^x)$ and $\text{Re}(n_{\text{eff}}^y)$ represent the real part of the effective index of the x-polarized mode and y-polarized mode, respectively. There is a difference between the metallized birefringence PCF and ordinary birefringence PCF and so $B = \text{Re}(n_{\text{eff}}^y) - \text{Re}(n_{\text{eff}}^x)$ is used to replace Eq. (3).

Fig. 3 presents the electric field intensity distribution along the y-axis in the y-polarized mode when the SPR is excited. Peaks 1 and 2 correspond to the positions of the silver-analyte interface ($y = 13.796 \mu m$) and fiber core, respectively. It is seen that a part of the energy leaks into the silver-analyte interface (peak 1) from the fiber core, indicating coupling between the plasmonic mode and core-guided mode.

Fig. 4(a) shows the relationship between the birefringence and real parts of the effective indexes of the two orthogonal polarized modes. Unlike the single peak in the confinement loss spectrum, the birefringence curve exhibits two peaks, an upper peak and lower peak as shown in Fig. 4(a). The real parts of the effective indexes decrease gradually as the wavelength increases. However, there is an irregular change in the real part curve of the y-polarized mode resulting in the appearance of the lower peak. Fig. 4(b) plots the birefringence curve when the silver layer of the sensor is removed and there is no peak in the curve. Therefore, this lower peak is inevitably related to the silver layer, which may be attributed to the intrinsic structure of metallized birefringence PCF. In the metallized birefringence model, the lower peak wavelength and birefringence difference between the two peaks can be defined as the resonance wavelength and resonance intensity, respectively. It is noteworthy that the birefringence of pure PCF is visibly lower than that of metallized PCF by comparing Fig. 4(a) and (b), which can be explained by that the birefringence increases as the structural asymmetry increases and the metallized PCF has a stronger rotational asymmetry [20].

Silver and gold are extensively used as plasmonic materials to excite SPR because of the abundance of free conduction electrons [1,34]. Fig. 5 displays the birefringence curves of the core-guided modes when the SPR exciting layers are made of silver and gold, respectively. For the same analyte RI, the sensor with a silver coating has a smaller resonance wavelength than the gold coating. Additionally, the sensor with a silver coating exhibits a sharper birefringence peak and larger resonance intensity thus enhancing the sensing accuracy. Therefore, silver is selected as the plasmonic material in this structure.

Fig. 6 shows the birefringence curves of the core-guided mode when the thickness of silver layer is varied from 55 nm to 45 nm. The resonance wavelength shifts to the short wavelength and the resonance intensity rises as the thickness of the silver layer decreases. This can be explained as follows. SPR occurs at the silver-analyte interface as confirmed by the electronic field distribution in Fig. 3. The thicker silver layer causes more damping in the evanescent wave penetration towards the silver-analyte interface giving

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**Fig. 5.** Birefringence curves of the core-guided modes of silver and gold with the analyte RI being 1.41 and 1.42 ($r_1 = 0.6 \mu m$, $r_2 = 4 \mu m$, $\Lambda = 12 \mu m$, and $t_{Ag/Au} = 45 nm$).

**Fig. 6.** Dependence of the birefringence curves of the core-guided mode on the silver layer thickness ($n_{ana} = 1.42$, $r_1 = 0.6 \mu m$, $r_2 = 4 \mu m$, and $\Lambda = 12 \mu m$).
rise to a smaller resonance intensity. The depth of penetration ($d_p$) of the evanescent wave can be defined as [35]:

$$d_p = \frac{1}{k\beta} = \frac{\lambda}{2\pi\beta},$$

(4)

where $k$ and $\beta$ are the wave number and decay constant, respectively. The penetration depth is directly proportional to the wavelength of the incident light and therefore, in order to penetrate the thicker silver layer, a longer wavelength is required.

Fig. 7 shows the dependence of the birefringence curves of the core-guided mode on the radii of the edge air holes and central air hole. The resonance wavelength is hardly affected by the edge air holes radius, whereas the resonance wavelength exhibits a slight red-shift with increasing central air hole radius. Furthermore, the resonance intensity increases as the radii of the edge air holes and central air hole increase. Fig. 8(a) shows the birefringence curves of the core-guided mode for different distances between the edge air holes and central air hole. The resonance wavelength exhibits a blue-shift and the resonance intensity decreases gradually when the distance increases from 11 $\mu$m to 13 $\mu$m. The variation in the resonance intensity can be explained by the light distribution. Figs. 8(b), (c), and (d) display the light distributions at the resonance wavelength when the distances between the edge air holes and central air hole are 11 $\mu$m, 12 $\mu$m, and 13 $\mu$m, respectively. In this sensor, coupling between the plasmonic mode and core-guided mode occurs mostly in the upper and lower gaps as shown in Figs. 8(b), (c), and (d). When $\Lambda$ is 11 $\mu$m, light confinement in the location near the gaps improves compared to that when $\Lambda$ is 12 $\mu$m or 13 $\mu$m thereby enhancing the coupling efficiency. This is why the resonance intensity decreases as $\Lambda$ increases. The same argument is applicable to explain the variation in the resonance intensity as shown in Figs. 7(a) and (b).

Fig. 9 shows the birefringence curves of the core-guided mode for different analyte RIs. When the analyte RI increases from 1.33 to 1.42, the resonance intensity increases gradually and the birefringence curve shifts towards longer wavelengths, corresponding to the resonance wavelengths of 611 nm for 1.33, 646 nm for 1.35, 696 nm for 1.37, 776 nm for 1.39, 929 nm for 1.41, and 1096 nm for 1.42. For the PCF based on the SPR sensor, the spectral sensitivity ($S(\lambda)$) is one of the major performance parameters and can be calculated by [36,37]:

$$S(\lambda) = \frac{\Delta\lambda}{\Delta n_{ana}} \text{ (nm/RIU)},$$

(5)

where $\Delta\lambda$ is the shift of the resonance wavelength and $\Delta n_{ana}$ is the difference between two analyte RI. According to Eq. (5), a maximum spectral sensitivity of 16,700 nm/RIU is obtained for the analyte RI of 1.41–1.42. The analyte RI resolution ($R$) which is another performance indicator of the PCF-SPR sensor can be expressed as follows [38]:

$$R = \frac{\Delta n_{ana}\Delta \lambda_{\min}}{\Delta \lambda} = \frac{\Delta \lambda_{\min}}{S(\lambda)},$$

(6)
where $\Delta \lambda_{\text{min}}$ is the wavelength resolution. Supposing $\Delta \lambda_{\text{min}} = 0.1 \text{ nm}$, the maximum RI resolution is $5.99 \times 10^{-6} \text{ RIU}$ for the analyte RI of $1.41 - 1.42$.

Fig. 10 shows the numerical relationship between the resonance wavelength and analyte RI. The discrete data points show that the resonance wavelength is nonlinear with increasing analyte RI. A nonlinear curve fit is used to obtain the regression equation as shown in the following:

$$\lambda_{\text{peak}} = 2.38906 \times 10^{-19} \times \exp\left(-\frac{n_{\text{ana}}}{0.02894}\right) + 598.96814,$$

(7)

where $\lambda_{\text{peak}}$ is the resonance wavelength and $n_{\text{ana}}$ is the analyte RI varying between $1.33$ and $1.42$. The calculated R-square value of the fitted curve is as large as $0.99478$ corroborating the excellent fit. The equation plays a prominent role in the design of the PCF-SPR sensor.
4. Conclusion

A new birefringent PCF-SPR sensing configuration is designed and investigated by the lower-birefringence peak method. Our results show that the lower-birefringence peak method can overcome the deficiencies of the reported zero-birefringence point method and replace the conventional confinement loss method. The structure parameters such as the silver layer thickness, air holes radii, and distance between air holes affect the sensing performance and the influence of the penetration depth penetration and location of light confinement is analyzed. The sensing configuration shows a maximum spectral sensitivity of 16,700 nm/RIU and broad RI detection range from 1.33 to 1.42. A nonlinear curve fit is used to obtain the regression equation of the resonance wavelength and analyte RI showing a high R-square value of 0.99478. The designed SPR sensor has potential applications in biomedical and chemical fields especially real-time and fast sensing.

Impact statement

1. We use a novel lower-birefringence peak method to study an asymmetrical PCF-SPR sensor.
2. The lower-birefringence peak method can overcome the two limitations of the reported zero-birefringence point method.
3. Upper and lower gaps are designed in the air holes to enhance the birefringence of the sensor and coupling efficiency.
4. High sensitivity are obtained both in wavelength interrogation.

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