Wide refractive index detection range surface plasmon resonance sensor based on D-shaped photonic crystal fiber

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Abstract
We propose and simulate a surface plasmon resonance (SPR) refractive index (RI) sensor based on a novel D-shaped photonic crystal fiber. We used an open air hole coated with gold film to improve SPR effect. The sensor uses photonic crystal fiber with the same air holes diameter. The effects of structural parameters on resonance spectrum were analyzed by finite element method (FEM). Three SPR peaks were obtained in the wavelength range of 800–1300 nm. The maximum sensitivity is 5626.86 nm/RIU and the maximum resolution is 1.78 × 10⁻⁵ RIU at the refractive index of 1.38. The simulation results show that the refractive index detection range of the sensor is 1.26–1.38. Compared with other D-shaped structures, our sensor can measure larger RI ranges of the analyte.

Keywords Surface plasmon resonance · Photonic crystal fiber · Refractive index detection · Sensor

1 Introduction

In the latest few decades, surface plasmon resonance (SPR) has attracted extensive attention due to its unique advantages in the fields of chemical sensing, biomedical diagnosis and biochemical reaction detection (Kretschmann and Raether 1968; Fan 2019; Gangwar and Singh 2017; Wang and Li 2019; Liu and Wang 2020). Resonance occurs when the wavelength of photons of the incoming electromagnetic wave matches with the wavelength of surface electrons. Under the condition of resonance, an unknown analyte with different refractive index (RI) can be detected through observing the variation of loss peak and corresponding resonance wavelength. Typical models of SPR sensors are Kretschmann (Kretschmann 1971) and Otto ( Otto 1968 ). However, their configurations are complicated and lack mobility. Therefore, the sensor made of optical fiber has entered the field of vision of researchers (Bender and Dessy 1994). In recent years, SPR sensor based on photonic
crystal fiber (PCF) has attracted much attention because of its flexible structure and low cross sensitivity to temperature (Otupiri et al. 2015). In general, SPR sensors based on PCF can be divided into two categories. The first type is the selective filling metal and liquid analytes into air holes, which has been widely reported (Zakaria and Kam 2017; Shuai et al. 2012; Liang and Xian 2017; Rifat and Firoz 2018). However, this type of sensor can not realize real-time sensing. Because the air holes need to be refilled when the RI of analyte changes. In addition, it is extremely difficult to coat metal film or fill infiltrate analyte into the micro holes of the sensor.

The emergence of the second structure (D-shaped PCF-SPR sensor) solves the limitations of the first structure. The D-shaped PCF-SPR sensor deposits metals and places analytes in the outer layer of the PCF to avoid the complex operation of filling air holes. In 2017, Liu et al. designed a SPR sensor with two open air holes based on PCF (Liu and Yang 2017). The sensor is designed to detect low refractive indexes between 1.23 and 1.29 with the operation wavelength in mid-infrared region. The spectral sensitivity is 11000 nm/RIU and a maximum resolution of 7.69×10^{-6} RIU can be obtained. In 2018, Chen et al. proposed a SPR sensor with two open-ring channels based on PCF (Chen et al. 2018). The simulation results show that the refractive index detection range of the sensor is 1.20–1.29. The maximum spectral sensitivity of 11,055 nm/RIU and high resolution of 9.05×10^{-6} RIU can be obtained at 1.29. In 2020, Pathak et al. proposed and analyzed a concave refractive index sensor based on surface plasmon resonance (Pathak and Singh 2020). Results exhibit a high sensitivity of 9314.28 nm/RIU, respectively for the RI varying between 1.33 and 1.38 with the resolution of 1.073×10^{-5} RIU. In 2020, Wang et al. investigated a SPR refractive index sensor based on a D-shaped Hi-Bi PCF (Wang and Sun 2020). Simulation results indicate that the highest sensitivity is 8920 nm/RIU and the RI varies from 1.33 to 1.39. In previous studies, the refractive index detection range of most D-type SPR sensors is narrow. Meanwhile, most of the sensors designed PCF with different air hole diameters. Which greatly increases the difficulty of making the sensor.

In this work, we designed a SPR sensor based on a novel D-shaped PCF structure. Gold plating in the damaged air hole is conducive to the leakage of evanescent field to the gold film to improve SPR effect. At the same time, the destroyed air holes can also provide channels for analytes. Three SPR peaks were obtained in the wavelength range of 800–1300 nm. Simulation results show that the refractive index sensor has a broad measurement range from 1.26 to 1.38 the maximum sensitivity can reach to 5626.86 nm/RIU. And the refractive index resolution is 1.78×10^{-5} RIU.

2 Sensor design and numerical modeling

The Schematic illustration of our proposed D-shaped PCF is shown in Fig. 1. This structure is composed of two layers regular hexagonal air holes with the same diameter, and the diameter d of the air holes is 1.4 μm. The hole-to-hole pitch is Λ = 3.1 μm. And H = 3.5 μm is the distance between the D-shaped section and the fiber core. In order to excite the SPR, a thin gold film with thickness t = 45 nm is deposited on the inner surface of the open air hole analyte channel. The core of the PCF, and gold film form a structure similar to Kretschmann model, to excite SPR. The distance between the gold film and the fiber core is reduced by cutting the side of the PCF and plating the gold film on the D-type platform. This method is conducive to the phase matching between evanescent wave and plasma wave so as to obtain higher sensitivity.
In this fiber, the D-shaped structure can be fabricated using stack-and-draw method and side polishing technique, and the gold film can be coated with a chemical deposition technique (Boehm and Alexandre 2011). In our simulation, the background material of the proposed PCF is fused silica, and its refractive index is determined by Sellmeier equation (Malitson 1965). The dielectric constant of gold is described by the Drude-Lorentz model (Vial and Grimault 2005).

The confinement loss of this sensor can be expressed as (An and Hao 2017):

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

(1)

where $\lambda$ is the wavelength of incident light, and $\text{Im}(n_{eff})$ is the imaginary part of the effective refractive index. As an important parameter to evaluate the sensing performance, the spectrum sensitivity is expressed as:

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

(2)

where $\Delta\lambda_{peak}$ represents the resonance wavelength shift and $\Delta n_a$ denotes the change in the analyte RI. The resolution of refractive index is defined as:

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

(3)

where $\Delta\lambda_{min}$ is the minimum spectral resolution assumed to be 0.1 nm.

For the purpose of accurate calculation, a perfect matched layer (PML) is introduced in the calculation zone edges to absorb radiation energy. The simulation process is accomplished by the commercial finite element method solver–COMSOL Multiphysics.
3 Results and discussion

Figure 2a shows the three peaks in the wavelength range of 800–1300 nm when analyte RI \( n_a = 1.3 \). Figure 2b, c and d illustrate the dispersion relations between SPP mode and fundamental mode of the three peaks. The inserts in Fig. 2 are the electric field distributions of the two modes at specific wavelengths. The characteristic of SPR is that the real part of the effective index of the fundamental mode and surface plasmon-polaritons (SPP) mode coincides, and a peak appears in the imaginary part of the effective index. The maximum energy transfers from the fundamental mode to the SPP mode at the resonant wavelength. These three resonance peaks are the result of the interaction between fundamental mode and SPP mode. Figure 2b shows that the resonance between \( x \)-polarization and high-order SPP mode occurs at 894 nm. The resonance between \( y \)-polarization and high-order SPP mode occurs at 1026 nm can be observed in Fig. 2c. It can be seen from Fig. 2d that the resonance between \( x \)-polarization and low-order SPP mode occurs at 1238 nm. It should be noted that there is a fourth resonance peak at a longer wavelength, which is caused by the resonance between \( y \)-polarization and low-order SPP mode. From peak1 to peak3, the intensity of the SPR formant excited by the sensor is gradually increasing, the loss value becomes larger, the formant becomes sharp, and the resonance wavelength extends to the long wavelength direction. Meanwhile, the sensitivity of the three formants to the change of the refractive index of the analyte is becoming stronger and stronger. However, the fourth resonant peak has a longer wavelength span and is not suitable for sensing research. According to the intensity and

![Fig. 2 Three resonance peaks excited by sensing structure (a), dispersion relation of fundamental core mode, SPP mode, and loss spectra (b–d)](image-url)
FWHM (Full width at half maxima) of the resonance peaks, we choose peak 3 as the research object.

In order to obtain the loss spectrums with large peak value and small FWHM, the effects of air hole diameter $d$ and hole-to-hole pitch $\Lambda$ on the loss spectrums were studied. Figure 3a displays the change of loss spectrums and resonance wavelength when the air hole diameter is 1.3, 1.4 and 1.5 $\mu$m respectively. Other parameters are fixed at $\Lambda = 3.1$, $H = 3.5$, $t = 45$ nm and $n_{eff} = 1.3$. As shown in Fig. 3a, with the increase of air hole diameter, the loss peak of the sensor moves to the longer wavelength direction. The reason is that larger sized holes lead to a smaller Re($n_{eff}$) value of fundamental mode. Eventually, the phase matching point will move towards the long wavelength. The air hole diameter of 1.4 $\mu$m has a sharper resonance peak than that of 1.3 and 1.5 $\mu$m, so it can be used as the best air hole diameter.

Figure 3b exhibits the loss spectra variations for different degrees of gold film thickness $t$ ranging from 40 to 50 nm. As is shown, the loss spectrum moves towards longer wavelength with $t$ decreasing from 50 to 40 nm. The reason is that if the gold film is too thick, the evanescent field will be significantly reduced, so the electric field cannot penetrate through the gold layer. If the gold film is too thin, the plasma wave will be strongly radiated and damped. We can also notice that the loss spectrum of $t = 45$ nm has a sharper resonance peak, thus $t = 45$ nm might be an optimal gold film thickness.

Figure 3c shows the loss spectrums at different distances $H$ from the D-shaped section to the fiber core. The larger $H$ makes the gold film area larger, which leads to the increase

![Fig. 3](image)

**Fig. 3** Loss curves of the proposed SPR-PCF sensor for different hole diameters $d$ (a), different gold film thickness $t$ (b), different D-section distance (c) and different pitch size $\Lambda$ (d)
of the real part of the effective refractive index of SPP mode. It can be seen from Fig. 3c that the resonance wavelength has a tendency to red shift with the increase of $H$. It is mainly because the effective refractive index of SPP mode increases. The loss spectrum with $H=3.5 \, \mu m$ has a sharper resonance peak, so $H=3.5 \, \mu m$ is the best numerical value. Figure 3d shows the impact of the $\Lambda$ on fiber sensing performance. The increase of hole-to-hole pitch $\Lambda$ leads to the decrease of gold film area, which is opposite to that of $H$. It can be seen from Fig. 3d that with the increase of $\Lambda$, there is blue shift in the resonance wavelength. Meanwhile, with the increase of $\Lambda$, the peak value and FWHM of the loss peak decrease. Thus $\Lambda=3.1 \, \mu m$ might be an optimal hole-to-hole pitch.

In the case of optimal structure parameters, we test the refractive index detection range and sensitivity of the sensor. Figure 4a shows the loss curves of the sensor for different RIs of analyte. With the increase of the RI of the analyte, the resonance wavelength generates red shift. Figure 4b shows the change of resonance wavelength when the refractive index of analyte changes from 1.26 to 1.38. The interpolation table shows the polynomial fitting results, and the slope of the fitting curve represents the sensitivity of our proposed sensor. The adjusted R-square value of this fitting is 0.99992, which indicates that the fitting is consistent. Table 1 shows the comparison of the present work with the earlier published works. Most of the reported sensors have high sensitivity, but their refractive index detection range is small. The refractive index detection value of these sensors is less than the

| References                  | Fiber type | SPR material      | Refractive index detection range | Sensitivity (nm/RIU) |
|-----------------------------|------------|-------------------|----------------------------------|----------------------|
| Fan (2019)                  | PCF        | Nano-ring gold film | 1.33–1.43                        | 2150 nm/RIU          |
| Rifat and Firoz (2018)      | PCF        | Gold film         | 1.33–1.42                        | 11,000 nm/RIU        |
| Liu and Yang (2017)         | Double D-shaped PCF | Gold film      | 1.23–1.29                        | 11,000 nm/RIU        |
| Chen et al. (2018)          | D-shaped PCF | Gold film       | 1.20–1.29                        | 11,055 nm/RIU        |
| This work                   | D-shaped PCF | Gold film       | 1.26–1.38                        | 5626.86 nm/RIU       |
refractive index of water (1.33) or greater than the refractive index of water. The sensor designed in this paper can detect the refractive index of analytes in two ranges at the same time.

4 Conclusion

In this paper, a novel D-type PCF sensor based on simple structure is proposed, and its numerical study is carried out. The sensor structure is a PCF based on two layers of regular hexagonal air holes. The SPR effect can be excited and the resonance effect can be enhanced by coating a thin gold film on the open air hole. The simulation results show that the maximum sensitivity is 5626.86 nm/RIU and the resolution is $1.78 \times 10^{-5}$ RIU in the refractive index detection range of 1.26–1.38. The sensor uses PCF composed of air holes with the same diameter, which simplifies the manufacturing process of the sensor. Meanwhile, the measurement of analytes with low refractive index (Less than the refractive index of water) and high refractive index (Greater than the refractive index of water) can be realized. The wide RI range enables the sensor to detect a variety of liquid refractive index, which has a broad application prospect. For example, it can be used to detect the concentration of alcohol, formaldehyde, glucose and some salt solutions.

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Declarations

Conflict of interest The authors declare that they have not known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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