Highly Sensitive Plasmonic Refractive Index Sensor Based on Dual D-Shaped Photonic Crystal Fiber with Aluminum Nitride-Silver Films

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Abstract

A dual-core and dual D-shaped photonic crystal fiber (PCF) based surface plasmon resonance (SPR) sensor with silver and Aluminum Nitride (AlN) films is designed. The distribution characteristics of the electromagnetic fields of core and plasmon modes, as well as the sensing properties are numerically studied by finite element method (FEM). The structure parameters of the designed sensor are optimized by the optical loss spectrum. The results show the resonance wavelength variation of 489 nm for the refractive index (RI) range of 1.36~1.42. In addition, a maximum wavelength sensitivity of 13400 nm/RIU with the corresponding RI resolution of 7.46×10^{-6} RIU is obtained in the RI range of 1.41~1.42. The proposed sensor with the merits of high sensitivity, low cost and simple structure has a wide application in the fields of RI sensing, such as hazardous gas detection, environmental monitoring and biochemical analysis.

Introduction

Surface plasmon resonance (SPR) as a kind of remarkable RI sensing technology shows great research value in the fields of environmental monitoring [1], medical diagnosis [2] and biochemical analysis [3] due to outstanding advantages of high sensitivity, wide operating wavelength range, free label and fast response [4-6]. Photonic crystal fiber (PCF) are well known as micro-structured fiber (MSF) with prominent virtues, such as large mode field area, low loss and endlessly single mode transmission [7,8]. Recently, the sensors based on PCF-SPR have achieved a great leap in the fields of fiber sensing because of flexible structure design, anti-electromagnetic interference, compactness, remotely real-time and online measurement [9-11]. A variety of PCF-SPR sensors for refractive index (RI) sensing have been reported [12-14]. Yang et al proved a PCF-SPR sensor adopting alternate holes coated with graphene-silver (G-Ag) bimetallic layers, which obtained the spectral sensitivity of up to 2520 nm/RIU in the RI range of 1.33~1.35 [15]. Rifat et al proposed a PCF-SPR sensor with a gold layer selectively coated in a large cavity, achieving a maximum sensitivity of 11,000 nm/RIU in the RI range of 1.33~1.42 [16]. Chen et al designed a PCF-SPR sensor based on dual optofluidic channel, realizing a maximum wavelength sensitivity of 5500 nm/RIU in the RI range of 1.32~1.38 [17].

The PCF-SPR sensors mentioned above have something in common, that is, the analytes or plasmonic materials are filled or deposited inside the air holes. However, it is a great challenge for filling or coating mediums into the air holes of PCF in practice. In addition, it is also very inconvenient to change the analytes RI. In order to solve the above problems, a great deal of efforts have been put into the structure design of D-shaped PCF-SPR sensors to meet different sensing and detection requirements [18-21]. For example, Wang et al confirmed a dual-polished PCF-SPR sensor covered with gold film, showing a maximum sensitivity as high as 8000 nm/RIU in the range of 1.30~1.42 [22]. Chen et al verified a D-shaped PCF-SPR sensor with a open-ring channel coated with gold film, whose maximum sensitivity reached 11055 nm/RIU in the range of 1.20~1.29 [23]. Tian et al reported a PCF-SPR sensor based a quasi-D-shaped layout with ITO- graphene (ITO-G) films combination, revealing a maximum sensitivity of 12,000 nm/RIU in the range of 1.21~1.32 [24]. Fang et al demonstrated a D-shaped PCF-SPR sensor

utilizing silver-titanium dioxide (Ag-TiO_2) composite micro-grating, obtaining a maximum sensitivity of 10,300 nm/RIU in the range of 1.33~1.40 [25]. In addition, some sensors with tantalum pentoxide-gold ($\text{Ta}_2\text{O}_5\text{-Au}$) film [26], niobium-aluminum oxide ($\text{Nb-Al}_2\text{O}_3$) film [27], gold-molybdenum disulfide-graphene ($\text{Au-MoS}_2\text{-G}$) [28] film have also been reported. With the development of optical fiber technology and material science, some new materials integrated in the fiber sensors are used to improve the sensing performance.

In this paper, a dual D-shaped PCF-SPR sensor with the Aluminum Nitride (AlN) films coated on the silver films is designed. The PCF cladding with the D-shaped structure can be immersed directly into the liquid/gas environments and interact instantly with the analytes. In addition, the silver as the plasmonic material can form a relatively narrow spectrum to achieve the high detection accuracy. The AlN films deposited on the Ag film surfaces can prevent its oxidation, as well as enhance the resonance effect and detection sensitivity simultaneously. What's more, the AlN-Ag films can be easily prepared by the chemical vapor deposition technology (CVD) [29] and integrated on the surfaces of D-shaped PCF through the micro-machining technology [30]. The structure parameters of the designed sensor are optimized by the optical loss spectrum. The results show that the change in the resonance wavelength with 489 nm is obtained for the RI range of 1.36~1.42, and the maximum spectral sensitivity reaches up to 13400 nm/RIU, corresponding to the maximum RI resolution of 7.46×10^{-6} RIU, which has a bright application prospect in the fields of RI sensing.

Sensing Model And Method

The cross-section of the proposed PCF-SPR sensor is shown in Fig. 1(a). The cladding air holes of PCF with the radius of r are arranged in a triangular lattice layout, and the space distance between the adjacent cladding air holes is Λ . Two cladding air holes distributed in the symmetric positions on the PCF center are removed to form a high RI-guided dual-core structure. Both sides of the circular fiber structure are polished into the D-shaped structures, and the distance from the D-shaped surfaces to the center of PCF is d . The Ag films with the thickness of d_2 as the plasmonic material are coated on the dual D-shaped PCF surfaces, and a layer of AlN film with the thickness of d_1 is deposited on the Ag film surface to protect it from oxidation and strengthen the resonance coupling between the core mode and SPR mode at the same time. The length of AlN-Ag films is the same as the space distance of the adjacent cladding air holes considering that the core mode is leaked to the AlN-Ag film surfaces through the slits between two cladding air holes. Fig. 1(b) represents the schematic diagram of the experimental devices of the proposed sensor. The PCF-SPR sensor is directly surrounded by the analytes with the RI of n_a , which can reduce the difficulty of analytes filling and enhance the interaction between the plasmon mode and analytes. A broadband light source (BBS) as the input light is polarized by a polarization controller (PC) and then transmitted into the dual-core and dual D-shaped PCF-SPR sensor. Finally, the output light is immediately sent into the optical spectrum analyzer (OSA) to observe the corresponding loss spectrum.

Here, the initial structure parameters are as follows: $\Lambda = 4.0 \text{ } \mu\text{m}$, $r = 1.2 \text{ } \mu\text{m}$, $d = 8.5 \text{ } \mu\text{m}$, $d_1 = 20 \text{ nm}$, $d_2 = 40 \text{ nm}$, and $n_a = 1.40$. The above values will be used in the following numerical analysis without special instructions. In addition, the fused silica is used as the substrate material of PCF cladding, and its dispersion relationship with respect to the wavelength is described by Sellmeier equation [31], as shown in equation (1). The permittivity of Ag can be expressed by Drude model [32], as displayed in equation (2). The RI of AlN can be found in the reference [33], whose real part changes roughly from 2.14 to 2.12, and the imaginary part is zero in the wavelength range of 700-1500 nm.

$$n^2 - 1 = \frac{A_1 \lambda^2}{\lambda^2 - B_1^2} + \frac{A_2 \lambda^2}{\lambda^2 - B_2^2} + \frac{A_3 \lambda^2}{\lambda^2 - B_3^2} \quad (1)$$

$$\varepsilon_{Ag} = 1 - \frac{\lambda_c^2 \lambda_c}{\lambda_p^2 (\lambda_c + i\lambda)} \quad (2)$$

where $A_1 = 0.6961663$, $A_2 = 0.4079426$, $A_3 = 0.8974790$, $B_1 = 0.0684043 \text{ } \mu\text{m}$, $B_2 = 0.1162414 \text{ } \mu\text{m}$, and $B_3 = 9.8961610 \text{ } \mu\text{m}$. λ is the free-space wavelength, $\lambda_c = 17.61400 \text{ } \mu\text{m}$, and $\lambda_p = 0.14541 \text{ } \mu\text{m}$.

According to the coupled mode theory [34], when the dispersion curves of core mode and SPR mode intersect at a certain point, in other words, when the phase matching condition is met, a strong resonance coupling between two modes will occur, resulting in a large amount of energy being transferred from the core mode to the SPR mode and producing an obvious resonance loss peak in the spectrum. As a result, we can use the confinement loss of the core mode to characterize the SPR effect, which is proportional to the imaginary part of the mode effective RI ($\text{Im}(n_{\text{eff}})$) and can be defined as [35]

$$L_{\text{oss}} = 40\pi \cdot \text{Im}(n_{\text{eff}}) / (\ln(10)\lambda) \approx 8.68 \cdot k_0 \cdot \text{Im}(n_{\text{eff}}) \text{ (dB/cm)} \quad (3)$$

where $k_0 = 2\pi / \lambda$ is the vacuum wave-number.

Firstly, we analyze the electromagnetic field characteristics of the designed PCF-SPR structure in the COMSOL Multiphysics software based finite element method (FEM). A perfectly matched layer (PML) is arranged outside the fiber structure in order to seek the desired modes and save computing time. Fig. 2 shows the energy distribution in the dual-core at the resonance wavelength of 1095 nm. The red arrows is on behalf of the vector direction of the electric field. There are four core modes that can transmit stably in the dual-core, namely, x and y -polarized odd and even modes, whose

effective RIs are $1.443429 - 1.752059E-5i$ (Fig. 2(a)), $1.443515 - 1.617902E-5i$ (Fig. 2(b)), 1.443437 (Fig. 2(c)), and 1.443506 (Fig. 2(d)), respectively. It can be seen that there is a fraction of the core mode energy leakage to the AlN-Ag film surfaces (Fig. 2(a) and (b)), on the contrary, no light field is concentrated on the AlN-Ag film surfaces (Fig. 2(c) and (d)), which illustrates that y -polarized odd and even modes (Fig. 2(c) and (d)) cannot excite the SPR mode. Additionally, there is a maximum value of $\text{Im}(n_{\text{eff}})$ for the x -polarized odd mode (Fig. 2(a)), which indicates that the coupling strength between the x -polarized odd

mode (Fig. 2(a)) and SPR mode is higher than that of x -polarized even mode (Fig. 2(b)). As a consequence, the x -polarized odd mode (Fig. 2(a)) is used to assess the sensing performance in the following research.

In order to understand the energy transfer process better, the phase matching relationship between the core mode and SPR mode is plotted in Fig. 3. It can be noticed that the real parts of the effective RI ($\text{Re}(n_{\text{eff}})$) of core mode and SPR mode both reduce with the increment of incident wavelength. When the $\text{Re}(n_{\text{eff}})$ of two modes is equal at point (m), the phase matching condition is satisfied, causing more energy of the core mode leakage from dual-core to AlN-Ag film surfaces, which leads to a distinct loss peak at the resonance wavelength of 1095 nm in the spectrum. In addition, the phase matching relationship will be satisfied renewedly with the analyte RI changing, resulting in the resonance wavelength shift. Therefore, the corresponding relationship of the resonance wavelength in relation to the analyte RI can be established to achieve the RI sensing. Inset (a) shows the electric field distribution of x -polarized core mode, and the light field is almost entirely gathered in the dual-core at the non-resonance wavelengths. Inset (b) is the optical field distribution of SPR mode, whose light field is concentrated on the AlN-Ag film surfaces. The energy distribution at the resonance wavelength (point (m)) is drawn in Inset (c), and the obvious energy transfer from the dual-core to AlN-Ag film surfaces is observed, which generates the strong resonance coupling between the core mode and SPR mode.

Results And Discussions

Structure parameters optimization

The AlN films as the dielectric layers have the strong dependence on the designed sensor performance. Fig. 4 shows the loss spectrum of the core mode for different AlN thickness (d_1). The calculated resonance wavelengths are 916, 996 and 1092 nm for n_a of 1.39, as well as 990, 1095 and 1170 nm for n_a of 1.40 due to d_1 of 15, 20 and 25 nm, respectively. In addition, when n_a varies from 1.39 to 1.40, the changes in the resonance wavelength are 74, 99 and 78 nm, corresponding to the wavelength sensitivities of 7400, 9900 and 7800 nm/RIU. There is a maximum spectral sensitivity of 9900 nm/RIU for $d_1=20$ nm. So $d_1=20$ nm is chosen.

The Ag films as the region where the plasmon mode is excited have an important impact on the resonance peak intensity and position. Fig. 5 displays the effect of different Ag films thickness (d_2) on the loss spectrum. When n_a is 1.39 and 1.40, the resonance wavelengths both shift towards long wavelengths as d_1 increases from 35 to 45 nm with a step of 5 nm. Specifically, the resonance wavelengths are 958, 996, and 1039 nm for n_a of 1.39, as well as 1027, 1095 and 1125 nm for n_a of 1.40, corresponding to d_2 of 35, 40 and 45 nm, respectively. Additionally, the variations of the resonance wavelengths are 69, 99 and 86 nm, corresponding to the wavelength sensitivities of 6900, 9900 and 8600 nm/RIU. The $d_2=40$ nm selected as the optimal value realizes a maximum wavelength sensitivity of 9900 nm/RIU.

The confinement loss of the core mode is caused by the finiteness of the cladding air holes. As a result, the positions of the loss peak have strong dependence on the radius of the cladding air holes (r). Fig. 6(a) represents the loss spectrum of the core mode for different r . The results show that the resonance intensity diminishes from 20.567062 to 3.364749 dB/cm with the r increasing from 1.1 to 1.3 μm with a step of 0.05 μm . It can be explained by the fact that the greater the cladding air holes are, the smaller the equivalent RI of the cladding is, resulting in the $\text{Re}(n_{\text{eff}})$ difference between the dual-core and PCF cladding becoming large gradually, which leads to more energy being confined to the dual-core. In addition, the resonance wavelengths are almost unchanged and the full width at a half maximum (FWHM) of the loss spectrum expands with the increment of r . When n_a is 1.39 and 1.40, the effect of different r on the changes of the resonance wavelength is described in Fig. 6(b). The variations of the resonance wavelength enlarge from 91 to 112 nm, while the resonance strength reduces as the r increases in the calculated ranges. As a consequence, $r=1.2 \mu\text{m}$ is selected considering a compromise between the wavelength sensitivity and the resonance depth.

The spectral properties can be affected by the distance (d) from the D-shaped surfaces to the center of PCF, as shown in Fig. 7. In general, when n_a is 1.39 or 1.40, the resonance wavelengths create the redshift and the resonance intensity damps as d increases from 8.3 to 8.7 μm with a step of 0.2 μm . The shifts of resonance wavelength induced by the n_a changing between 1.39 and 1.40 are 118, 99 and 92 nm for d of 8.3, 8.5 and 8.7 μm , corresponding to the wavelength sensitivities of 11800, 9900 and 9200 nm/RIU, respectively. In addition, it can be found that there are two small loss peaks when d is 8.3 μm , whose positions are severally located at the resonance wavelength of 1043 nm for n_a of 1.39, and 1022 nm for n_a of 1.40. It may be responsible for the resonance coupling between the core mode and SPR mode with higher order, which makes the spectrum untidy and is adverse for the RI sensing and measurement. Therefore, $d=8.5 \mu\text{m}$ as an optimized value is adopted in the following analysis.

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Performance analysis

Generally, the sensitivity of the designed PCF-SPR sensor can be characterized by two ways, namely, wavelength and intensity interrogation modes. Here, the sensor performance is evaluated in a wavelength demodulation mode [36], whose sensitivity can be expressed as equation (4). At the same time, the

detection resolution as another important index is used to assess the minimum RI change that causes the spectral response [37], as shown in equation (5).

$$S(\text{nm/RIU}) = \Delta\lambda_{\text{peak}} / \Delta n_a \quad (4)$$

$$R(\text{RIU}) = \Delta n_a \times \Delta\lambda_{\text{min}} / \Delta\lambda_{\text{peak}} \quad (5)$$

where $\Delta\lambda_{\text{peak}}$ denotes the resonance wavelength variation as a response to the change (Δn_a) in the analyte RI, and $\Delta\lambda_{\text{min}}$ is set to 0.1 nm as the wavelength resolution of the spectral analyzer.

The detection performance of the designed PCF-SPR sensor is evaluated for the analyte RI (n_a) varying from 1.36 to 1.42 with a step of 0.01. Fig. 8(a) shows the loss spectrum of the core mode for different n_a . The resonance depth enlarges from 2.737063 to 99.575642 dB/cm with n_a increasing in the calculated range. Meanwhile, the resonance wavelength shifts towards long wavelength from 839 to 1328 nm, whose changes in the resonance wavelength are 489 nm, corresponding to an average wavelength sensitivity of 8150 nm/RIU. Fig. 8(b) represents the fitting relationship between

the resonance wavelength and n_a . The polynomial fitting function with the second order is adopted to describe the relationship between the resonance wavelength and n_a , as shown in equation (6), which obtains a better fitting precision of R-square=0.9992. In addition, it can easily acquire the sensitivity near a certain n_a through taking the derivative of the resonance wavelength in relation to n_a according to the equation (6).

$$y = (ax^2 - bx + c) \times 10^5 \quad (6)$$

where $a=0.9060$, $b=2.4382$, $c=1.6488$.

In order to further characterize the designed sensor performance, the wavelength sensitivity and RI resolution for different RI sensing regions are presented in Table 1. It can be seen that the wavelength sensitivities are 4400, 5200, 6100, 9900, 9900 and 13400 nm/RIU due to different RI range of 1.36~1.37, 1.37~1.38, 1.38~1.39, 1.39~1.40, 1.40~1.41, and 1.41~1.42, corresponding to the RI resolution improving from 2.27×10^{-5} to 7.46×10^{-6} RIU. A maximum wavelength sensitivity of 13400 nm/RIU with the RI resolution of 7.46×10^{-6} RIU is obtained. In addition, we make a performance comparison between the designed sensor and the reported PCF-SPR sensors in Table 2. It is no doubt that our sensor can achieve better sensing performance (maximum sensitivity and resolution) than that of the PCF-SPR sensors listed in Table 2 except Ref. 28.

Table 1
Performance analysis of the proposed PCF-SPR sensor

Refractive index (RIU)	Wavelength (nm)	Sensitivity (nm/RIU)	Resolution (RIU)	Depth (dB/cm)
1.36	839	4400	2.27×10^{-5}	2.737063
1.37	883	5200	1.92×10^{-5}	3.621325
1.38	935	6100	1.64×10^{-5}	4.968688
1.39	996	9900	1.01×10^{-5}	6.695344
1.40	1095	9900	1.01×10^{-5}	8.721958
1.41	1194	13400	7.46×10^{-6}	28.289090
1.42	1328	N/A	N/A	99.575642

Table 2
Performance comparison between the designed sensor and the existing PCF-SPR sensors

Ref	Sensor type	Refractive index (RIU)	Maximum sensitivity (nm/RIU)	Maximum resolution (RIU)	Year
[18]	D-shaped sensor with Au film	1.33~1.38	10493	9.53×10^{-6}	2017
[19]	D-shaped sensor with Au belts	1.15~1.36	12600	7.94×10^{-6}	2020
[20]	Dual-side polished sensor with Au-Si ₃ N ₄	1.395~1.415	12400	8.06×10^{-6}	2019
[21]	Quasi D-shaped sensor with G-ITO film	1.33~1.38	10693	9.35×10^{-6}	2017
[22]	Dual-side polished sensor with Au films	1.30~1.42	8000	1.30×10^{-5}	2019
[23]	D-shaped sensor with Au film opening	1.20~1.29	11055	9.05×10^{-6}	2018
[24]	D-shaped sensor with G-ITO film	1.21~1.32	12000	8.33×10^{-6}	2021
[25]	D-shaped sensor with segmented TiO ₂ -Ag films	1.33~1.40	10300	9.71×10^{-6}	2021
[27]	Sensor with Al ₂ O ₃ -Nb film	1.36~1.41	8000	1.25×10^{-5}	2018
[28]	D-shaped sensor with G-MoS ₂ -Au	1.33~1.40	14933.34	6.69×10^{-6}	2020
[38]	Sensor with TiN-Ag fim	1.32~1.34	7000	-	2019
Proposed	Sensor with AlN-Ag films	1.36~1.42	13400	7.46×10^{-6}	-

Conclusion

A PCF-SPR sensor based dual-core and dual D-shaped structures with the AlN-Ag composite film for RI measurement is numerically analyzed by FEM. The structure design of D-shaped PCF strengthens the interaction between the evanescent field and analytes, as well as overcomes the packaging difficulty of liquid filling. Firstly, the electromagnetic coupling characteristics between the core mode and SPR mode are studied. Then, the structure parameters of the designed sensor are optimized by utilizing the optical loss spectrum, which shows the resonance wavelength shift of 489 nm in the RI range of 1.36~1.42, and a maximum wave-length sensitivity of 13400 nm/RIU with the corresponding RI resolution of 7.46×10^{-6} RIU. Finally, we make a performance comparison between the proposed sensor and the reported PCF-

SPR sensors, which indicates that the introduction of AIN film makes great contribution to the improvement of detection sensitivity. As a consequence, the designed sensor realizes better detection performance, and has a potential prospect in the fields of RI sensing.

Declarations

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Author Contribution All authors contributed to the study conception and design. Data collection was performed by Sanfeng Gu and Meng Li. Data analysis was performed by Sanfeng Gu, Wei Sun and Ming Deng. The first draft of the manuscript was written by Sanfeng Gu. Data curation were performed by Sanfeng Gu and Ming Deng. Visualization was performed by Meng Li. Supervision was performed by Ming Deng. Funding acquisition was performed by Wei Sun and Ming Deng. All authors have read and agreed to the published version of the manuscript.

Availability of Data and Materials All data, models, and code generated or used during the study appear in the submitted manuscript

Ethical Approval All authors declare that this manuscript is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere. We understand that the corresponding author is the sole contact for the editorial process.

Consent to Participate We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. All authors read and approved the final manuscript.

Consent for Publication We would like to draw the attention of the editor to the following publications of one or more of us that refer to aspects of the manuscript presently being submitted where relevant copies of such publications are attached. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

Competing Interests The authors declare no competing interests.

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Figures

Figure 1

Diagrams of (a) cross-section and (b) experimental set-up of the designed sensor

Figure 2

Electric field distribution of the core modes. (a) x-polarized odd mode and (b) even mode, (c) y-polarized odd mode and (d) even mode

Figure 3

Dispersion relationship between the core mode and SPR mode, and loss spectrum with insets (a), (b) and (c) showing the mode field distribution

Figure 4

Loss spectrum of the core mode for different d_1

Figure 5

Loss spectrum of the core mode for different d_2

Figure 6

(a) Loss spectrum of the core mode, (b) Resonance wavelength and loss for different r

Figure 7

Loss spectrum of the core mode for different d

Figure 8

(a) Loss spectrum of the core mode for different n_a (b) Fitting curve of the resonance wavelength in relation to n_a