Surface plasmon resonance sensor based on the dual core D-shape photonic crystal fiber for refractive index detection in liquids

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Abstract. A dual-core D-shape photonic crystal fiber sensor based on surface plasmon resonance is designed and analyzed numerically by the finite element method employing the perfectly matched layer boundary conditions. The resonance peaks shift as the analyte refractive indexes are varied. An average sensitivity of $17 \pm 200$ nm/RIU is achieved in the RI range between 1.40 and 1.44 and the corresponding resolution is $5.8 \times 10^{-6}$ RIU. The various factors affecting the sensing properties are assessed and in particular, the combined effects of two variables are evaluated. © 2022 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.61.8.086111]

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1 Introduction

Surface plasmon resonance (SPR) is an optical phenomenon that occurs when polarized light with a matching frequency strikes a metal surface and the collective oscillations of free electrons resonate with the electric field of the incident light.1 As a sensing technology, SPR offers benefits over conventional sensing methods in environmental monitoring, medical diagnostics, and biological sensing.2-5 Many SPR-based configurations have been developed including the single-mode fiber,6 Bragg grating fiber,7 and photonic crystal fiber (PCF).8-10 Among them, the PCF-SPR sensor has distinct advantages, such as the small size, flexible structure, and phase-matching condition.11,12 The SPR mode will be closely linked with the core mode when the phase-matching conditions are met between the core mode and SPR mode. This can result in a prominent peak in the loss spectra. As a result, the variations in the resonance peak position at a particular wavelength can be employed to analyze the sensor’s performance.13 In recent decades, the use of PCF-SPR for sensing applications has garnered considerable attention, which can be utilized for surface enhanced Raman scattering,14 interferometry,15 quantum dots luminescence,16 and directional resonance coupling.17 Compared with other PCF-SPR sensors, dual-core PCF offers several impressive features, including flexibility in design, simplicity in demonstration, easy to fabricate, and light can be smoothly coupled with the metal surface.18,19

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Usually, metal films serve as the sensitive materials in the structure but manufacturing tends to be complex and it is also difficult to integrate a metallized fiber into a microfluidic device.

To control the thickness of the metal layer, externally coated PCF-SPR sensors have been proposed. In the D-shape photonic fiber sensor, the cross-section is formed by side polishing and it can be produced by microfabrication technology.\textsuperscript{20–24} Moreover, D-shaped as a flat surface improves the potential for homogeneous metal coating using standard metal deposition techniques. Because of the flat and outside metal coating, unknown analyte/sample might be easily detected by flowing through the metal surface when comparing with conventional PCF-SPR.\textsuperscript{25} Several types of D-shape PCF-SPR sensors have been proposed. For example, Tian et al. designed a D-shape SPR sensor with a detection range of 1.33 to 1.38 and sensitivity of 7300 nm/RIU.\textsuperscript{26} Dash and Jha presented a D-shape PCF-SPR sensor consisting of graphene and silver, and graphene enables absorption of biomolecules arising from the π–π stacking interaction.\textsuperscript{27} A thin titanium dioxide layer is utilized as the adhesive layer in the PCF-SPR sensor proposed by Rifat et al.\textsuperscript{28} for refractive index (RI) sensing in the visible to near infrared (IR) region. Cardoso et al. studied a D-shape PCF-SPR sensor with three adjacent gold layers of different thicknesses and plasmon resonance at different wavelengths is tailored to obtain second-order dispersion.\textsuperscript{29} The effects of various structural parameters on the characteristics of the sensors have been studied and shown to impact the sensing performance. However, there have been few studies on the effects of structural parameters and RI simultaneously on the sensing performance. Therefore, efforts are required for dual RI detection by PCF-SPR sensors in the infrared range. In this paper, the influence of double parameter variation on the sensor characteristics under different structural parameters and RI variation are presented simultaneously.

Herein, a dual-core D-shape PCF-SPR sensor with an elliptical air hole in the center is investigated by the finite element method (FEM) based on COMSOL Multiphysics software. The appearance of D-shape PCF-SPR is a breakthrough in fiber-optic technology, combining with a dual-core structure, which lead to unprecedented properties that overcome many limitations. The flexible design, unique structure, and high spectral sensitivity make it own many advantages, which cannot be realized with the conventional PCF-based sensors. In contrast to the complicated structures reported in the literature, this D-shape PCF-SPR structure is characterized by ease of fabrication and makes the PCF-SPR sensor more practical in sensing applications. The sensor boasts an RI detection range of 1.40 to 1.44 and average spectral sensitivity of 17,200 nm/RIU. In addition, the combined influence of two variables is investigated in details. Compared with other sensor performance analysis, the influence of dual parameters variation on sensor performance is more comprehensive and the sensor processes a relative high sensitivity of 17,200 nm/RIU, and these unique results make the study advanced compared to already published literature.

2 Simulated Model

The cross-section of the D-shape PCF-SPR sensor shown in Fig. 1 contains an elliptical hole and 20 circular air holes with an RI of \( n = 1.0 \). The major axis and minor axis of the ellipse are \( a = 0.6 \, \mu m \) and \( b = 2 \, \mu m \), respectively, and the distance between the flat side polished surface to the center of the ellipse is \( D = 4.5 \, \mu m \). The distance between adjacent circular air holes is \( \Lambda = 2 \, \mu m \). During COMSOL simulations, we initially chose a D-shape PCF-SPR sensor with diameters \( d_1 \), \( d_2 \), and \( d_3 \) are 1.2, 0.8, and 1.0 \( \mu m \), respectively, and higher confinement loss was expected to occur in the optical range. This structural design is based on the fact that the PCF is a microstructured optical fiber with periodically arranged air holes spanning the length of the fiber, thus the structural asymmetry of the PCF can be enhanced by adjusting the air hole distribution in the fiber. Now, it is possible to manufacture a PCF-SPR sensor with multihole structure, and the experimental progress in the fabrication of such structures was reported in Refs.\textsuperscript{30} to \textsuperscript{33}. The perfectly matched layer (PML) on the outside constitutes the virtual boundary condition to absorb the light energy.\textsuperscript{34} Depending on the element order in the model, a finer mesh is employed. The complete mesh consists of 16,586 domain elements, 1231 boundary elements, and the PML contains 1056 elements. The maximum element growth rate in the structure is 1.25 and the minimum element quality is equal to 0.0035. Pure silica is the matrix and the RI change with incident light wavelength and material dispersion can be expressed as follows:\textsuperscript{15}
where $\lambda$ is the wavelength of the incident light in micrometer ($\mu$m), $A_1 = 0.696166300$, $A_2 = 0.407942600$, $A_3 = 0.897479400$, $B_1 = 4.67914826 \times 10^{-3} \mu$m$^2$, $B_2 = 1.35120631 \times 10^{-2} \mu$m$^2$, and $B_3 = 97.9340025 \mu$m$^2$. Gold with a thickness of $t_{\text{Au}} = 50$ nm is deposited on the flat side polished surface and the relative permittivity of the nanoscale gold film can be calculated by the Drude–Lorentz model:\textsuperscript{36}

$$
\varepsilon_{\text{Au}}(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\omega_c)},
$$

(2)

where $\varepsilon_\infty = 9.75$, $\omega_p = 1.36 \times 10^{16}$ rad/s, and $\omega_c = 1.45 \times 10^{14}$ rad/s.

The characteristics of the sensor are analyzed by the full vector FEM based on the Comsol Multiphysics software. The confinement loss which is a pivotal performance indicator is defined as follows:\textsuperscript{37}

$$
L_{\text{con}}(\text{dB/cm}) = \frac{40\pi \text{Im}(n_{\text{eff}})}{\text{ln}(10)\lambda} \times 10^7 = 8.686k_0 \text{Im}(n_{\text{eff}}) \times 10^7,
$$

(3)

where $k_0 = \frac{2\pi}{\lambda}$, $\lambda$ is the wavelength in nanometers, and $\text{Im}(n_{\text{eff}})$ is the imaginary part of the effective mode index. The loss peak indicates that the particular wave matches the surface plasmon wave, so the RI can be determined by measuring the shift in the resonance wavelength.

### 3 Results and Discussion

Figure 2 shows the loss spectra for different air hole diameters. Before drawing the loss spectrum under different air hole diameters, plenty of calculation has been done to get the optimal structural parameters. A representative parameter range was selected to explain the specific effect of air hole variation on the loss spectrum. Figure 2(a) shows that the resonance peak shifts gradually to a longer wavelength as the air hole diameter ($d_1$) increases and although the influence of air hole diameter ($d_1$) on the resonance wavelength of the sensor is relatively small, the resonance intensity increases significantly. Meanwhile, the optical loss spectra of the intensity increases gradually, thus indicating higher confinement loss for $d_1 = 1.6 \mu$m, which attributed to more energy transferred from the fundamental mode to the SPP mode. The position and intensity of the resonance peaks can be optimized by adjusting $d_1$ and Fig. 2(b) shows that the resonance wavelength shifts to a shorter wavelength with increasing air hole diameter ($d_2$). The difference between the confinement loss for 1.425 and 1.430 increases initially and then decreases with
increasing diameter \((d_2)\) of the air holes. In the design of the D-shape PCF-SPR structure, the air holes \((d_2)\) near the gold film can control the coupling strength of the guide mode and SPP mode to a certain extent. As shown in Fig. 2(b), the curve exhibits pronounced peak at the air holes diameter of \(d_2 = 0.4 \, \mu m\) for an RI of 1.425, and the loss spectra becomes broad and hump-shaped as a result of weak coupling for an RI of 1.430. The half-width of the resonance peaks is also expanded when \(d_2 > 0.8 \, \mu m\). Therefore, the coupling strength between the fundamental mode and SPP mode becomes stronger and most of the energy of the fundamental mode is transferred to the SPP mode for \(d_2 = 0.8 \, \mu m\) and an RI of 1.430. As shown in Fig. 2(c), the loss decreases with increasing diameter \((d_3)\) of the air holes for an RI of 1.425. When the RI is 1.43, the loss increases first and then decreases. The peak positions of the loss spectra remain nearly unchanged, indicating that the air hole diameter \((d_3)\) has little influence on the optical loss spectra of the D-shape PCF-SPR sensor. The results imply that the air hole diameters have a large influence on the resonance wavelength and resonance intensity, suggesting that they can be tuned to the desired values by adjusting the air holes diameters.

Figure 3(a) shows the loss spectra of the sensor for different pitches of the air holes from 1.8 to 2.1 \(\mu m\). The confinement loss of the peaks increases initially and then decreases with increasing pitch. The half-width of the loss peak decreases noticeably and the resonance wavelength exhibits a blueshift. As shown in Fig. 3(b), the resonant peak shifts to a longer wavelength when the RI increases by 0.005. The pitch of the air holes is a significant factor influencing the half-width and amplitude of the resonant peak. When the air holes are 1.9, 2.0, and 2.1 \(\mu m\), the shifts of the loss peaks are \(\Delta 1 = 165 \, nm\), \(\Delta 2 = 80 \, nm\), and \(\Delta 3 = 45 \, nm\), respectively. While the RIs are 1.425 and 1.430, the loss increases first, then decreases, which indicates that it has an optimal wavelength sensitivity. The reason is that the incident light will not be confined well in the dual core, and then the mode coupling is weakened. It is obvious that the loss shift caused by changing the RI is greater when the air hole is 2.0 \(\mu m\).
Figure 4 shows the dependence of the optical loss on the gold film thickness ranging from 45 to 65 nm. Figure 4(a) shows the dependence of the loss spectra of the fundamental mode on the gold layer thickness for an RI of 1.425. The resonance wavelength shifts a longer wavelength from 1030 to 1150 nm when the gold layer thickness increases from 45 to 65 nm. The half bandwidth of the loss curve is smaller when the gold layer thickness is 50 nm, indicating that there is an optimal thickness. It is shown in Fig. 4(b) that the loss shows a trend of increasing first and then decreasing, and the resonance wavelength redshifts when the gold layer thickness increases from 45 to 65 nm for an RI of 1.430. To obtain more information about the optical properties of the PCF-SPR, the electric field distribution of core mode, SPP, and coupling mode with \( n = 1.425 \) is shown in Figs. 4(c)–4(e). The proposed electric field profile of core mode shows that the mode tightly confined at the core region. This SPP mode shows that the interaction of plasmonic materials with analytes properly. Figure 4(e) shows that most of the energy is confined to the fiber core and the energy is introduced to the surface of the metal at the resonance wavelength. It is clear that part of the core mode light energy leaked into the gold film sensing area as SPP mode light signal. There is an obvious loss at the resonance wavelength thus providing a significant signal for detection of the analyte. As shown in Fig. 4(f), the loss increases with increasing RI for a fixed gold film thickness and changes more when the RI is 1.430, revealing that the confinement loss is more sensitive to the change in the metal film thickness when the RI is bigger.

Figure 5 shows the loss spectra of the fundamental mode for different minor and major axes of the elliptical air hole. The resonance peaks in the loss spectra shift to longer wavelengths when the minor axis of the elliptical air hole increases as shown in Fig. 5(a). The confinement loss changes by about 8 and 20 dB/cm for RI of 1.425 and 1.430, respectively, when the minor axis of the ellipse is increased to 0.4 μm. Hence, the confinement loss is more sensitive to the change in the minor axis of the elliptical air hole for a larger RI. Figure 5(b) shows that the confinement loss changes only a little when the long axis is increased by 6 μm and compared to the short axis, the change in the long axis by 1 μm has less effects on the change in the loss peak.

Figure 6 shows the wavelength dependence of the loss spectra on the polishing depth (\( D \)). The loss curve shows a redshift with increasing depth for the same RI. When the polishing depths are 4.4, 4.5, and 4.6 μm, the shifts in the long wavelength direction are expressed as \( \Delta 1 \), \( \Delta 2 \), and \( \Delta 3 \) when the RI changes by 0.005. The results disclose that the blue spectral line exhibits a larger shift of 110 nm.

Figure 7(a) shows the optical loss spectra of the sensor for different analytes and the confinement loss is quite sensitive to the RI of the analytes. The resonance wavelength increases from 840 to 1530 nm when the RI changes from 1.40 to 1.44. The half-width of the loss peak decreases noticeably with increasing RI and the confinement loss increases. The relationship between the analyte RI and resonance wavelength is presented in Fig. 7(b). The resonance wavelength increases approximately parabolically with RI. The \( R \)-square value is 0.98404 which is close to unity suggesting that the D-shape PCF-SPR sensor shows good continuous response in
the RI range from 1.40 to 1.44 and the performance is expected to be more stable in practice. In general, this calibration curve can serve as a reference in case of practical application. Through fitting, the values that are not simulated can be used as the reference of resonance wavelength. Simulation or experiments can only improve the accuracy as much as possible, but there are always incomplete simulation values, which can help improve accuracy.

By detecting the changes in the resonance peak positions and variations of the analyte RI, the spectral sensitivity can be determined as

$$S_{sp} (\lambda) = \frac{\Delta \lambda_{\text{peak}}}{\Delta n_a} \text{ (nm/RIU)},$$  \hspace{1cm} (4)$$

where $\Delta \lambda_{\text{peak}} = 86.2 \text{ nm}$ is the shift in the resonant peak for $\Delta n_a = 0.005$ (RI change). An average spectral sensitivity of 17,200 nm/RIU is achieved. The sensor resolution is defined as the smallest change in the RI that can be distinguished by the sensor and is calculated as

$$\Delta n_{\text{res}} = \frac{\Delta \lambda_{\text{peak}}}{S_{sp} (\lambda)} \text{ (RIU)}.$$ 

Fig. 4 Dependence of the optical loss on the gold film thickness (a) $n = 1.425$, (b) $n = 1.430$. Field profile of (c) core mode, (d) SPP mode, (e) coupling mode, and (f) dependence of the optical loss on the gold film thickness and RI.
Fig. 5 Dependence of the optical loss on the minor axis and major axis of the elliptical air hole.

Fig. 6 Dependence of the optical loss on the polishing depth ($D$).

Fig. 7 (a) Dependence of the optical loss on the RI of the analyte and (b) relationship between the analyte RI and resonance wavelength.
\[ R = \frac{\Delta n_a \Delta \lambda_{\text{min}}}{\Delta \lambda_{\text{peak}}}, \]  

where \( \Delta \lambda_{\text{peak}} \) represents the resonant peak shift. The wavelength resolution is assumed to be \( \Delta \lambda_{\text{min}} = 0.05 \) nm when the variation in the analyte RI is 0.01 resulting in a sensing resolution of \( 5.8 \times 10^{-6} \) RIU. When the RIs of the analyte and bulk materials are similar, the coupling strength of the fundamental mode and SPP mode increases consequently yielding better spectra sensitivity, resolution, and resonance intensity.

4 Conclusion

A PCF-SPR sensor consisting of a central elliptical air hole is designed and studied numerically by COMSOL Multiphysics software based on the FEM. The 21 air holes in the sensor divide the PCF into two energy sensing channels. The spectral sensitivity is demonstrated to be 17,200 nm/RIU and the sensing resolution is \( 5.8 \times 10^{-6} \) RIU for analyte RI between 1.40 and 1.44. The influence of the various structural parameters on the sensing characteristics is investigated and the dependence of two parameters on the loss spectrum is assessed as well. Owing to the excellent sensing characteristics, the sensor has large potential in RI detection in liquids.

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References


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