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Research on dual-channel and dual-core plasmonic sensor based photonic crystal fiber for refractive index sensing

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Abstract

A dual-core photonic crystal fiber (PCF) with dual-channel based surface plasmon resonance (SPR) sensor is designed. The silver and gold films are severally coated in the inner walls of two large ring detection channels to excite the plasmon modes, which can make the designed sensor achieve the dual-channel sensing. The effect of structure parameters on the sensing properties and loss spectrum is numerically analyzed by finite element method (FEM). When the analyte refractive index (RI) changes from 1.340 to 1.360, the average spectral sensitivities of 4280 and 3940 nm/RIU are obtained for the left and right channels, corresponding to the RI resolutions of 2.34×10^{-5} and 2.54×10^{-5} RIU, respectively. The simulation results suggest that the designed dual-channel sensor can realize highly sensitive detection of two analytes simultaneously, which has a wide application in the fields of biomedical analysis and environmental monitoring.

Keywords photonic crystal fiber, surface plasmon resonance, finite element method, refractive index

Introduction

Under a certain incident light wavelength or frequency, the free electrons in metal interact with the incident photons and the electromagnetic waves is strongly absorbed, forming an evanescent wave with exponential attenuation on the surface of the metal and dielectric, which is called surface plasmon resonance (SPR) wave [1,2]. Due to the high sensitivity of SPR to the change in the refractive index (RI) of surrounding environment [3], it can be used to analyze the concentration, affinity constant and specificity caused by the absorption of the target molecules [4,5]. As a result, the SPR sensors have made great progress in the environmental monitoring [6], medical diagnosis [7], biotechnology [8], food safety [9] because of high sensitivity, high specificity and label-free detection [10,11]. Usually, SPR can be excited by traditional prism-coupled configuration based Kretschmann, but the Kretschmann structure has large volume and is not suitable for real-time and remote sensing [12,13]. The SPR sensors based photonics crystal fiber (PCF) have overcome above drawbacks due to small size [14], high

integration and miniaturization of PCF [15]. In addition, the PCF with flexible structure design [16] and low transmission loss [17] is easy to satisfy the phase matching and achieve a strong coupling between the core mode and SPR mode [18], which makes the PCF-SPR sensors become a research hotspot.

Recently, in order to expand the application scope and satisfy the needs of reality, the researchers have done a lot of work on the structure design of PCF-SPR sensors, and the sensing characteristics have been studied by the loss spectrum method based on the mode coupling theory [19,20]. At present, dual-channel or multi-channel sensing has greatly potential value to master more information of the analytes, so many efforts are devoted to the relevant research. Hassani et al proposed a PCF-SPR sensor with two large semi-circular channels and developed the design principles of PCF in plasmonic sensing [21]. Otipiri et al designed a SPR sensor with a small air hole introduced into the center of PCF, obtaining the RI resolutions of 5×10^{-5} RIU for HE_{11}^x mode and 6×10^{-5} RIU for HE_{11}^y mode in the RI range 1.33~1.34 [22]. A PCF-SPR sensor with four ring channels distributed in the PCF cladding was proposed, and utilizing four modes (HE_{11}^x , HE_{11}^y , HE_{12}^x , and HE_{12}^y) achieved the wavelength sensitivities of 2200, 2400, 2200 and 2400 nm/RIU for the RI range 1.33~1.34, respectively [23]. A PCF-SPR sensor with gold film and nanowire coated and filled separately into channel-1 and channel-2 was proposed, which achieved the measurement of temperature and magnetic field simultaneously [24]. Additionally, a multi-channel PCF-SPR sensor with elliptical and circular air holes arranged in a hexagonal lattice was reported, and the resolutions of 5×10^{-5} and 6×10^{-5} RIU were verified for HE_{11}^x and HE_{11}^y modes, respectively [25]. It is more concise that using a single polarized mode on behalf of several resonance peak signals achieves the multi-channel sensing in the spectrum than that of the multiple polarized modes.

In this paper, a simple dual-channel and dual-core PCF-SPR sensor is designed, and the sensing layers adopting silver and gold films are deposited in two large ring detection channels, respectively. The dual-core structure of PCF can improve the detection sensitivity and the dual-channel sensing can be realized by using different resonance characteristics of silver and gold materials. Here, a single polarized

mode is adopted to characterize the resonance signal peaks of two channels at the same time. The results show that the average sensitivities of 4280 nm/RIU for the left channel and 3940 nm/RIU for the right channel are demonstrated in the wavelength interrogation.

Sensing Model and Method

The schematic of the designed dual-channel and dual-core PCF-SPR sensor is as shown in Fig. 1. It can be seen that a large air hole with a radius of r_1 is located in the model center, which is used to adjust the coupling between the core mode and SPR mode [26]. The PCF cladding consists of two layers of air holes with a radius of r_2 in a circular lattice distribution, and they have a space pitch of Λ in the radial direction. The cladding air holes in the first layer are distributed at 60 degree intervals, and the missing air holes are used to form a dual-core structure with the light transmission. For the second layer, the cladding air holes are arranged at 30 degree intervals to limit the propagation of light in the dual-core. The silver and gold films as the sensing layers with the thickness of d_m are covered on the inner walls of two large ring channels, the left channel (L-channel) and right channel (R-channel), which can generate two independent resonance signals utilizing different optical resonance characteristics of two materials. In addition, two metallized detection channels with a diameter of d_2 (1.6 μm) are symmetrically distributed outside the fiber structure, and have a center distance of d_1 (3.3 μm) from the central air hole, which can achieve the packaging easily and strengthen the microfluidics flow simultaneously.

Here, the background material of PCF is pure silica and the relationship between RI and free space wavelength can

Fig. 1 Schematic of the proposed dual-channel and dual-core PCF-SPR sensor

be defined by Sellmeier equation [27] :

$$n = \sqrt{1 + \sum_{i=1}^N \frac{A_i \lambda^2}{\lambda^2 - B_i^2}} \quad (1)$$

where λ is the incident wavelength, $N=3$, $A_1=0.6961663$, $A_2=0.4079426$, $A_3=0.8974790$, $B_1=0.0684043 \mu\text{m}$, $B_2=0.1162414 \mu\text{m}$, and $B_3=9.8961610 \mu\text{m}$.

The L-channel and R-channel are deposited with the silver and gold films, respectively. As shown in equations (2) and

(3), the dielectric constants of silver and gold materials can be described by Drude model in visible and near-infrared bands [28, 29].

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

$$\epsilon_{\text{Au}} = \epsilon_{\infty} - \frac{w_p^2}{w^2 + iw w_{\tau}} \quad (3)$$

where the angular frequency can be expressed as $\omega=2\pi c/\lambda$, c is the speed of light in a vacuum, $\lambda_c=17.61400 \mu\text{m}$, $\lambda_p=0.14541 \mu\text{m}$, $\epsilon_{\infty}=9.75$, $w_p=1.36 \times 10^{16} \text{ rad/s}$, and $w_{\tau}=1.45 \times 10^{14} \text{ rad/s}$.

When the plasmon mode is strongly coupled with the core mode, most of the energy leaks from the dual-core to metal surface and it will create a sharp loss peak in the spectrum. We can use the limiting loss of core mode to characterize the plasmon mode, which is as a function of the imaginary part of mode effective RI and can be calculated by the following equation [30]:

$$L_{\text{oss}} (\text{dB/cm}) = 8.686 \times \frac{2\pi}{\lambda [\mu\text{m}]} \text{Im}(n_{\text{eff}}) \times 10^4 \quad (4)$$

The sensitivity is used to evaluate the sensing performance of the designed sensor, which plays an important role in the detection field. When analyte RI changes, the wavelength with the resonance peak signal will create significant movement. Therefore, the spectral sensitivity in a wavelength interrogation mode can be defined by [31] :

$$S (\text{nm/RIU}) = \Delta \lambda_{\text{peak}} / \Delta n_a \quad (5)$$

where Δn_a denotes the change in the analyte RI, and $\Delta \lambda_{\text{peak}}$ is the resonance wavelength drift as a response to Δn_a . In addition, the detection resolution as another important index can be used to determine the minimum change in the analyte RI through the following equation [32] :

$$R (\text{RIU}) = \Delta n_a \cdot \Delta \lambda_{\text{min}} / \Delta \lambda_{\text{peak}} \quad (6)$$

where $\Delta \lambda_{\text{min}}$ represents the wavelength resolution of spectrometer and is assumed to be 0.1 nm.

Analysis and Discussions

In this paper, we adopt 2D simulation environment in the COMSOL Multiphysics software based FEM to numerically analyze the mode distribution and sensing performance of the designed PCF-SPR sensor. In order to solve the required mode, a perfectly matched layer (PML) as boundary condition is considered in the simulation [33]. Firstly, when the analytes RI of L-channel (n_{a1}) and R-channel (n_{a2}) are set to 1.340, the electric field distribution of the core mode at the resonance wavelengths ($\lambda_{\text{peak}}=528$ and 658 nm) is plotted in Fig. 2 and Fig. 3, respectively. The red arrows represent the polarization direction of electric field. It can be seen that there are four core modes, which are called even and odd modes for x -polarization and y -polarization, respectively. The effective RI of four core modes at the resonance wavelength ($\lambda_{\text{peak}}=528$ nm) in Fig. 2 are 1.447521-1.421774E-5i (Fig. 2(a)), 1.447290-1.072611E-5i (Fig. 2(b)),

1.447050-6.785469E-5i (Fig. 2(c)), 1.446784-7.680090E-5i (Fig. 2(d)), respectively. Similarly, the effective RI of four core modes at the resonance wavelength ($\lambda_{\text{peak}}=658$ nm) in Fig. 3 are 1.436892-7.890037E-5i (Fig. 3(a)), 1.436364-6.425048E-5i (Fig. 3(b)), 1.436066-1.715782E-4i (Fig. 3(c)), 1.435465-2.068961E-4i (Fig. 3(d)), respectively. As we can see, compared to y -polarized core modes (Fig. 2(a) and (b), Fig. 3(a) and (b)), a small fraction of the light field is merely concentrated on the surface of silver and gold films for x -polarized core modes (Fig. 2(c) and (d), Fig. 3(c) and (d)), and most of the energy is confined in the dual-core, which illustrates that y -polarized core modes can't excite plasmon mode. In addition, it can be also found that the plasmon mode is only generated on the L-channel coated with silver film in Fig. 2(c) and (d), while the R-channel deposited with gold film has no light field. Correspondingly, the opposite result appears in Fig. 3(c) and (d). It means the independence of L-channel and R-channel and can work in two spectral regions, which provides possibility for the realization of dual-channel detection. What's more, the complex effective RI of odd mode for x -polarization (Fig. 2(d) and Fig. 3(d)) has a maximum value of imaginary part, which can make it more strongly coupled with SPR mode than other core modes. Therefore, the odd mode for x -polarization is selected as the research object for further study.

Fig. 2 Electric field distribution of the core mode. (a) even mode and (b) odd mode for y -polarization, (c) even mode and (d) odd mode for x -polarization. ($\Lambda=0.9$ μm , $r_1=0.40$ μm , $r_2=0.20$ μm , $d_m=45$ nm, $n_{a1}=n_{a2}=1.340$, $\lambda_{\text{peak}}=528$ nm)

Fig. 3 Electric field distribution of the core mode. (a) even mode and (b) odd mode for y -polarization, (c) even mode and (d) odd mode for x -polarization. ($\Lambda=0.9$ μm , $r_1=0.40$ μm , $r_2=0.20$ μm , $d_m=45$ nm, $n_{a1}=n_{a2}=1.340$, $\lambda_{\text{peak}}=658$ nm)

Fig. 4 represents the dispersion and phase matching relationship of the core mode and SPR mode. The blue solid and dotted lines are the dispersion curves of SPR modes generated on the L-channel and R-channel, respectively. The black and red solid lines are the dispersion curve and loss spectrum of the core mode. When the real parts of effective RI of the core mode and SPR modes excited on the L-channel and R-channel are equal, the phase matching relationships are severally satisfied at the points (m) and (n), which caused most of the core mode energy being strongly coupled to the surface of silver and gold films, forming two sharp resonance loss peaks at the resonance wavelengths of 528 nm and 658 nm in the spectrum. There is a wavelength interval of 130 nm

Fig. 4 Dispersion relationship of the core mode (black line) and SPR modes (blue solid and dotted lines) and loss spectrum (red line) with insets (a), (b), (c), (d) and (e) showing the electric field distribution. ($\Lambda=0.9$ μm , $r_1=0.40$ μm , $r_2=0.20$ μm , $d_m=45$ nm, $n_{a1}=n_{a2}=1.340$)

between the points (m) and (n), and it can provide a wide enough wavelength range to ensure the independence of L-channel and R-channel. Inset (a) represents the energy distribution of core mode at the non-resonance wavelengths and it is principally focused in the dual-core to maintain the light transmission. Insets (b) and (d) are the light field distribution of L-channel and R-channel where the SPR modes are excited on the surfaces of silver and gold films, respectively. The electric field distribution at the resonance wavelengths (points (m) and (n)) is drawn in Insets (c) and (e), and the energy coupling between the core mode and SPR modes is observed obviously, and it is sensitive to the changes in the analytes RI near the metal surface caused by the molecular absorption, which can achieve dual-channel sensing through a single optical fiber mode in the composite spectrum.

As the sensing layers, the influence of metal film thickness on the half width and intensity of the resonance peak has been systematically studied [34,35]. Fig. 5 shows the effect of the thickness of silver and gold films (d_m) on the loss spectrum. It can be seen that the resonance wavelength of L-channel increases from 518 to 536 nm, and the resonance intensity decreases from 120.3801 to 51.5931 dB/cm with the increase of d_m from 40 to 50 nm. It has the same change trend for R-channel, which is that the resonance wavelength enlarges from 644 to 670 nm and the resonance strength reduces from 253.2790 to 133.4043 dB/cm in the calculated range. The reason is that the incident light will be strongly absorbed by the silver and gold films with large imaginary parts, resulting in less energy penetrating the metal surface. with d_m increasing. In addition, the half width of resonance peak and loss at the off-resonance wavelength also expand [36].

The effect of space pitch (Λ) on the loss spectrum of the core mode is shown in Fig. 6. When Λ changes from 0.8 to 1.0 μm , the resonance wavelength of L-channel blueshifts from 566 to 513 nm, and the R-channel moves towards a short wavelength from 701 to 633 nm. While the resonance loss shows the same trend of decrease first and then increase for two channels, there are minimum values of 79.7665 dB/cm for L-channel and 171.4112 dB/cm for R-channel

Fig. 5 Loss spectrum of the core mode for different d_m from 40 to 50 nm. ($\Lambda=0.9 \mu\text{m}$, $r_1=0.40 \mu\text{m}$, $r_2=0.20 \mu\text{m}$, $n_{a1}=n_{a2}=1.340$)

Fig. 6 Loss spectrum of the core mode for different Λ from 0.8 to 1.0 μm . ($r_1=0.40 \mu\text{m}$, $r_2=0.20 \mu\text{m}$, $d_m=45 \text{ nm}$, $n_{a1}=n_{a2}=1.340$)

when Λ is 0.9 μm , which can reduce the light transmission loss and promote the coupling between the core mode and SPR modes better. In addition, there is a small peak close to the main peak of R-channel for $\Lambda=1.0 \mu\text{m}$, which makes the spectrum become untidy and is adverse to the dual-channel sensing.

The influence of the air holes radius of the PCF center (r_1) and cladding (r_2) on the sensing properties of the designed

Fig. 7 (a) Loss spectrum of the core mode for different r_1 from 0.30 to 0.50 μm and (b) different r_2 from 0.18 to 0.22 μm . ($\Lambda=0.9 \mu\text{m}$, $d_m=45 \text{ nm}$, $n_{a1}=n_{a2}=1.340$)

sensor is simulated and discussed. Fig. 7(a) shows the loss spectrum of the core mode for r_1 varying from 0.30 to 0.50 μm with a step of 0.05 μm . It can be seen that the resonance wavelength is tuned in the range from 526 to 533 nm with a variation of 7 nm for L-channel and the range from 654 to 664 nm with a variation of 10 nm for R-channel, corresponding to the resonance peak changing from 58.0115 to 128.8000 dB/cm and 128.8270 to 268.9466 dB/cm, respectively. Likewise, the effect of r_2 on the loss spectrum of the core mode is studied. As shown in Fig. 7(b), the resonance wavelength remains almost unchanged for two channels, while the resonance intensity decreases from 124.1700 to 49.5493 dB/cm for L-channel and diminishes from 255.9930 to 112.7286 dB/cm for R-channel as r_2 increases from 0.18 to 0.22 μm with a step of 0.01 μm . It can be explained by the fact that a large air hole located in the center can lower the effective RI of core mode [37], leading to the RI difference of the core mode and cladding mode reducing, which causes more energy leakage from the dual-core to metal surfaces. On the contrary, the equivalent RI of the PCF cladding decreases with the increase of r_2 , corresponding to the RI difference enlarging, resulting in more energy being confined in the dual-core. Therefore, it provides a method to regulate the position of resonance peak by changing r_1 and r_2 .

The detection sensitivity of the designed dual-channel PCF-SPR sensor is evaluated. When the RI of L-channel

Fig. 8 (a) Loss spectrum of the core mode for different n_{a2} from 1.340 to 1.360. (b) Linear fitting line of λ_{peak2} with respect to n_{a2} . ($\Lambda=0.9 \mu\text{m}$, $r_1=0.40 \mu\text{m}$, $r_2=0.20 \mu\text{m}$, $d_m=45 \text{ nm}$, $n_{a1}=1.340$)

(n_{a1}) is fixed as 1.340 and the RI of R-channel (n_{a2}) varies from 1.340 to 1.360 with a step of 0.005, the loss spectrum of the core mode is drawn in Fig. 8 (a). As we can see, the

$$\lambda_{\text{peak2}} = 3860n_{a2} - 4517.2 \quad (R^2 = 0.9894) \quad (7)$$

resonance wavelength redshifts from 658 to 736 nm with the increase of n_{a2} for the R-channel, and without change for the L-channel, which illustrates that the L-channel and R-channel are independent channels and the R-channel can be used as a sensing channel separately. Fig. 8(b) shows the linear fitting line of the resonance wavelength of R-channel (λ_{peak2}) in relation to n_{a2} . The fitting relationship with a linearity of $R^2=0.9894$ is expressed by equation (7). The coefficient of first order is on behalf of an average spectral sensitivity of 3860 nm/RIU for R-channel in the n_{a2} range of 1.340~1.360. At the same time, a RI resolution of 2.59×10^{-5} RIU is also obtained according to equation (6).

Similarly, Fig. 9(a) shows the loss spectrum of the core mode when $n_{a2}=1.340$ and n_{a1} changes from 1.340 to 1.360 with a step of 0.005. It can be seen that λ_{peak1} for L-channel enlarges from 528 to 614 nm with the increase of n_{a1} , and λ_{peak2} for R-channel is unchanged. When n_{a1} is greater than 1.360, the resonance signals carried by λ_{peak1} and λ_{peak2} will create the overlap, which is no longer appropriate for L-channel as a separate sensing channel to complete the detection. The linear fitting line of λ_{peak1} with respect to n_{a1} is plotted in Fig. 9(b). The fitting relationship with a better linearity of $R^2=0.9937$ is expressed by equation (8). As a

Fig. 9 (a) Loss spectrum of the core mode for different n_{a1} from 1.340 to 1.360. (b) Linear fitting line of λ_{peak1} with respect to n_{a1} . ($\Lambda=0.9 \mu\text{m}$, $r_1=0.40 \mu\text{m}$, $r_2=0.20 \mu\text{m}$, $d_m=45 \text{ nm}$, $n_{a2}=1.340$)

consequence, an average spectral sensitivity of 4280 nm/RIU for L-channel is obtained in the n_{a1} range of 1.340~1.360, corresponding to a RI resolution of 2.34×10^{-5} RIU.

Fig.10 (a) Loss spectrum of the core mode for different n_{a1} and n_{a2} from 1.340 to 1.360. (b) Linear fitting curves of λ_{peak1} and λ_{peak2} with respect to n_{a1} and n_{a2} , respectively. ($\Lambda=0.9 \mu\text{m}$, $r_1=0.40 \mu\text{m}$, $r_2=0.20 \mu\text{m}$, $d_m=45 \text{ nm}$)

Through the above analysis (Fig. 8 and Fig. 9), when the analyte RI of L-channel or R-channel is fixed, both can serve as independent detection channels and can be used alone. During the simultaneous operation mode of L-channel and R-channel, the loss spectrum of the core mode is as shown in Fig. 10(a) for n_{a1} and n_{a2} varying from 1.340 to 1.360 with a step of 0.005. The resonance wavelengths of two channels (λ_{peak1} and λ_{peak2}) both move towards long wavelengths, corresponding to the changes of λ_{peak1} from 528 to 614 nm and λ_{peak2} from 658 to 738 nm. They are almost identical to the values given in Fig. 8 and Fig. 9, which verifies the independence of two channels again. In addition, the linear fitting curves of λ_{peak1} and λ_{peak2} with respect to n_{a1} and n_{a2} are simultaneously plotted in Fig. 10(b) and the fitting relationships are shown in equation (9). In the operation mode of dual-channel, the wavelength sensitivities of 4280 nm/RIU with a linearity of $R^2=0.9937$ and 3940 nm/RIU with a linearity of $R^2=0.9877$ are obtained in the RI sensing

range between 1.340 and 1.360, corresponding to the RI resolutions of 2.34×10^{-5} and 2.54×10^{-5} RIU, respectively, which can achieve better sensing performance than that of Ref [22], [23] and [25].

$$\begin{cases} \lambda_{\text{peak1}} = 4280n_{a1} - 5209.8 & (R^2 = 0.9937) \\ \lambda_{\text{peak2}} = 3940n_{a2} - 4624.6 & (R^2 = 0.9877) \end{cases} \quad (9)$$

Conclusion

A dual-core PCF-SPR sensor with dual-channel separately covered with silver and gold films is designed. Utilizing different optical resonance properties of the silver and gold materials, the proposed sensor can operate in two modes: single channel and dual-channel sensing. The odd mode for x-polarization is selected as the research object through the coupling properties analysis by FEM, which can simultaneously characterize two resonance signal peaks. In the operation mode of single channel detection, the spectral sensitivities of 4280 nm/RIU for L-channel and 3860 nm/RIU for R-channel are obtained. At the same time, it also achieves the wavelength sensitivities of 4280 nm/RIU for L-channel and 3940 nm/RIU for R-channel in the operation mode of dual-channel sensing when analytes RI changes between 1.340 and 1.360, which can be used for biochemical detection and environmental monitoring in the multi-component analysis.

Declarations

Ethical Approval All authors declare that this manuscript is original, has not been published before and is not currently being considered 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 to Publish 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.

Authors Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Shengxi Jiao and Xiaolei Ren. The first draft of the manuscript was written by Xiaolei Ren. Data curation and visualization by Hanrui Yang, Shibo Xu and all authors commented on previous versions of the manuscript.

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

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Figures

Figure 1

Schematic of the proposed dual-channel and dual-core PCF-SPR sensor

Figure 2

Electric field distribution of the core mode. (a) even mode and (b) odd mode for y-polarization, (c) even mode and (d) odd mode for x-polarization. ($\Lambda=0.9 \mu\text{m}$, $r_1=0.40 \mu\text{m}$, $r_2=0.20 \mu\text{m}$, $dm=45 \text{ nm}$, $n_{a1}=n_{a2}=1.340$, $\lambda_{\text{peak}}=528 \text{ nm}$)

Figure 3

Electric field distribution of the core mode. (a) even mode and (b) odd mode for y-polarization, (c) even mode and (d) odd mode for x-polarization. ($\Lambda=0.9\ \mu\text{m}$, $r_1=0.40\ \mu\text{m}$, $r_2=0.20\ \mu\text{m}$, $d_m=45\ \text{nm}$, $n_{a1}=n_{a2}=1.340$, $\lambda_{\text{peak}}=658\ \text{nm}$)

Figure 4

Dispersion relationship of the core mode (black line) and SPR modes (blue solid and dotted lines) and loss spectrum (red line) with insets (a), (b), (c), (d) and (e) showing the electric field distribution. ($\Lambda=0.9 \mu\text{m}$, $r_1=0.40 \mu\text{m}$, $r_2=0.20 \mu\text{m}$, $d_m=45 \text{ nm}$, $n_{a1}=n_{a2}=1.340$)

Figure 5

Loss spectrum of the core mode for different d_m from 40 to 50 nm. ($\Lambda = 0.9 \mu\text{m}$, $r_1 = 0.40 \mu\text{m}$, $r_2 = 0.20 \mu\text{m}$, $n_{a1} = n_{a2} = 1.340$)

Figure 6

Loss spectrum of the core mode for different Λ from 0.8 to 1.0 μm . ($r_1=0.40 \mu\text{m}$, $r_2=0.20 \mu\text{m}$, $d_m=45 \text{ nm}$, $n_{a1}=n_{a2}=1.340$)

Figure 7

(a) Loss spectrum of the core mode for different r_1 from 0.30 to 0.50 μm and (b) different r_2 from 0.18 to 0.22 μm . ($\Lambda=0.9 \mu\text{m}$, $d_m=45 \text{ nm}$, $n_{a1}=n_{a2}=1.340$)

Figure 8

a) Loss spectrum of the core mode for different n_{a2} from 1.340 to 1.360. (b) Linear fitting line of λ_{peak2} with respect to n_{a2} . ($\Lambda=0.9 \mu\text{m}$, $r_1=0.40 \mu\text{m}$, $r_2=0.20 \mu\text{m}$, $d_m=45 \text{ nm}$, $n_{a1}=1.340$)

Figure 9

(a) Loss spectrum of the core mode for different n_{a1} from 1.340 to 1.360. (b) Linear fitting line of λ_{peak1} with respect to n_{a1} . ($\Lambda=0.9 \mu\text{m}$, $r_1=0.40 \mu\text{m}$, $r_2=0.20 \mu\text{m}$, $d_m=45 \text{ nm}$, $n_{a2}=1.340$)

Figure 10

(a) Loss spectrum of the core mode for different n_{a1} and n_{a2} from 1.340 to 1.360. (b) Linear fitting curves of λ_{peak1} and λ_{peak2} with respect to n_{a1} and n_{a2} , respectively. ($\Lambda = 0.9 \mu\text{m}$, $r_1 = 0.40 \mu\text{m}$, $r_2 = 0.20 \mu\text{m}$, $d_m = 45 \text{ nm}$)