High-sensitivity three-core photonic crystal fiber sensor based on surface plasmon resonance with gold film coatings

Youpeng Yang*, Yafei Qin*, Xinyu Lu*, and Yu Zeng*

The Faculty of Mechanical and Electrical Engineering, Kunming University of Science and Technology, Kunming, Yunnan, 650500, People’s Republic of China

*E-mail: yp_ykm@163.com; qinyafei_kmust@foxmail.com; 15565484464@163.com; zy15922808102@163.com

Received July 30, 2021; revised September 6, 2021; accepted October 7, 2021; published online November 10, 2021

A high-sensitivity three-core photonic crystal fiber (PCF) sensor based on surface plasmon resonance (SPR) is proposed in this paper. The gold film is selected as the plasmonic metal and coated on the outside surface of the PCF to excite the SPR phenomenon. There are three different diameter air holes of d1, d2, and d3 distributed on the cross-section of the sensor. Among them, sensor performance can be affected by changing the diameter of the central hole and the thickness of the gold film. The sensor shows the maximum confinement loss value and spectral sensitivity of 50 dB cm−1 and 30600 nm RIU−1, respectively, at analyte RI (na = 1.41), and the corresponding maximum resolution is 3.27 × 10−6. The above simulation result shows that the sensor has excellent performance, thus laying the foundation for future research.

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1. Introduction

In past decades, PCF sensors based on surface plasmon resonance (SPR) have rapidly developed, and can be used for many research fields such as that of protein and other biological macromolecules, environment index monitoring, biomedical analysis, and food safety control.1−7) The SPR phenomenon was caused by collective oscillations and involved the resonance of free electrons at the interface between the metal and medium.8,9) However, the traditional SPR sensors were fabricated by the prism, which possesses many disadvantages such as large volume, single method detection and the failure to realize remote measurement compared with the proposed sensor.9,10) In addition, plasmonic materials are important composing elements for the SPR sensor. In recent years, optical fiber sensors based on SPR have been presented by many researchers and have been manufactured to resolve the above deficiencies. Among them, gold, silver, ITO, and conductive composite materials are selected as plasmonic material and coated on the interior or exterior of the fiber to initiate the SPR phenomenon.8,11−15) Until now, reflective SPR sensors16) and photonic crystal fiber SPR (PCF-SPR) sensors have been widely used to detect the refractive index of analytes. However, the compared PCF sensors based on SPR have smaller volumes and higher detection accuracy. Meanwhile, the proposed SPR sensor possesses such advantages as remote measurement, real-time measurement, smaller volumes, and wider application fields compared with the traditional SPR sensor.

In PCF-SPR sensors, the structure of the PCF can be designed accordingly to detect different objects, and are more flexible compare with the previous structure. Generally, the D-type optical fiber has been made by polishing the external surface of the PCF.14) Meanwhile, the structure of the air holes inside the PCF has changed to achieve the demanded purpose. Wu et al.17) described a D-shaped PCF sensor with gold film coated on the surface of the fiber. The maximum sensitivity is 21700 nm RIU−1 for the analyte RI range between 1.33 and 1.34. Emranul Haque et al. proposed a photonic crystal fiber sensor based on surface plasmon resonance to detect a low refractive index analyte with a maximum spectral sensitivity of 51000 nm RIU−1.18) Alok Kumar Paul et al. reported a dual-core photonic crystal fiber (DC-PCF) sensor that offers a maximum amplitude sensitivity of 554.9 RIU−1 and 636.5 RIU−1 with a maximum wavelength sensitivity of 5800 nm RIU−1 and 11500 nm RIU−1, and the sensor resolutions of 1.72 × 10−5 RIU and 8.7 × 10−6 RIU, at an analyte refractive index (RI) of 1.40 for x- and y-polarized modes, respectively.19) In the above reports, the main studies are both single-core and dual-core PCF-SPR sensors. There are few studies of three-core and multi-core PCF-SPR sensors. Therefore, Tong et al. presented a three-core PCF-SPR sensor, whose average sensitivity can reach 3435 nm RIU−1 with the analyte RI varying from 1.33 to 1.4.20) This has been widely applied in the real-time monitoring of biosensors. In addition, Zhang et al. reported a multi-core PCF sensor with a spectral sensitivity of 3300 nm RIU−1.21)

The plasmonic metals of the external surface of the sensor are selected to optimize the parameter of the sensor. Usually, the coating materials are gold, silver, graphene, and some metal oxides, such as ITO and TiO2. In this paper, the surface of the optical fiber is coated with gold since it possesses greater stabilization of chemical properties, which may be better at exciting the SPR phenomenon. In addition, the thickness of the gold film plays a critical role in the performance of the sensors. One of the other critical parameters is the value of the air hole diameter. Therefore, the performance of the PCF-SPR sensors is optimized by changing the size of the air holes and the thickness of the metal layer. We choose gold as the plasma material by considering the above factors. Meanwhile, the thickness of the gold film is optimized to improve the sensor performance in the following works.

In this paper, a three-core photonic crystal fiber sensor is designed in which the gold film is coated with the outside. Meanwhile, the proposed sensor is numerically analyzed by COMSOL Multiphysics software-based finite element
method (FEM). The manufacturing difficulty of coating metal on the external is lower compared with the coating on the inner. In addition, the test object can directly and more quickly contact with the plasmonic material in order to realize real-time detection. Therefore, the performance of the three-core sensor can be improved by optimizing the value of the air holes and the gold film thickness. Our sensor shows high spectral sensitivity and amplitude sensitivity compared with previously proposed sensors. The average spectral sensitivity of the sensor is 6900 nm RIU−1 in the analyte refractive index (RI) range of 1.33 to 1.41, corresponding to a spectral sensitivity and maximum resolution of 30600 nm RIU−1 and 3.27 × 10−6 RIU, respectively.

2. Design and modeling of proposed three-core PCF-SPR sensor

Figure 1 shows the schematic diagram of the three-core sensor with fused silica as the cladding material. The sensor possesses three fiber cores with an angle between adjacent fiber cores of 120 degrees. These air holes are in a regular hexagon distribution around the fiber core. Three big air holes are distributed on the exterior of the fiber core. Meanwhile, the four air holes in the middle are shared by the three fiber cores. The sensor presented consists of three air holes with different diameters. Among them, the air hole d3 has a specific influence on the phase matching and coupling between fundamental mode and the surface plasmon polariton (SPP) mode in our work. The concrete values of the other parameters are as follows: d3 = 0.4 μm, d2 = 0.6 μm, and d1 = 1 μm, respectively. The lattice pitch of the internal air holes is denoted by the symbol Λ with Λ = 2 μm and the diameter of the fiber is 8.6 μm. In addition, the thickness of the gold film is denoted by tg. The metal film can be coated on the polished surface of the PCF by chemical and physical methods such as sputtering technology and high-pressure chemical vapor deposition technology. The plasmon material is the gold film in this model, and the dielectric function of gold has denoted by the Drude model.

\[
\varepsilon(w) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i \gamma)}, \quad (1)
\]

where \(\varepsilon\) is defined as the permittivity of Au, and \(\varepsilon_\infty\) refers to the high-frequency permittivity with the value of 9.75. The plasma frequency of gold is \(\omega_p = 1.36 \times 10^{16}\) Hz, and \(\omega_s = 1.45 \times 10^{14}\) Hz is the scattering frequency of the electron. The coating thickness changing range of the gold film is 35–50 nm, and the steplength is 5 nm. Pure silica is selected as the background material in the sensor. The refractive index of pure silica is defined by the Sellmeier equation:

\[
n = \sqrt{1 + \frac{0.691663 \lambda^2}{\lambda^2 - 0.004679} + \frac{0.407943 \lambda^2}{\lambda^2 - 0.013512} + \frac{0.897479 \lambda^2}{\lambda^2 - 97.934003}} \quad (2)
\]

where \(\lambda\) is defined as the operating wavelength.

To absorb radiation energy, a perfect matching layer (PML) and perfect electrical conductor (PEC) are added to the outer boundary of the optical fiber in using COMSOL in the model simulation in order to increase the accuracy of the simulation result. In the simulation, a free triangle mesh is used, and the amount of edge units and vertex units is 817 and 80, respectively. The confinement loss is obtained by the following equation:

\[
\alpha_{\text{loss}} = 8.686 \times \frac{2\pi}{\lambda} \times \text{Im}(\varepsilon_{\text{eff}}) \times 10^4 (\text{dB cm}^{-1}). \quad (3)
\]

In Eq. (3), \(\text{Im}(\varepsilon_{\text{eff}})\) represents the imaginary part of the effective refractive index. The real part of the fundamental mode and SPP mode has a point of intersection for the confinement loss reaching the peak. In addition, in this study, the confinement loss of the y polarization changes little compared with the x polarization. The majority of the energy of the core fiber is transferred from the fundamental mode to the SPP mode. Hence, our study concentrates on the y polarization of the fundamental mode.

The working process of the sensor is as follows.

Firstly, the fiber of the three-core sensor is spliced with a single fiber. Then, the light incident ray provided by the wideband light source launches light into the fiber, and the variation of the spectra is recorded by optical spectrum analysis (OSA). Then, because the peak of confinement loss is sensitive to tiny variations of analyte RIs, the sample RI can be detected by observing the variation of the resonance peak.

In this paper, the optimal thickness of the gold film is 40 nm. When the light enters the surface between the substrate and gold film at an incident angle greater than the critical angle, the evanescent wave still exists at the boundary between the outer side of the metal film and the medium, since the thickness of the gold film is less than the depth of the penetration of the evanescent. The component of the wave vector interface is defined by the following equation:

\[
k_{\text{ev}} = \frac{\omega}{c} \sqrt{\varepsilon_0 \varepsilon_{\text{clad}}} \sin \theta, \quad (4)
\]

where \(\omega\), c represent the angular frequency of the incident light and the speed of the light, respectively. \(\varepsilon_0\), \(\theta\) are the dielectric constant of the cladding and the angle of incidence light, respectively.

![Fig. 1.](Color online) Cross-section of the PCF-SPR sensor.
The surface plasmon wave is generated due to the attenuation of the metal surface plasma oscillation at the interface between the film and the ambient medium. The wave vector is described by the following equation:

$$k_{sp} = \frac{\omega}{c} \sqrt{\varepsilon_1 \varepsilon_2 / (\varepsilon_1 + \varepsilon_2)},$$

where $\varepsilon_1$, $\varepsilon_2$ represent the dielectric constant of the metal film and the samples of the metal surface.

3. Simulation results and discussion

Figure 2 shows that the real part of the fundamental mode and the SPP mode, as well as the loss curve of the y-polarized mode, varies with increasing wavelength for RI = 1.40. The green and black curves describe the distribution relation of the RI real part of the fundamental mode and SPP mode, respectively. The red curve represents the distribution of the confinement loss of the fundamental mode. Figure 2 depicts that the real part of the fundamental mode decreases with an increase of wavelength. Moreover, the real part of the SPP mode decreases rapidly compared with the fundamental mode. Meanwhile, at the resonant wavelength of 917 nm, confinement loss peak values reach a point of intersection with the real part of the fundamental mode and the SPP mode in which the phase-matching condition is satisfied. Here, the confinement loss directly reflects the phase matching and coupling between the fundamental mode and the SPP mode. Figure 2 shows that the confinement loss reaches the peak, in which stronger SPR occurs, when major energy is transferred from the fundamental mode to the SPP mode. Therefore, an obvious peak of confinement loss is observed. Moreover, due to the variation of the plasmon mode, $\text{Re}(n_{\text{eff}})$ displaces the results in the resonant wavelength position shifts when the analyte varies from 1.33 to 1.41. Finally, analyte RI is detected by observing the shift of the resonant wavelength.

The status of the coupling between the fundamental mode and the SPP mode is demonstrated in Figs. 3(a)–3(d). The electric field distribution of the SPP mode and fundamental mode is described by Figs. 3(a) and 3(b), respectively. The arrows in Fig. 3 represent the direction of the electric field. It is seen from Fig. 3(a) that the SPP mode is excited by a specific wavelength, and the energy is distributed around the gold film. The energy is concentrated on the middle of the fiber core, under the condition of the fundamental mode, as shown in Fig. 2. Figure 3(c) shows the coupling between the fundamental mode and the SPP mode at the resonance wavelength and the energy transformed to the SPP mode from the fundamental mode. The resonance wavelength appears when the real parts of the fundamental mode and of the SPP mode are equal. The super mode is described in Fig. 3(d). The super modes do not excite the SPP mode due to the energy concentrated on the fiber core. At the wavelength of 950 nm for $n_a$ of 1.4, the real part of the effective refractive index of the super mode and fundamental mode is 1.4322, 1.4324, 1.4362. There is a small difference between the real part of the effective refractive index of the super mode and the fundamental mode. Even so, there is a large difference between the direction of the electric field of the fundamental mode with super mode.20)

Fig. 2. (Color online) Distribution of the real part of the core-guide mode, plasmonic mode, and confinement loss of the core-guide mode.

Fig. 3. (Color online) Distribution of the mode of the sensor: (a) plasmonic mode, (b) core-guided mode, (c) plasmonic mode and core-guided mode in resonant wavelength, and (d) super mode ($d_1 = 0.6 \text{ \mu m}$, $d_2 = 0.4 \text{ \mu m}$, $t_g = 40 \text{ nm}$, $\Lambda = 2 \text{ \mu m}$).
hole diameter and pitch. Figure 4(a) shows that the resonance wavelength moves toward longer wavelengths with the redshift appearing with and corresponding to the maximum confinement loss of 98 dB cm$^{-1}$ at a wavelength of 880 nm for $d_3 = 0.4 \mu m$ as the value of $d_2$ increases from 0.4 $\mu m$ to 0.6 $\mu m$. Note that the confinement loss gradually increases when the size of the $d_2$ changes from 0.6 $\mu m$ to 0.4 $\mu m$, indicating the appearance of stronger coupling between the fundamental mode and the SPP mode. Thus the performance of the proposed sensor is optimized by adjusting the air hole $d_2$. Moreover, considering the performance and fabrication of the sensor, $d_2 = 0.6 \mu m$ is chosen as the optimal size of $d_2$.

In addition, the energy conversion between the fundamental mode and the SPP mode is affected by the change of the central air holes. Figure 4(b) presents the variation of the confinement loss of the fundamental mode for different sizes of air hole $d_3$ corresponding to resonance peaks shifts toward longer wavelengths. It is worth noting that a redshift appears. The resonance wavelength increases gradually when the center hole diameter is increased from 0.2 $\mu m$ to 0.4 $\mu m$. Meanwhile, the coupling strength increases with the $d_3$ increase from 0.2 $\mu m$ to 0.4 $\mu m$ due to the greater energy transfer from the fundamental mode to the SPP mode. Thus considering the manufacturing difficulty and detecting sensitivity of the sensor, the $d_3$ is chosen to be 0.4 $\mu m$ as the optimal value. The coupling between the fundamental mode and the SPP mode has improved at a $d_2$ of 0.6 $\mu m$ and $d_3$ of 0.4 $\mu m$, with an improved sensitivity of 30600 nm RIU$^{-1}$ at $n_a = 1.41$, indicating that the changing of $d_2$ and $d_3$ affects the sensing performance.

From Fig. 4(c), we can see the resonant wavelength change towards shorter wavelengths when the pitch varies from 1.9 $\mu m$ to 2.1 $\mu m$. It is clearly observed that the resonance wavelength produces a blue shift. It is shown that the confinement loss of the fundamental mode is slightly changed by the rise of the lattice pitch $\Lambda$ from 1.9 $\mu m$ to 2.1 $\mu m$, as shown in Fig. 4(c), which means that less energy is transferred to the surface of the optical fiber from the fiber core. This is because the leaky channel of the fiber core is restrained with the increasing lattice pitch. Thus, considering the sensitivity and confinement loss, we choose $\Lambda = 2 \mu m$ as the optimal pitch of the air holes.

Gold film thickness is a pivotal parameter affecting phase matching and coupling between the fundamental mode and the SPP mode in our proposed sensor. Figure 5 shows the confinement loss spectra for different gold film thicknesses.

![Fig. 4. (Color online) Loss curve of the proposed sensor for variations in (a) $d_2$, (b) $d_3$, (c) $\Lambda$.](image1)

![Fig. 5. (Color online) Loss curve of the proposed sensor for variations in thickness of the gold film $t_g$.](image2)
thickness of the gold film, and the resonant peaks exhibit an obvious redshift. Meanwhile, less energy is transferred from the fundamental mode to the SPP mode as the thickness of the gold film rises from 35 nm to 45 nm. Figure 5 indicates that the resonant wavelength increases as the thickness of the gold film increases from 35 nm to 45 nm while the values of the air holes remain constant at d2 = 0.6 μm and d3 = 0.4 μm, respectively. This is because the gold film is too thick, preventing the electric field from penetrating the gold layer. The plasmonic wave encountered was violently damped due to the radiation damping when the value of the gold film is smaller, leading to the confinement loss peak being remarkably reduced.\textsuperscript{19,29} Considering the above facts, we choose tg = 40 nm as the optimal thickness of the gold film to achieve the optimal sensing performance of the proposed sensor.

The proposed sensor is sensitive to the variation of the surrounding analyte RI. In Fig. 6, we note that the confinement loss curves are affected by the analyte RI. This is because the resonant peak shifts towards longer wavelengths with analyte RI varying from 1.33 to 1.41. It is obvious that the resonance peaks appear to redshift. Moreover, when the analyte RI varied from 1.33 to 1.40, the coupling intensity of the fundamental mode and SPP mode increased gradually while the confinement loss increased. In addition, the spectral sensitivity could be calculated by Eq. (6) with the $\Delta \lambda_{\text{peak}}$ of 17, 21, 26, 33, 44, 64, 110, 306 nm for the variation of na from 1.33 to 1.41, and correspondingly the maximum spectral sensitivity of 30600 nm RIU$^{-1}$ appears for $\Delta \lambda_{\text{peak}} = 306$ nm at an RI of 1.4–1.41. In addition, the confinement loss is slightly reduced at an analyte RI of 1.41, where the confinement loss possesses a slight secondary peak, and there is only one peak in the analyte RI range of 1.33–1.4. Therefore, our proposed sensor is more suitable for stable detect analytes. The phase-matching coupling between the fundamental mode and the SPP mode experiences an incomplete-to-complete transition. This is because the SPP mode is affected by the variation of analyte RI. This is because the decrease in the binding capacity of the fiber to the core modes results in more energy leaking from the fundamental mode to the SPP mode. Meanwhile, coupling between the fundamental mode and the SPP mode is enhanced with the gradual increase in analyte RI, which is caused by the gradual increase of the peak loss intensities.\textsuperscript{30} In addition, the spectral sensitivity is a crucial parameter for the sensor and can be defined as

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

where $\Delta \lambda_{\text{peak}}$ represents the difference of the resonance wavelength of the refractive index of adjacent analytes, and the parameter $\Delta \text{na} = 0.01$. The values of the analyte RI increase from 1.33 to 1.41, where the average and the maximum of $\Delta \lambda_{\text{peak}}$ are 69 nm and 306 nm, respectively. Hence, the average and maximum spectral sensitivities are 6900 nm RIU$^{-1}$ and 30600 nm RIU$^{-1}$, respectively. In addition, the resolution of analyte RI is also a vital parameter for the sensor and is expressed by the following formula:

$$R = \frac{\Delta \text{na}}{\Delta \lambda_{\text{min}}},$$

where $\Delta \lambda_{\text{min}}$ of the wavelength resolution is assumed to be 0.1 nm. When the analyte RI na variation step length is 0.01, the maximum sensing resolution of the PCF-SPR three-core sensor is $3.27 \times 10^{-4}$ RIU at an analyte RI na of 1.41 and the minimum values of 5.88 $\times 10^{-5}$ RIU at an analyte RI na of 1.34.

Figure 7 shows the variation of the resonance wavelength with the changing of the analyte RI na from 1.33 to 1.41. The changing of the resonance wavelength followed the fit curves when the analyte RI na increases from 1.33 to 1.41. It is clearly visible that the resonance wavelength increases gradually with the analyte RI increase, and more energy is transformed from the fundamental mode to the SPP mode. This is because the increasing analyte RI reduces the refractive index contrast between the fundamental mode and the SPP mode, resulting in strong coupling.\textsuperscript{31} Moreover, in the adopted fitting method of the polynomial, the third-order fitting is carried out to optimize the curve.
Here, the slope of the fit curve can be used to reflect the sensitivity of the sensor. The inset table in Fig. 7 shows the value of R-square (COD) and Adj. R-square: 0.9863 and 0.9781, respectively. These results indicate that the resonance wavelength of the sensor demonstrated a great fitting curve, in which the maximum spectral sensitivity of 30600 nm RIU\(^{-1}\) appears for an analyte RI \(n_a\) of 1.4. However, the PCF sensor sensitivity response appears nonlinear when the analyte RI is present in the range of 1.33 to 1.41. Although the fitting curve is nonlinear, this allows for the dynamic monitoring of the sensor.

The amplitude sensitivity is another important parameter in estimating the performance of the sensor and can be defined as follows:

\[ S(\lambda) = \frac{1}{\alpha(\lambda, n_a)} \frac{\partial \alpha(\lambda, n_a)}{\partial n_a} (\text{RIU}^{-1}). \]  

(8)

The amplitude sensitivity is an essential factor in evaluating the properties of the sensor. The amplitude sensitivity is calculated based on Eq. (8). It should be noted that the amplitude sensitivity increases and then slightly decreases with an analyte RI of 1.33 to 1.41, as shown in Fig. 8. Note that the amplitude sensitivity peak shifts towards longer wavelengths. The amplitude sensitivity varies from 181 RIU\(^{-1}\) to 633 RIU\(^{-1}\) for the variation of the analyte RI \(n_a\) from 1.33 to 1.41, and correspondingly the maximum amplitude sensitivity of 633 RIU\(^{-1}\) appears at 1.39–1.40, as shown in Fig. 8(a). Furthermore, the coupling between the fundamental mode and the SPP mode is also influenced by the changing thickness of the gold film. Figure 8(b) shows that the amplitude sensitivity increases with varying the thickness of the gold film from 45 nm to 35 nm. From Fig. 5, it can be seen that decreasing the gold film thickness results in an incremental increase of confinement loss. Due to the increment increase of the confinement loss, the interaction between the evanescent field and the analyte is enhanced, leading to a decrease in the amplitude sensitivity. There is an obvious peak when the amplitude sensitivity reaches a maximum with the varying of gold film from 35 nm to 40 nm, corresponding to a maximum amplitude sensitivity of 736.67 RIU\(^{-1}\).

This work proposed a three-core sensor in which many vital aspects of performance were improved compared with previous research. Table I shows a comparison of some critical parameters. The effect of the value of the air hole and the gold film variation on the phase-matching coupling intensity between the fundamental mode and the SPP mode is analyzed in the above studies. Therefore, in this paper, the performance of the proposed sensor is an improvement by changing the values and position of air holes and the gold film thickness.

The figure of merit (FOM) plays an important role in evaluating the overall performance of sensors. A larger FOM means a better performing SPR sensor. The FOM can be calculated by Eq. (9):\(^{22}\)

\[ \text{FOM} = \frac{S}{\text{FWHM}}, \]  

(9)

where \(S\), FWHM represent the slope of the polynomial fit curve and the half-maximum at full-width at the resonance peak, respectively. The FOM should be as high as possible to achieve a high-performance sensor. This can be attained with the slope increasing and the FWHM decreasing. Figure 9 shows the variation of FOM and FWHM with the changing of the refractive index from 1.33 to 1.41, respectively. The FOM increases gradually with the rise of the analyte RI, and the corresponding to the maximum FOM of 300.34 1/RIU appears for an RI of 1.4.

4. Conclusions

In this paper, a three-core PCF-SPR sensor has been designed, and compared with previous studies, the position...
and number of air holes have been changed. The spectral sensitivity of the sensor is improved since energy is transferred from the fundamental mode to the SPP mode. The gold film, possessing stable chemical and physical properties, was selected as the plasmonic material to initiate the SPR phenomenon. The gold film and analyte layer are placed on the outside of the PCF-SPR sensor to facilitate processing and manufacturing. After changing the thickness of the gold film, the size of air holes, and the lattice pitch, the performance of the sensor is studied by utilizing the finite element method. The calculation results indicate that the spectral and amplitude sensitivity ranges are from 1700 nm RIU$^{-1}$ to 30600 nm RIU$^{-1}$ and from 181 RIU$^{-1}$ to 633 RIU$^{-1}$, respectively. The proposed sensor demonstrates excellent performance in the analyte RI range of 1.33–1.41, and the maximum FOM is achieved at an RI of 1.4. This result indicates that it possesses great potential in biosensor fields.

Acknowledgments

This research is supported by the National Natural Science Foundation of China (Grant No. 52165066), and Yunnan province basic research program special (Grant No. 202101AT070106).

Fig. 9. (Color online) Variation of the FOM with the analyte RI.