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A Plasmonic Structure of Fano Resonance in the MIM Waveguide with r-Shaped Resonator for Refractive Index Sensor

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Abstract
A plasmonic structure of metal-insulator-metal (MIM) waveguide consisting of a single baffle waveguide and an r-shaped resonator is designed to produce Fano resonance. The finite element method uses the finite element method to analyze the transmission characteristics and magnetic field distributions of the plasmonic waveguide distributions. The simulation results exhibit two Fano resonances that can be achieved by the interference between a continuum state in the baffle waveguide and a discrete state in the r-shaped resonator. The Fano resonances can be simply tuned by changing geometrical parameters of the plasmonic structure. The value variations of geometrical parameters have different effects on sensitivity. Thus, the sensitivity of the plasmonic structure can achieve 1333 nm/RIU, with a figure of merit of 5876. The results of the designed plasmonic structure offer high sensitivity and nano-scale integration, which are beneficial to refractive index sensors, photonic devices at the chip nano-sensors, and biosensors applications.
Keywords: Surface plasmon polaritons; Fano resonance; r-shaped resonator; Refractive index sensor

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**Introduction**

Surface plasmon polaritons (SPPs), which originate from the interaction of incident photons and free electrons on the metal surface, propagate along with the metal-dielectric interface and have the potential to overcome the light diffraction limit, localization of light in subwavelength, and high level of integration capability [1–3]. SPPs have applications in optical devices such as switches [4, 5], sensors [6–9], integrated photonic devices [10], demultiplexers [11], and filters [12, 13]. One of the greatly pledged waveguide structures is the metal-insulator-metal (MIM) waveguide, which has excesses such as low bending loss, simple structure, long propagation distance, deep sub-wavelength confinements, and easy integration [14–18]. Fano resonance is a fundamental resonance phenomenon excited by the interference between a continuum state and a discrete state and typically has sharp resonance peaks and asymmetrical line shapes [19, 20]. Fano resonance can be applied in lasers, slow light devices, and switches [21, 22]. The research developments in Fano resonance based on the MIM waveguide structures have been widely studied and applied to sensors. By way of instance, Wang et al. studied the Fano resonances in MIM waveguide with a baffle and a circular split-ring resonator cavity, and they discussed the refractive index nanosensor with the maximum sensitivity of 1114.3 nm/RIU and a figure of merit of 55.71 [18]. Chen et al. designed a MIM waveguide composed of a circular split-ring resonance cavity and a double symmetric rectangular stub waveguide to generate Fano resonance, and the sensitivity was up to 1180 nm/RIU, and the FOM was 5585.3 [23]. Liu et al. proposed the MIM waveguide structure consisting of a side-coupled rectangular cavity, a rightward opening semi-ring cavity, and a bus waveguide with a silver-air-silver barrier to realize Fano resonances and the sensitivity reached 1550.38 nm/RIU [24].

This paper designs the plasmonic structure of the MIM waveguide consisting of a baffle waveguide and an r-shaped resonator. The transmission characteristics and magnetic field distributions of the plasmonic structure are investigated using the finite element method (FEM). Two Fano resonances result from the interaction between a continuum state in the baffle waveguide and a discrete state in the r-shaped resonator. Then the effects of the geometrical parameters of the plasmonic structure on the Fano resonances are investigated. High sensitivity and figure of merit (FOM) can be achieved by optimizing this structure's parameters.
Structure Model

The plasmonic structure of the MIM waveguide consists of a single baffle waveguide and an r-shaped resonator is schematically designed in Fig. 1. The r-shaped resonator is formed of a rectangular resonator and a quarter-ring resonator. The width \( W \) of the bus waveguide and r-shaped resonator is set at 50 nm to assure that only the fundamental transverse magnetic mode (TM\(_0\)) mode exists in the MIM waveguide [25]. The width of the baffle is \( S \), the coupling distance between the bus waveguide and the r-shaped resonator is \( g \), the height of the rectangular resonator is \( H \), and the effective radius of the quarter-ring resonator is defined as \( R'=(R+R_0)/2 \), where \( R \) and \( R_0 \) are the outer and inner radii of the quarter-ring resonator.

Fig. 1  The schematic and geometrical parameters of the designed plasmonic structure

In Fig. 1, the blue and the white areas denote silver and air, respectively. Usually, the relative dielectric constant of air is \( \varepsilon_{in}=1 \), and the relative dielectric constant of silver is characterized by the Debye-Drude model [26]:

\[
\varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2+i\gamma},
\]

(1)

where \( \varepsilon_\infty=3.7 \) is the dielectric constant at infinite frequency, \( \omega \) is the angular frequency of incident light in vacuum, \( \omega_p=1.38\times10^{16} \) Hz is the bulk plasma frequency of free conduction electrons, and \( \gamma=2.73\times10^{13} \) Hz is the electron collision frequency.

According to the standing wave theoretic, constructive interference should become when the resonance condition is satisfied: \( 4\pi Re(n_{eff})l_1/\lambda + \phi = 2m\pi, m = 1, 2, 3, \ldots \) [27]. Thus, the resonance wavelength can be derived as [28, 29]:

\[
\text{resonance wavelength} = \frac{4\pi Re(n_{eff})l_1}{2m\pi}.
\]
\[ \lambda = \frac{2Re(n_{\text{eff}})l_1}{m - \phi/2\pi}, \quad m = 1, 2, 3, \ldots \]  

where \( \phi \) is the phase shift introduced by the reflection in the resonance resonator, \( l_1 \) is the length of the resonator, \( m \) is the resonant mode order, and \( Re(n_{\text{eff}}) \) is the real part of the effective index \( n_{\text{eff}} \).

The two-dimensional finite element method (FEM) is used to analyze the transmission characteristics of the plasmonic structure. We set the perfect matching layers (PMLs) at the top and bottom of the plasmonic structure to absorb the escaping waves. Light is inputted from Port 1 and then outputted from Port 2. Therefore, the transmittance is expressed as \( T = |S_{21}|^2 \), where \( S_{21} \) is the transmission coefficient from Port 1 to Port 2 [30].

**Results and Discussions**

In this part, Fig. 2 shows the transmission spectra of the single baffle waveguide, the single r-shaped resonator, and the entire structure that are numerically calculated to investigate the optical properties of the designed structure. The geometrical parameters of the plasmonic structure are set as \( R=200 \) nm, \( R_0=150 \) nm, \( H=300 \) nm, \( S=10 \) nm, and \( g=10 \) nm. In Fig. 2, the baffle waveguide produces a continuum state, as indicated by the black line. Meanwhile, the r-shaped resonator coupled with the bus waveguide without the baffle produces discrete states and is marked with two symmetric Lorentzian shapes at 725 nm and 1275 nm, as described in the red line. As a result, two Fano resonances are obtained by the interference between the continuum state and the discrete state, shown by the blue line in Fig. 2. To simplify the discussion, we name the left Fano resonance as FR\(_1\) and the right Fano resonance as FR\(_2\). In order to further investigate the two Fano resonances, the magnetic field intensity distributions of the plasmonic structure at \( \lambda=720 \) nm (FR\(_1\) peak), 735 nm (FR\(_1\) dip), 1265 nm (FR\(_2\) peak), and 1305 nm (FR\(_2\) dip) are shown in Fig. 3. In Figs. 3a and 3c, the magnetic field intensity distributions at Fano resonance peaks are generated owing to the constructive interference between the continuum state and the discrete state and enhanced transmission of the plasmonic structure. However, at Fano resonance dips are generated owing to
the destructive interference [31]. Thus the energy is centralized in the r-shaped resonator and cannot be transmitted through the structure, as shown in Figs. 3b and 3d.

**Fig. 2** Transmission spectra of the single baffle waveguide (black line), the single r-shaped resonator (red line), and the entire structure (blue line)

**Fig. 3** Magnetic field intensity distributions of the plasmonic structure at a \( \lambda=720 \text{ nm} \) (FR\(_1\) peak), b \( \lambda=735 \text{ nm} \) (FR\(_1\) dip), c \( \lambda=1265 \text{ nm} \) (FR\(_2\) peak), and d \( \lambda=1305 \text{ nm} \) (FR\(_2\) dip)

The transmission characteristics of the plasmonic structure can be tuned by varying the parameters. We investigate the effects of the coupling distance \( g \) and the baffle width \( S \) on the Fano resonances of the plasmonic structure. Fig. 4a describes the transmission spectra of plasmonic structure with different coupling distances \( g \), in which \( g \) is enhanced from 5 nm to 20 nm with an interval of 5 nm, and other parameters are set as \( R=200 \text{ nm} \), \( R_0=150 \text{ nm} \), \( H=300 \text{ nm} \), and \( S=10 \text{ nm} \). The increasing values of \( g \) produce considerable blueshifts of the two Fano resonance wavelengths. The transmission of the Fano resonances gradually decreases when the value of \( g \) increases because the further the r-shaped resonator is from the baffle waveguide, the weaker the coupling strength. Fano resonance wavelength and different values of \( g \) have linear relationships, as shown in Fig. 4b. It can be seen that FR\(_1\) and FR\(_2\) make blueshifts from 710 nm to 730 nm and from 1320 nm to 1235 nm, respectively. Fig. 5a exhibits the transmission spectra of the plasmonic structure with different baffle widths \( S \), increasing \( S \) from 5 nm to 20 nm with an interval of 5 nm, and other parameters are set as \( R=200 \text{ nm} \), \( R_0=150 \text{ nm} \), \( H=300 \text{ nm} \), and \( g=10 \text{ nm} \). With the increasing values of \( S \), the Fano resonances appear closer to Lorentz resonance, indicating the line shapes becoming sharper and more symmetric. In Fig. 5b, the increasing values of \( S \) hardly change the Fano resonance wavelengths. The resonance wavelengths of FR\(_1\) and FR\(_2\) change slightly from 715 nm to 720 nm and from 1260 nm to 1265 nm, respectively.

**Fig. 4** a Transmission spectra of the plasmonic structure with different coupling distances \( g \), b Relationships between Fano resonance wavelengths and different values of \( g \)
Furthermore, the height of rectangular resonator $H$ and the outer radius of the quarter-ring resonator $R$ are varied. Fig. 6a describes the transmission spectra of the plasmonic structure with different heights of the rectangular resonator $H$, which $H$ is enhanced from 290 nm to 320 nm with an interval of 10 nm, and other parameters are set as $R=200$ nm, $R_0=150$ nm, $S=10$ nm, and $g=10$ nm. The increasing value of $H$ produces significant redshifts of the Fano resonance wavelengths, and the shift of FR$_2$ is more significant than that of FR$_1$. Relationships between the Fano resonance wavelengths and different values of $H$ have good linearity, which is indicated by significant redshifts on wavelength peaks of FR$_1$ and FR$_2$ from 710 nm to 735 nm and from 1235 nm to 1325 nm, as shown in Fig. 6b. Transmission spectra of the plasmonic structure for different outer radius $R$ of the quarter-ring resonator are shown in Fig. 7a. As the increasing value of $R$, the transmission of FR$_1$ and FR$_2$ gradually decreases, whereas the resonance wavelength of FR$_1$ and FR$_2$ produce obvious redshifts from 700 nm to 755 nm and 1225 nm to 1340 nm shown in Fig. 7b. It is also seen that the shift of FR$_2$ is also more significant than that of FR$_1$.

Next, we investigate the refractive index sensing based on the effects of the refractive index of the r-shaped resonator on the resonance wavelengths. Generally, sensitivity ($S$) and figure of merit (FOM) are crucial parameters for assessing the performances of sensors, which are defined as:

$$S = \frac{\Delta \lambda}{\Delta n},$$  \hspace{1cm} (3)  

$$FOM = \frac{\Delta T}{T \Delta n},$$  \hspace{1cm} (4)
where $\Delta \lambda$ is the resonance wavelength shift, $\Delta n$ is the change of the refractive index, $T$ is the transmittance, and $\Delta T$ is the transmittance change induced by $\Delta n$ at a fixed wavelength [32].

The transmission spectra of the plasmonic structure with different refractive indices are shown in Fig. 8a, wherein the refractive index is enhanced from 1.00 to 1.12 with an interval of 0.03, and the other parameters are set as $R=200$ nm, $R_0=150$ nm, $H=300$ nm, $S=10$ nm, and $g=10$ nm. From Fig. 8a, the Fano resonance wavelengths produce significant redshifts with the refractive index increases. Fig. 8b exhibits the linear relationships between the Fano resonance wavelengths and the refractive index. The good linearity of FR$_1$ and FR$_2$ is of great importance for a high-performance sensor. Thus, the sensitivities of the refractive index sensor are about 667 nm/RIU for FR$_1$, and 1250 nm/RIU for FR$_2$, respectively. Thus, it is known that the sensitivity of FR$_2$ is higher than the sensitivity of FR$_1$.

Moreover, we investigate the effects of the coupling distance $g$, the baffle width $S$, the height of the rectangular resonator $H$, and the outer radius of the quarter-ring resonator $R$ on sensitivity. The surrounding refractive index enhances from 1.00 to 1.12 with an interval of 0.03. Sensitivities of the plasmonic structure on FR$_1$ and FR$_2$ for the different parameters at $g$, $S$, $H$, and $R$ are shown in Fig 9. As observed in Figs. 9a-d, the value variations of $g$, $S$, $H$, and $R$ have different effects on sensitivity. With optimizing geometrical parameters, the maximum sensitivity is 1333 nm/RIU at $R=220$ nm. Fig. 10 describes the FOM of the plasmonic structure with surrounding refractive index varies from 1.00 to 1.12 with an interval of 0.03. From the calculation, the obtained FOM is about 5876. The comparison of the sensitivity and FOM between this paper and some other published papers are presented in Table 1.
To prove that the designed plasmonic structure can be applied for biosensors, we study sensing of chemical and biological parameters such as sucrose concentration in a much more exact and efficient manner due to their ability to detect small changes in refractive index. The reason is that the refractive index has unique characteristics for each material [36]. The plasmonic structure can be used for sucrose concentration sensing. The refractive index is taken by ranging from 1.333 to 1.403 can be gained by varying the sucrose solution concentration [37]. The transmission spectra of the plasmonic structure with different refractive indices of sucrose solution concentrations are shown in Fig. 11a. The refractive index in the r-shaped resonator is enhanced from 1.333 to 1.393 with an interval of 0.02. The refractive index can affect the two Fano resonance wavelengths, exhibiting obvious redshifts. From Fig. 11b, the resonance wavelengths and the refractive index have good linearity relationships. As a result, the sensitivities of FR$_1$ and FR$_2$ are about 675nm/RIU and 1250nm/RIU, respectively. The designed plasmonic structure has a useful application in high-sensitivity nanosensors through the proof of refractive indices of sucrose concentration sensing.
Fig. 11  a  Transmission spectra of the plasmonic structure with the different refractive indices of sucrose solution concentrations, b Relationships between Fano resonance wavelengths and the refractive indices

Conclusions

This paper designs a plasmonic structure of a MIM waveguide consisting of a baffle waveguide and an r-shaped resonator to produce Fano resonance and investigate its Fano transmission characteristics using the Finite Element Method. Two Fano resonances can be produced and tuned by changing the geometrical parameters of the plasmonic structure. The value variations of coupling distance, baffle width, height of the rectangular resonator, and outer radius of the quarter-ring resonator have different effects on the sensitivity. Thus, the maximum sensitivity can achieve 1333 nm/RIU, with a FOM of 5876. In addition, this plasmonic structure also has the ability of sucrose concentration sensing. Based on these results, the designed plasmonic structure has prospective applications in refractive index nanosensors, nano-photonic devices, and biosensors.

Declarations

Funding

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Conflicts of Interest

The authors declare that they have no conflict of interest.

Availability of data and material

Not applicable

Code availability
Author's contributions

Siti Rohimah have contributed to Conceptualization, design, analysis, writing, review, and editing.

He Tian has contributed to Supervision, Funding acquisition, review, and editing manuscript.

Jinfang Wang, Jianfeng Chen, Jina Li, Xing Liu, Jingang Cui, Qiang Xu, and Yu Hao contributed to validating and editing the manuscript. All authors have read and agreed to the published version of the manuscript.

Ethics approval

Not applicable

Consent to participate

Not applicable

Consent to Publish

The manuscript has not been published before and is not being considered for publication elsewhere. All authors have contributed to the manuscript creation and read and approved the final manuscript.
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Figures

Figure 1

The schematic and geometrical parameters of the designed plasmonic structure

Figure 2

Transmission spectra of the single baffle waveguide (black line), the single r-shaped resonator (red line), and the entire structure (blue line)

Figure 3

Magnetic field intensity distributions of the plasmonic structure at a $\lambda=720$ nm (FR$_1$ peak), b $\lambda=735$ nm (FR$_1$ dip), c $\lambda=1265$ nm (FR$_2$ peak), and d $\lambda=1305$ nm (FR$_2$ dip)

Figure 4

a Transmission spectra of the plasmonic structure with different coupling distances $g$, b Relationships between Fano resonance wavelengths and different values of $g$

Figure 5

a Transmission spectra of the plasmonic structure with different baffle widths $S$, b Relationships between Fano resonance wavelengths and different values of $S$
Figure 6

\( a \) Transmission spectra of the plasmonic structure with different heights of rectangular resonator H, \( b \) Relationships between Fano resonance wavelengths and different values of H

Figure 7

\( a \) Transmission spectra of the plasmonic structure with different outer radii R, \( b \) Relationships between Fano resonance wavelengths and different values of R

Figure 8
a Transmission spectra of the plasmonic structure with different refractive indices, b Relationships between Fano resonance wavelengths and different refractive indices

Figure 9

Sensitivities of the plasmonic structure on FR₁ and FR₂ for the different parameters at a the coupling distances g, b the baffle widths S, c the height of rectangular resonator H, and d the outer radius of the quarter-ring resonator R

Figure 10

FOM for different refractive indices

Figure 11

a Transmission spectra of the plasmonic structure with the different refractive indices of sucrose solution concentrations, b Relationships between Fano resonance wavelengths and the refractive indices