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

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27 **Keywords:** Surface plasmon polaritons; Fano resonance; r-shaped resonator; Refractive index
28 sensor

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55 **Introduction**

56 Surface plasmon polaritons (SPPs), which originate from the interaction of incident photons and
57 free electrons on the metal surface, propagate along with the metal-dielectric interface and have
58 the potential to overcome the light diffraction limit, localization of light in subwavelength, and
59 high level of integration capability [1–3]. SPPs have applications in optical devices such as
60 switches [4, 5], sensors [6–9], integrated photonic devices [10], demultiplexers [11], and filters
61 [12, 13]. One of the greatly pledging waveguide structures is the metal-insulator-metal (MIM)
62 waveguide, which has excesses such as low bending loss, simple structure, long propagation
63 distance, deep sub-wavelength confinements, and easy integration [14–18]. Fano resonance is a
64 fundamental resonance phenomenon excited by the interference between a continuum state and a
65 discrete state and typically has sharp resonance peaks and asymmetrical line shapes [19, 20]. Fano
66 resonance can be applied in lasers, slow light devices, and switches [21, 22]. The research
67 developments in Fano resonance based on the MIM waveguide structures have been widely
68 studied and applied to sensors. By way of instance, Wang et al. studied the Fano resonances in
69 MIM waveguide with a baffle and a circular split-ring resonator cavity, and they discussed the
70 refractive index nanosensor with the maximum sensitivity of 1114.3 nm/RIU and a figure of merit
71 of 55.71 [18]. Chen et al. designed a MIM waveguide composed of a circular split-ring resonance
72 cavity and a double symmetric rectangular stub waveguide to generate Fano resonance, and the
73 sensitivity was up to 1180 nm/RIU, and the FOM was 5585.3 [23]. Liu et al. proposed the MIM
74 waveguide structure consisting of a side-coupled rectangular cavity, a rightward opening semi-ring
75 cavity, and a bus waveguide with a silver-air-silver barrier to realize Fano resonances and the
76 sensitivity reached 1550.38 nm/RIU [24].

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

84

85 **Structure Model**

86 The plasmonic structure of the MIM waveguide consists of a single baffle waveguide and an r-
 87 shaped resonator is schematically designed in Fig. 1. The r-shaped resonator is formed of a
 88 rectangular resonator and a quarter-ring resonator. The width W of the bus waveguide and r-shaped
 89 resonator is set at 50 nm to assure that only the fundamental transverse magnetic mode (TM_0)
 90 mode exists in the MIM waveguide [25]. The width of the baffle is S , the coupling distance
 91 between the bus waveguide and the r-shaped resonator is g , the height of the rectangular resonator
 92 is H , and the effective radius of the quarter-ring resonator is defined as $R'=(R+R_0)/2$, where R and R_0
 93 are the outer and inner radii of the quarter-ring resonator.

94

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

96

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

100

$$101 \quad \varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}, \quad (1)$$

102

103 where $\varepsilon_\infty=3.7$ is the dielectric constant at infinite frequency, ω is the angular frequency of incident
 104 light in vacuum, $\omega_p=1.38 \times 10^{16}$ Hz is the bulk plasma frequency of free conduction electrons, and
 105 $\gamma=2.73 \times 10^{13}$ Hz is the electron collision frequency

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

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$$\lambda = \frac{2\text{Re}(n_{eff})l_1}{m - \phi/2\pi}, \quad m = 1, 2, 3, \dots \quad (2)$$

where ϕ 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 $\text{Re}(n_{eff})$ is the real part of the effective index n_{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** $\lambda=720$ nm (FR₁ peak), **b** $\lambda=735$ nm (FR₁ dip), **c** $\lambda=1265$ nm (FR₂ peak), and **d** $\lambda=1305$ nm (FR₂ 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 $R=200$ nm, $R_0=150$ nm, $H=300$ nm, and $S=10$ 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 FR₁ and FR₂ 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 $R=200$ nm, $R_0=150$ nm, $H=300$ nm, and $g=10$ 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 FR₁ and FR₂ 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

Fig. 5 a Transmission spectra of the plasmonic structure with different baffle widths S, **b** Relationships between Fano resonance wavelengths and different values of S

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, R₀=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 FR₂ is more significant than that of FR₁. Relationships between the Fano resonance wavelengths and different values of H have good linearity, which is indicated by significant redshifts on wavelength peaks of FR₁ and FR₂ 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 FR₁ and FR₂ gradually decreases, whereas the resonance wavelength of FR₁ and FR₂ 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 FR₂ is also more significant than that of FR₁.

Fig. 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

Fig. 7 a Transmission spectra of the plasmonic structure with different outer radii R, **b** Relationships between Fano resonance wavelengths and different values of R

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:

$$S = \frac{\Delta\lambda}{\Delta n}, \quad (3)$$

$$FOM = \frac{\Delta T}{T\Delta n}, \quad (4)$$

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195 where $\Delta\lambda$ is the resonance wavelength shift, Δn is the change of the refractive index, T is the
196 transmittance, and ΔT is the transmittance change induced by Δn at a fixed wavelength [32].

197 The transmission spectra of the plasmonic structure with different refractive indices are shown
198 in Fig. 8a, wherein the refractive index is enhanced from 1.00 to 1.12 with an interval of 0.03, and
199 the other parameters are set as $R=200$ nm, $R_0=150$ nm, $H=300$ nm, $S=10$ nm, and $g=10$ nm. From
200 Fig. 8a, the Fano resonance wavelengths produce significant redshifts with the refractive index
201 increases. Fig. 8b exhibits the linear relationships between the Fano resonance wavelengths and
202 the refractive index. The good linearity of FR_1 and FR_2 is of great importance for a high-
203 performance sensor. Thus, the sensitivities of the refractive index sensor are about 667 nm/RIU for
204 FR_1 , and 1250 nm/RIU for FR_2 , respectively. Thus, it is known that the sensitivity of FR_2 is higher
205 than the sensitivity of FR_1 .

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207 **Fig. 8** a Transmission spectra of the plasmonic structure with different refractive indices, b Relationships
208 between Fano resonance wavelengths and different refractive indices

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210 Moreover, we investigate the effects of the coupling distance g , the baffle width S , the height
211 of the rectangular resonator H , and the outer radius of the quarter-ring resonator R on sensitivity.
212 The surrounding refractive index enhances from 1.00 to 1.12 with an interval of 0.03. Sensitivities
213 of the plasmonic structure on FR_1 and FR_2 for the different parameters at g , S , H , and R are shown
214 in Fig 9. As observed in Figs. 9a-d, the value variations of g , S , H , and R have different effects on
215 sensitivity. With optimizing geometrical parameters, the maximum sensitivity is 1333 nm/RIU at
216 $R=220$ nm. Fig. 10 describes the FOM of the plasmonic structure with surrounding refractive
217 index varies from 1.00 to 1.12 with an interval of 0.03. From the calculation, the obtained FOM is
218 about 5876. The comparison of the sensitivity and FOM between this paper and some other
219 published papers are presented in Table 1.

220

Fig. 9 Sensitivities of the plasmonic structure on FR_1 and FR_2 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

Fig. 10 FOM for different refractive indices

Table 1 Comparison the sensitivity and FOM with some other published papers

Structure	Sensitivity	FOM	Reference
MIM waveguide coupled with rectangular and ring resonators.	1125 nm/RIU	75	[33]
MIM waveguide coupled tangent-ring resonators.	880 nm/RIU	964	[34]
MIM waveguide with a baffle and a circular split-ring resonator cavity.	1114.3 nm/RIU	55.71	[18]
MIM waveguide structures consist of a cross-shaped cavity and baffle.	1100 nm/RIU	9.95×10^4	[35]
MIM waveguide system with asymmetric X-shaped resonant cavity.	1303 nm/RIU	3113	[10]
MIM waveguide with an r-shaped resonator.	1333 nm/RIU	5876	This paper

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-phonic devices, and biosensors.

Declarations

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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

271 Not applicable

272

273 **Author's contributions**

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

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

276 Jinfang Wang, Jianfeng Chen, Jina Li, Xing Liu, Jingang Cui, Qiang Xu, and Yu Hao contributed

277 to validating and editing the manuscript. All authors have read and agreed to the published version

278 of the manuscript.

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280 **Ethics approval**

281 Not applicable

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283 **Concent to participle**

284 Not applicable

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286 **Consent to Publish**

287 The manuscript has not been published before and is not being considered for publication

288 elsewhere. All authors have contributed to the manuscript creation and read and approved the final

289 manuscript.

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384

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 (FR₁ peak), **b** $\lambda=735$ nm (FR₁ dip), **c** $\lambda=1265$ nm (FR₂ peak), and **d** $\lambda=1305$ nm (FR₂ 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 FR_1 and FR_2 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