Multiple-Mode Bowtie Cavities for Refractive Index and Glucose Sensors Working in Visible and Near-Infrared Wavelength Range

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Multiple-mode bowtie cavities for refractive index and glucose sensors working in visible and near-infrared wavelength range

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Abstract

A multiple-mode metal-insulator-metal plasmonic sensor with four coupled bowtie resonators containing two pair of silver baffles is numerically investigated using the finite element method and verified by the temporal coupled-mode theory. The proposed structure can function as the plasmonic refractive index and glucose sensors working in visible and near-infrared wavelength range. Simulation results show that introducing the silver baffles in bowtie cavities can modify the plasmon resonance modes and give a tunable way to enhance the sensitivity and figure of merit. The highest sensitivity (S) can reach $S=1500.00$, 1400.00 , and 1100.00 nm/RIU and the high figure of merit (FOM) of 50.00 , 46.67 , and 36.67 RIU⁻¹ from mode 1 to mode 3. The sensitivity obtained from three modes with operating wavelengths in visible and near-infrared simultaneously exceeds 1100.00 nm/RIU along with remarkably high FOM, which are not attainable from other reported literature. The proposed structure can realize multi-mode and shows impressive practical prospects that can be applied for integrated optics circuits (IOCs) and other nanophotonics devices.

Keywords: metal-insulator-metal, plasmonic sensor, bowtie resonator, silver baffle, finite element method

1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic (EM) wave coupled to the collective oscillations of free electrons on the metal surface and propagate between the metal-dielectric interface[1-8]. Plasmonic metal-insulator-metal (MIM) waveguide, one of the SPPs waveguide schemes, has received fascinated attentions because of its attractive features, such as bonding strongly localized surface plasmon resonance (SPR), overcoming diffraction limit in conventional optics, low propagation loss, simple manufacturing steps, and compatible integration optics circuits (IOCs)[5, 9-15]. Therefore, a variety of functional plasmonic components utilizing MIM waveguides have been designed experimentally and demonstrated theoretically, such as sensors[16], all-optical switches[17], splitters[18], modulators[19], demultiplexers[20], filters[21], interferometers[22], etc. A plasmonic MIM waveguide consists of the cavities (i.e., resonators) and the bus waveguides[7, 11, 17, 20, 23-31]. The MIM waveguides' cavities greatly impact the SPPs modes and resonance conditions because they can support an excellent mechanism for achieving wavelength and sensing selective. In other words, the SPR, cavity plasmon resonance (CPR), and gap surface plasmon resonance (GPR) properties of the plasmonic cavity-waveguide system pick out the specific operating wavelength which required exactly[1, 9, 32-37].

In SPPs sensors, the resonance modes generate in the bus waveguide coupled with the cavity under satisfying the Fabry-Pérot resonance condition. The SPPs wave can be reflected back and forth in the cavity, which is highly sensitive to the refractive index's change in the bus waveguide and the cavity's geometrical shape. Resonators (or cavities) with different structural configurations undergo a potential role in generating a better light-matter interaction in the MIM-cavity waveguide system[38-40]. Recently, several MIM waveguide with different shape of cavities has been proposed and investigated for the plasmonic sensor, such as rectangular/circular ring cavity[41], tooth-shaped cavity[42], trapezoid cavity[43], ring cavity with metal baffles[44], asymmetric double

elliptic cylinders[45], Bragg grating cavity[46], fillet cavity[47], metallic nanorods in hexagonal configuration[48], stub coupled with a square cavity[49] and so forth.

One of the cavity schemes is the bowtie (BT) shaped resonator, which has an excellent light-matter coupling between the incident EM wave and nanostructures. For example, BT nanoantennas[50-54], which possesses the advantage of hybrid SPR, CPR and GPR modes in a plasmonic nanostructure system, and is less discussed in the plasmonic MIM-cavity system. This paper numerically investigated the optical properties of a multi-mode waveguide configuration consisting of two MIM bus waveguides connected with the centrally coupled BT cavities containing the silver (Ag) baffles. The finite element method (FEM) systematically simulates BT cavities' resonance modes in the proposed structure. We focus on the flexible optical characteristics of this plasmonic sensor structure for sensing applications. The resonance wavelength-shift features of resonant modes in the BT-shaped cavity inspected by the temporal coupled-mode theory are verified[55]. The calculated transmittance spectra have also been investigated by analyzing the magnetic and electric field's spatial distributions at the resonant wavelengths. The sensitivity analysis of the SPP modes is calculated for two cavity schemes, i.e., the BT cavities excluding and including the Ag baffles. The influence of the geometrical dimension and coupling distance corresponding to the transmittance features was also calculated. The effect of the structural parameters' variation on its sensing characteristics, refractive index sensitivity, figure of merit and quality factor are calculated. The proposed device sensor can achieve multiple modes working in visible and infrared and could be used as practical nanophotonic devices that functionally perform as chemical sensors and biosensors. This study suggests a promising design strategy and improves the plasmonic sensors on the nanoscale and examines their performance before realizing to time-consuming and expensive IOCs construction.

2. Structure and basics

Figure 1 shows the schematic plot of the proposed plasmonic refractive index sensor that consists of two bus waveguides (width w) and four coupled BT cavities (bottom length $L=6w$ and height $H=5w$) containing two pairs of silver baffles in the BT cavities. We termed the Ag baffles as pair 1 in x -direction and pair 2 in the y -direction. The length and width of the bigger Ag baffles in pair 1 and pair 2 are $3w$ and $2w$, while the length and width of the smaller Ag baffles in pair 1 and pair 2 are set the same value of w . The center to center distance of bigger and smaller Ag baffles is fixed as $2w$. The gap distance between the coupled cavities and the bus waveguides is set as g , while the gap distance among four BT cavities is d . Simulations were performed by a two-dimensional (2-D) FEM using COMSOL Multiphysics [34, 56] with perfectly matched layer absorbing boundary conditions for absorbing outgoing EM waves surrounding the input and output ends. Besides, scattering boundary conditions (SBC) are used at the FEM simulation window's outer edges. In COMSOL simulations, the proposed structure's subdomains are divided into triangular mesh elements with a fine mesh grid size for the MIM-cavity waveguide geometries. This setting permits us to achieve accurate calculation results within the available computer resources.

A TM-polarized incident EM wave is coupled with the fundamental SPP mode[57] into the bus waveguide's input end. The transmittance (T) can be described as $T = (S_{21})^2$, where S_{21} is the transmittance. In a real situation, the incident EM wave can be coupled into the bus waveguide by photonic crystal fiber (PCF)[58, 59]. Confocal Raman Microscopy can measure the output EM wave. The frequency-dependent complex relative permittivity ϵ_m of silver can calculate using the Drude model as[60].

$$\epsilon_m(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega\gamma} \quad (1)$$

Where ϵ_∞ (the dielectric constant at the infinite angular frequency)=3.7, ω is the angular frequency of incident light, ω_p (bulk plasma frequency)=9.10 eV=1.38×10¹⁶ rad/s, and γ (the electron collision frequency concerning loss)=18 meV =2.7×10¹³ rad/s. The resonance

wavelength (λ_{res}) can obtain from the temporal coupled-mode theory[61]. When the SPPs propagate through the proposed structure, they will be confined in the cavity to produce an oscillation. The cavity including Ag baffles can play as a Fabry-Pérot cavities. The gathered phase change per cycle in the cavities can be expressed as $\Delta\phi=4\pi n_{\text{eff}}\ell_{\text{eff}}/\lambda+\phi$, where n_{eff} is the effective refractive index of the SPPs, ℓ_{eff} is the effective lengths of cavity, ϕ is the phase shift generated from the reflection at the metal-dielectric interface in the cavity, respectively. If $\Delta\phi=2\pi j$ (j is an integer), the resonance wavelength λ_{res} of the cavity can be described by temporal coupled-mode theory.

$$\lambda_{\text{res}} = \frac{2\ell_{\text{eff}}\text{Re}(n_{\text{eff}})}{j - \frac{\phi}{2\pi}} \quad (j = 1, 2, 3 \dots) \quad (2)$$

$\text{Re}(n_{\text{eff}})$ represents the real part of the effective refractive index obtained from the dispersion equation[62].

Fig. 1 Schematic diagram of the proposed plasmonic refractive index sensor consisting of two bus waveguides (width w), four coupled BT cavities, including two pairs of Ag baffles in the BT cavities.

Furthermore, sensitivity (S) and figure of merit (FOM) are penitential characteristics extensively used to evaluate the sensor performance. The definition of sensitivity is

$S=\Delta\lambda/\Delta n$ nanometer per refractive index (nm/RIU), where $\Delta\lambda$ is the shift of the resonant wavelength of transmittance, λ_{res} is the resonant wavelength at transmittance peak, and Δn is the change in the refractive index of the medium in the space of bus waveguides and BT cavities. The figure of merit (FOM) and quality factor (Q factor) can be defined as S/FWHM and $\lambda_{\text{res}}/\text{FWHM}$, respectively, where FWHM is the full width at half-maximum of the transmittance peak.

The fabrication of the proposed structure can use E-beam lithography and chemical etching. First, we can deposit Ag's thin layer on a silica substrate utilizing E-beam lithography, which can inscribe desired patterns with sub-10 nm resolution[63, 64]. To fabricate MIM bus waveguides, we can remove Ag metal's unwanted parts using chemical etching [27, 65-67].

3. Simulation results and discussions

First, we compare the transmittance spectrum of the SPPs mode for two cavities configurations, i.e., the BT cavities excluding and including the Ag baffles as shown in Fig. 2. The structural parameters and the related sizes are denoted in Fig. 1. The initial values w , g , and d are 50 nm, 10 nm, 10 nm, and air ($n=1$) is used as a medium in the bus waveguides and BT cavities. Note that bus waveguide width (w) is set as 50 nm to ensure that the fundamental mode can be excited in the bus waveguide. The proposed plasmonic sensor can function as band-pass and band-stop filters, limiting and prohibiting propagating specific incident EM wave wavelengths. An apparent discrepancy after the Ag baffles are included in the plasmonic BT-cavity waveguide system, and the different resonance modes formed in the BT cavities can explain this difference. In Fig. 2, the two cases' transmittance spectrum shows discrete peaks and behaves as a multiple-mode plasmonic filter, leading to the EM wave can be transmitted at the resonance wavelength (λ_{res}). The transmittance reached a peak value when the SPP modes satisfied the resonance condition in the BT cavities. There are four transmittance peaks found at

λ_{res} =823 nm, 731 nm, 609 nm and 494 nm (denoted by mode 1 to mode 4, hereafter) for the case excluding Ag baffles and four modes at λ_{res} =1121 nm, 888 nm, 654 nm and 525 nm for the case including Ag baffles, respectively. It is evident that the transmittance peaks of the case excluding Ag baffle are weaker than the case including Ag baffles, i.e., the case including Ag baffles reveals better light-matter interaction than the case excluding Ag baffle. Besides, the working wavelengths of the case excluding Ag baffle exist in the visible wavelength range.

In contrast, the Ag baffle case's working wavelengths can be reshifted to visible and infrared. These results can ascribe to the different degree of resonant modes that occurred in the BT cavities. It can be interpreted from Eq. (2) that λ_{res} is closely related to n_{eff} and ℓ_{eff} of the BT cavities. Ag baffles in the BT cavities can generate a larger n_{eff} and increase λ_{res} (i.e., redshift).

Fig. 2 Transmittance spectra of the proposed plasmonic sensor excluding (black color) and with (red color) Ag baffles in the BT cavities.

To explain the physical mechanism, Fig. 3 and Fig. 4 show the steady-state of the magnetic field ($|H|$) and electric field ($|E|$) distributions of the case excluding Ag baffles (Figs. 3(a)-(d) and Figs. 4(a)-(d)) and including Ag baffles (Figs. 3(e)-(h) and Figs. 4(e)-(h)) in the BT cavities at corresponding λ_{res} from mode 1 to mode 4, respectively. The BT cavities can regard as the Fabry-Pérot cavities, i.e., optical waves can pass through the optical cavities only when resonating with it. The inclusion of Ag baffles in BT cavities allows the strong confinement of SPPs formed among the gaps of Ag baffles and BT's sharp tips, as shown in Fig. 3 and Fig. 4. In Fig. 3, the $|H|$ field intensities show strong field confinement inside the BT cavities, a magnetic dipole resonance feature. In contrast,

the $|E|$ field intensities can enhance at the edge and sharp surface of the Ag nanometals, showing a signature of electric field dipole resonance (see Fig. 4). It is worth noting that the $|H|$ and $|E|$ field profiles offer different distribution patterns in the BT cavities depending on the different incident wavelengths at λ_{res} . It is evident from Fig. 3 and Fig. 4 that the SPPs wave is coupled to the BT cavities well at λ_{res} , which can form the standing-wave patterns between the bus waveguide and the BT cavities. The $|E|$ profiles as shown in Figs. 4 (a)-(h) exhibit standing wave-like EM wave patterns on the surface of Ag baffles and Ag wall of BT cavities with a remarkably field enhancement since the hybridization of SPR, GPR, and CPR[68, 69]. Ag baffles' case facilitates the stronger SPPs mode confinement on the metal surface than the case excluding Ag baffles due to the GPR. The gap regions formed in BT cavities are among the Ag baffles and the wall of BT cavities. High sensitive SPPs modes can confine among the gap. As shown in Figs. 4 (a)-(h), the electric field intensity can reach its maximum value at the gap regions and sharp edges. SPPs modes in the BT cavities have substantial field enhancements and can constraint the EM waves to the nanometer scale. This critical observation implies that the gap and cavity plasmon resonances can significantly contribute to the field enhancement in the proposed plasmonic BT cavities system including the Ag baffles.

Fig. 3 Truncate views of magnetic field intensity ($|H|$) of (a)-(d) the case excluding Ag baffles and (e)-(h) including Ag baffles in the BT cavities at corresponding resonance wavelengths from mode 1 to mode 4, respectively.

Fig. 4 Truncate views of electric field intensity ($|E|$) of (a)-(d) the case excluding Ag

baffles and (e)-(h) including Ag baffles in the BT cavities at corresponding resonance wavelengths from mode 1 to mode 4, respectively.

Fig. 3 and Fig. 4 provide high confinement of $|H|$ and $|E|$ field distributions of SPPs mode in the narrow region between BT cavities and Ag baffles. Consequently, the n_{eff} of the mode increases and is highly responsive to the surrounding medium. When the proposal plasmonic sensor system includes the testing medium, the n_{eff} of the bus waveguide and BT cavities is changed. Consequently, λ_{res} experiences a redshift. SPPs modes are highly sensitive to the variation of the surrounding refractive index, which will change λ_{res} , intensity, or phase. Based on Fig. 2, we can use the proposed structure as a refractive index sensor. We can fill the testing medium in the bus waveguides and BT cavities with the different refractive index. Figures 5 (a) and (b) compare the proposed plasmonic sensors' transmittance spectra excluding and including Ag baffles in the BT cavities. The refractive index of the test medium, n , is set to be 1.01, 1.03, 1.13, and 1.15, respectively, and other ranges of refractive indices values have the same trend of transmittance spectrum. The other structural parameters, w , and g are 50 nm and 10 nm, respectively. As seen in Fig. 5, both cases' transmission peaks redshift with the increasing refractive index due to the rising n_{eff} in the BT cavities, giving a linear relationship between wavelength shift with n of the medium being tested. This result is in good agreement with Eq. (2). The increasing redshift is because of the enhancing EM wave in a BT cavity, mostly interacting with the refractive index change. Since there is a hybridization of the SPR, GPR, and CPR modes in the BT-cavity waveguide system, a little refractive index change (Δn) leads to a remarkable λ_{res} shift.

Fig. 5 Transmittance spectra of the proposed plasmonic sensors (a) excluding and (b) including Ag baffles in the BT cavities. The test medium's refractive index, n , is set as 1.01, 1.03, 1.13, and 1.15, respectively. The other structural parameters, w , and g , are 50 nm and 10 nm, respectively.

Figure 6 shows the calculated resonance wavelength (λ_{res}) versus the refractive index (n) of the cases including Ag baffles in the BT cavities. As seen, there is a linear relationship between λ_{res} and n . The λ_{res} increases linearly by varying the refractive index, and we can see an apparent redshift. A small variation of n can lead to an enormous shift in λ_{res} . A redshift of λ_{res} with the increase in the value of n is most significant for mode 1 compared to other modes. Consequently, the value of n can obtain from λ_{res} based on its linear relationship obtained from Eq. (2). This result demonstrates the characteristics of the sensing function of our proposed structure as a refractive index sensor. We can summarize the S and FOM of the case excluding and including Ag baffles from mode 1 to 4 in table 1.

Table 1: The S and FOM of the case excluding Ag baffle and the case including Ag baffles in BT cavities from mode 1 to mode 4.

			Mode 1	Mode 2	Mode 3	Mode 4
excluding baffles	Ag	S (nm/RIU)	700.00	700.00	600.00	400.00
		FOM (RIU ⁻¹)	23.33	70.00	60.00	40.00
Including baffles	Ag	S (nm/RIU)	1100.00	900.00	600.00	500.00
		FOM (RIU ⁻¹)	27.25	90.00	60.00	50.00

Compared to the case excluding Ag baffle, Ag baffles' existence in the BT cavities generates an increase of device's sensitivity by 57.14% for mode 1 and 28.57% for mode 2, correspondingly. Note that a very sharp transmittance peak (i.e., high resolution or narrow FWHM) can be seen in Fig. 4(b), yielding a high Q factor. The calculated average Q factors are 28.02, 98.67, 109.00, and 105.00 in modes 1 to 4 of the case including Ag

baffles. The proposed structure with the features of high sensitivity, FOM, and Q factors can transfer the desirable wavelength-noise-limited performance, which is attributed to the sharp transmittance peaks and results in acceptable spectral resolution.

Fig. 6 Calculated resonance wavelength (λ_{res}) from mode 1 to mode 4 for the cases including Ag baffles versus refractive index (n).

The transmittance features of the proposed plasmonic sensor system can be affected by its structural parameters by changing the size of structural parameters, leading to a variation of ℓ_{eff} and n_{eff} . The resonance wavelength will be changed to keep the phase match condition if the resonant cavity's environment is varied[70]. Next, we will inspect the impact of structural parameters on sensitivity and figure of merit from mode 1 to mode 3, summarized in Tables 2, 3, 4, and 5, respectively. As observed in Table 2, 3, and 4, the influence of coupling distance between bus waveguides and BT cavities (g), bottom

length of the BT cavity (L), and coupling distance among each BT cavity (d) appears to have little influence on sensitivity performance. At the same time, the FOM exhibits a different value because of the different FWHM. It is worth noting that the variation of Ag baffle's size (i.e., x -direction width of pair 1 and y -direction width of pair 2) can significantly improve the sensitivity when their size increases from 20 nm to 100 nm. The Ag baffles's size plays a potential role in enhancing EM waves in the narrow region of the BT cavities. Simulation results (not shown) reveal that λ_{res} redshifts with the increased baffle's size, which results in a higher sensitivity to the variation of baffle's size than the other structural parameters (i.e., g , L and d). In Table 5, The highest sensitivity can achieve $S=1500.00$, 1400.00 , and 1100.00 nm/RIU along with the high FOM= 50.00 , 46.67 , and 36.67 RIU⁻¹ from mode 1 to mode 3, respectively. These results offer the highest mode sensitivity since the large shift of λ_{res} when exposed to a little variation in the medium refractive index. The sensitivity obtained from mode 1 to mode 3 can simultaneously reach above 1100.00 nm/RIU in the wavelength range of visible and near-infrared that is considerably greater than that of previously reported sensor designs. Note that a suitable modifying of the Ag baffle's size in the BT cavities can dramatically increase the sensitivity and FOM of the proposed structure excluding increasing the BT cavity size. Table 6 summarizes the comparisons among several published sensitivity and FOM values for diverse MIM-based sensor designs. The high quantity of sensitivity attained in the proposed structure gives a path toward optical on-chip sensors.

Table 2 The influence of coupling distance between bus waveguides and BT cavities (g) on sensitivity and figure of merit from mode 1 to mode 3. The other structural parameters referred to Fig. 1 are set as $w=50$ nm and $d=10$ nm, respectively.

	g (nm)	5	8	10	11	12
Mode 1	S (nm/RIU)	1100	1100	1100	1000	1100
	FOM (RIU ⁻¹)	13.75	22.00	27.50	20.00	110.00
Mode 2	S (nm/RIU)	900	900	900	800	900
	FOM (RIU ⁻¹)	60.00	81.82	90.00	80.00	180.00

Mode 3	S (nm/RIU)	600	600	600	600	600
	FOM (RIU ⁻¹)	33.33	40.00	60.00	50.00	40.00

Table 3 The influence of bottom length (L) of the BT cavity on sensitivity and figure of merit from mode 1 to mode 3. The other structural parameters referred to Fig. 1 are $w=50$ nm, $g=10$ nm, and $d=10$ nm, respectively.

	L (nm)	6w	7w	8w	9w	9.5w
Mode 1	S (nm/RIU)	1100	1000	1000	1000	1100
	FOM (RIU ⁻¹)	27.50	62.50	40.00	50.00	44.00
Mode 2	S (nm/RIU)	900	1000	900	900	1000
	FOM (RIU ⁻¹)	90.00	66.67	36.00	40.91	45.45
Mode 3	S (nm/RIU)	600	800	800	500	800
	FOM (RIU ⁻¹)	60.00	80.00	80.00	25.00	40.00

Table 4 The influence of coupling distance among each BT cavity (d) on sensitivity and figure of merit from mode 1 to mode 3. The other structural parameters referred to Fig. 1 are set as $w=50$ nm and $g=10$ nm, respectively.

	d (nm)	8	10	12	15	18
Mode 1	S (nm/RIU)	1100	1100	1100	1000	1100
	FOM (RIU ⁻¹)	24.44	27.25	36.67	50.00	55.00
Mode 2	S (nm/RIU)	800	900	800	900	800
	FOM (RIU ⁻¹)	88.89	90.00	66.67	60.00	100.00
Mode 3	S (nm/RIU)	600	600	600	600	500
	FOM (RIU ⁻¹)	50.00	60.00	60.00	30.00	62.50

Table 5 The influence of each baffle's size (i.e., x -direction size of pair 1 and y -direction size of pair 2) on sensitivity and figure of merit from mode 1 to mode 3. The other structural parameters referred to Fig. 1 are $w=50$ nm, $g=10$ nm, and $d=10$ nm, respectively.

<i>Baffle's width</i> (nm)	20	50	70	90	100
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Mode 1	S (nm/RIU)	1100	1100	1200	1300	1500
	FOM (RIU ⁻¹)	18.18	27.25	48.00	52.00	50.00
Mode 2	S (nm/RIU)	800	900	1100	1000	1400
	FOM (RIU ⁻¹)	80.00	90.00	36.67	60.00	46.67.00
Mode 3	S (nm/RIU)	600	600	1000	800	1100
	FOM (RIU ⁻¹)	33.33	60.00	40.00	53.33	36.67

Table 6 Comparison of the sensitivity and FOM between this work and some other published works.

Reference/year	Structure	Sensitivity (nm/RIU)/operating wavelength range	FOM (1/RIU)
[71]/2015	Induced transparency resonator	733/700nm< λ_{res} <1000nm	30.50
[72]/2016	Coupled double rectangular cavities	596/450nm< λ_{res} <800nm	7.50
[73]/2017	Two circular cavities	840/750nm< λ_{res} <1300nm	100
[30]/2018	Side-coupled stub-hexagon resonators	550/400nm< λ_{res} <800nm	178.00
[74]/2019	Rectangular ring resonator	1367/1300nm< λ_{res} <2000nm	22.30
[75]/2020	Semi-ring shape resonator	1084/600nm< λ_{res} <900nm	57.06
This work	Bowtie cavity configuration	1500, 1400,1100/450nm< λ_{res} <1500nm	50,46.67,36.67

4. Application as a glucose sensor

Comprehending optical features of liquid (e.g., water or glucose) is considerable for solving problems in medical optics and biosensors. As a result of the SPPs could resonant at varied wavelengths due to their changing of refractive index. For nano-medicine applications, it is crucial to develop a sensor structure to monitor the glucose concentrations. With the capability to detect the refractive index's little changes, plasmonic sensors can serve as various biomedical analytes sensing[76, 77]. The SPPs modes in the proposed plasmonic MIM BT cavity sensor system are a promising candidate for efficiently inspecting the glucose value[78]. In the simulations, we can describe the refractive index of the glucose solution as[46, 79]:

$$n_g = 0.00011889 \times c_g + 1.33230545 \quad (3)$$

c_g denotes the glucose concentration (g/L), and n_g represents the glucose concentration's refractive index. Eq. (3) describes the linear relationship between the c_g and n_g . A

relationship can be built between n_g and λ_{res} through FEM simulations since the variation of λ_{res} also varies the n_g . Figure 7 depicts the transmittance spectrum of the solution of mode 1 to mode 4 when the glucose concentration, c_g , varies from 0 g/L, 120 g/L to 240 g/L, respectively. When the c_g increases, the n_g increases from 1.33230545 to 1.36083905 based on Eq. (3). As seen, all curves reveal the linear relations with c_g . For comparison, the structural parameters are the same as those used in Fig. 5(b). As shown in Fig. 7, the λ_{res} are red-shifted with the increasing c_g . In these cases, the calculated density for mode 1 to mode 4 can reach $S=1100, 900, 600$, and 500 nm/RIU, respectively, which are in good agreement with the results obtained from Fig. 6.

Fig. 7 Transmittance spectrum of the solution of mode 1 to mode 4 when the glucose concentration, c_g , varies from 0 g/L, 120 g/L to 240 g/L, respectively. For comparison, the

structural parameters are the same as those used in Fig. 5(b).

Fig. 8 Calculated resonance wavelength (λ_{res}) from mode 1 to mode 4 versus the glucose concentration (c_g) in the range from 0 to 240 g/L.

5. Conclusion

This study proposes a new design strategy of a plasmonic sensor with multi-mode based on MIM-BT cavity configuration working in visible and infrared for refractive index and glucose sensing applications. Finite element method was used to simulate the influence of the BT cavities' geometrical parameters on the fine structure of transmittance spectra and sensor performance. Ag baffles in BT cavities can effectively adjust multiple resonant modes, which considerably raises the sensitivity by 57.14% for mode 1 compared to its counterpart excluding Ag baffles. Variation of the baffle's width (see Table 5) results in the appearance of remarkably resonances wavelength shift towards longer wavelength, which provides the highest mode sensitivity since the large change of resonance

wavelength when exposed to a little variation in the medium refractive index. This research offers the theoretical foundation for comparing designs for guided nanostructures that enable the measurement of a wide variety of refractive index medium and analytes. The high sensitivity of 1500 nm/RIU and FOM of 50.00 RIU⁻¹ can be achieved. We believe that the proposed structure can find significant applications in the future optical sensing domain.

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Figures

Figure 1

Schematic diagram of the proposed plasmonic refractive index sensor consisting of two bus waveguides (width w), four coupled BT cavities, including two pairs of Ag baffles in the BT cavities.

Figure 2

Transmittance spectra of the proposed plasmonic sensor excluding (black color) and with (red color) Ag baffles in the BT cavities.

Figure 3

Truncate views of magnetic field intensity ($|H|$) of (a)-(d) the case excluding Ag baffles and (e)-(h) including Ag baffles in the BT cavities at corresponding resonance wavelengths from mode 1 to mode 4, respectively.

Figure 4

Truncate views of electric field intensity ($|E|$) of (a)-(d) the case excluding Ag baffles and (e)-(h) including Ag baffles in the BT cavities at corresponding resonance wavelengths from mode 1 to mode 4, respectively.

Figure 5

Transmittance spectra of the proposed plasmonic sensors (a) excluding and (b) including Ag baffles in the BT cavities. The test medium's refractive index, n , is set as 1.01, 1.03, 1.13, and 1.15, respectively. The other structural parameters, w , and g , are 50 nm and 10 nm, respectively.

Figure 6

Calculated resonance wavelength (λ_{res}) from mode 1 to mode 4 for the cases including Ag baffles versus refractive index (n).

Figure 7

Transmittance spectrum of the solution of mode 1 to mode 4 when the glucose concentration, c_g , varies from 0 g/L, 120 g/L to 240 g/L, respectively. For comparison, the structural parameters are the same as those used in Fig. 5(b).

Figure 8

Calculated resonance wavelength (λ_{res}) from mode 1 to mode 4 versus the glucose concentration (c_g) in the range from 0 to 240 g/L.