Sensing analysis based on fano resonance in arch bridge structure

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Abstract

An arch bridge structure, comprising of a semiring cavity resonator coupled with bus waveguide, has been investigated numerically and theoretically. Due to the interaction of broad bright state and the narrow dark state caused by the semiring cavity and bus waveguide, respectively, fano resonance can be accrued in transmission spectra which possess a sheer asymmetrical profile that can be adjusted by changing the parameters of the structure with the finite-difference time-domain (FDTD) method. A plasmonic nanosensor is devised based on fano resonance in a metal-insulator-metal (MIM) waveguide system, which has a sensitivity of 1500 nm/RIU as well as a figure of merit (FOM) of 5500. Our findings can provide the guidance for further fundamental research of nanosensor in highly integrated optical circuits.

1. Introduction

Fano resonance, which results from the coherent coupling and interference between narrow discrete state and broad continuum state, has asymmetric line shape [1, 2]. Owing to their great sensitivity and large figure of merit (FOM), fano resonance has been applied extensively in the plasmonic nanosensor which based on kinds of structures, has been investigated numerically and theoretically in the past years. Considering the advantages of nano-integrated photonics, fano resonance is also broadly researched by using the metal-insulator-metal (MIM) waveguides, which are simple for the integrated optical circuits on account of the deep-sub-wavelength confinement of light. Recently surface plasmon polaritons (SPPs) has attracted great interest since it can regulate light in a sub-wavelength field. Among variety of plasmonic devices, the MIM waveguide can spread the SPPs [1, 3, 4]. Fano resonance can be attained in coupled optical resonator cavity ground on the features of MIM waveguide, which has been experimentally proved in recent researches. Zhan et al reported the sensing characteristic based on plasmon induced transparency in nano cavity coupled metal-dielectric-metal waveguide [5], Li et al discussed the sensing application in fano resonance with T-shape structure [6]. Wen et al proposed ultra-high figure of merits based on MIM waveguides in fano resonance [7]. The predecessors have already done a lot of preparations of this work. Based on this, we proposed a simpler structure and achieved good sensing performance also. The cavity resonator based on MIM waveguide has merits of small size and easiness in fabrication.

The plasmonic nanosensor is a new type of sub-wavelength device prepared by plasmon polaritons with high sensitivity to surrounding media environment. This SPPs can not only overcome the traditional diffraction limit, but also be manipulated in the nanometer scale [4, 8, 9], which is beneficial for manufacturing micro-nano devices with unique performance, high miniaturization and integration. Fano resonance originates from the coupling effect between a wide continuous state and a narrow discrete state, resulting in an apparently asymmetric linearity in the spectral response [10–14]. Subtle disturbances can cause resonance or linear drift. Special effects can be applied in the field of nonlinear optics, lasers, modulator, optical switch, filters and slow light. In this letter, an arch bridge shape structure which consists of a semiring cavity coupled with bus waveguide has been studied numerically and theoretically. The results derived from the coupled mode theory (CMT) are consistent with that of FDTD simulation experiments. Fano resonance can be observed in transmission spectra. We proved...
theoretically that the resonance mode can come up or not in the cavity by adjusting the inner radius of the semiring, which caused the emergence or disappearance of the transmission dip. The nanosensor we proposed has the sensitivity of 1500 nm/RIU and the FOM as high as 5500. These unique features will be applied in optical switch, slow light devices, nanosensor and highly integrated optical circuits.

2. Structure and theory

The proposed structure is schematically shown in figure 1(a), an arch bridge structure consists of a cavity resonator which coupled with bus waveguide. The dielectric and metal in the model are air and silver, respectively. The structure parameters include the width of the bus waveguide \( h = \) 100 nm, the outer radius \( R \) and inner radius \( r \) of semiring cavity resonator. The distance between the cavity and the bus waveguide is \( d \).

Gaussian light pulse with wide waveguide profile and standardized amplitude is guided to \( x \)-axis as an incident light, SPPs wave can be generated in metal-insulator surface and restricted in the waveguide, can be coupled into the semiring cavity resonator. The intensity of the light conforms to Gaussian distribution. Two power monitors are set at the points \( P_{in} \) and \( P_{out} \) of the waveguide to detect the incident power and the transmitted power, respectively. The transmittance is calculated as \( T = P_{out}/P_{in} \) [14]. The characteristic spectral responses of the proposed structure are numerically investigated by using FDTD method which is usually applied to simulate the light performance in the two-dimensional waveguide. The perfectly matched layers (PML) are acted as the boundary conditions. Time step is set as \( \Delta x/2c \), where \( c \) is the velocity of the light in vacuum. Mesh step is set as \( dx = dy = 5 \) nm [15, 16]. The surface plasmon polaritons (SPPs) can be activated on the metal-dielectric interface when an incident Gaussian source injects along \( x \)-axis in the bus waveguide. To simplify the calculation, the dielectric and metal we chose are air and plasma silver, respectively. In figure 1(a), blue and white areas denote metal and dielectric, respectively. The permittivity of the silver is delineated by the Drude model \( \varepsilon_{sl}(\omega) = \varepsilon_{\infty} - \omega_p^2/\omega^2 + i\omega\gamma_p \). Here, \( \varepsilon_{\infty} = 3.7 \) is the permittivity of metal at the infinite angle frequency, \( \varepsilon_m \) represents the angle frequency of incident wave, \( \omega_p \) is the bulk plasma frequency which is equal to \( 1.38 \times 10^{16} \) rad s\(^{-1}\), and the damping rate \( \gamma_p = 2.73 \times 10^{13} \) rad s\(^{-1}\) which represents the absorption loss [17–20]. Once the Gaussian wave is injected and coupled into the bus waveguide, SPPs will be guided in the bus waveguide, in the meanwhile energy is coupled into the semiring cavity.

Then we study the theoretical transmission characteristics of the proposed structure by coupled mode theory (CMT) [21–23]. As shown in figure 1(b), the input and output waves are represented by \( S_{in} \) \((j = 1, 2, 3, 4)\), and \( a_1, a_2 \) indicate the energy amplitude which satisfy the following relational expressions:

\[
\frac{da_1}{dt} = \left( \omega_1 - \frac{1}{\tau_1} - \frac{1}{\tau_1} \right) a_1 + S_1 + \frac{1}{\tau_1} S_2 - \frac{1}{\tau_1} S_3 \tag{1}
\]

\[
\frac{da_2}{dt} = \left( \omega_2 - \frac{1}{\tau_2} - \frac{1}{\tau_2} \right) a_2 + S_3 + \frac{1}{\tau_2} S_4 - \frac{1}{\tau_2} S_1 \tag{2}
\]

where \( \omega_1 \) and \( \omega_2 \) are resonant angular frequency of the input optical pulse correspond to the order of \( nth \) \((n = 1, 2)\) resonance, \( 1/\tau_{in} = \omega_n/(2Q_{in}) \) \((n = 1, 2)\) characterizes the decay rate of internal losses, \( 1/\tau_{cn} = \omega_n/(2Q_{cn}) \) \((n = 1, 2)\) represents the cavity loss which coupled to the semiring resonator. \( Q_{in} \) and \( Q_{cn} \) are the related inner and cavity quality factors. With the conversation of energy, we can get the equations:

Figure 1. (a) Schematic of MIM waveguide coupled to the semiring cavity. (b) Theoretical model of the proposed structure.
Combining the equations 3. Results and discussions

When resonance condition is satisfied, where resonance mode cavities. It can be expressed as:

\[ \text{transmission} = \frac{S_{2+}}{S_{1+}} = \frac{1}{a_1} a_2, S_{4+} = S_{4+} - \frac{1}{a_2}, S_{4+} = S_{4+} - \frac{1}{a_2} \]  

Where \( \varphi \) denotes the phase shift, \( C \) is the related damping coefficient and \( c \) is the light velocity in vacuum. Combining the equations (1)–(4), we calculated the transmission function of the model, and \( T \) is indicative of the transmission coefficient.

\[ T = |t|^2 \]

The guided modes inside the MIM waveguide are expressively affected by the effective refractive index \( n_{eff} \), which can be obtained from the dispersion equation [7]:

\[ \varepsilon_m \sqrt{n_{eff}^2 - \varepsilon_d} \tan \left( \frac{h \pi \sqrt{n_{eff}^2 - \varepsilon_d}}{\lambda} \right) + \varepsilon_d \sqrt{n_{eff}^2 - \varepsilon_m} = 0 \]

where \( h \) is the width of the waveguide, \( \varepsilon_m \) and \( \varepsilon_d \) are the dielectric constants of metal and dielectric, respectively. Based on the coupled mode theory (CMT), \( \varphi \) is defined as the phase shift caused by the reflection of SPPs on the metal-dielectric interface in the semiring cavity which is described as \( \varphi = 4 \pi n_{eff} l_{eff} / \lambda_m \), \( \lambda_m \) is the resonance wavelength, and \( l_{eff} \) is the effective length of SPPs in plasmonic semiring cavity. \( l_{eff} \) can be obtained by the following expression:

\[ l_{eff} = \frac{\pi}{2} (R + r) \]

when resonance condition is satisfied \( \Delta \varphi = 2m \cdot \pi \) \((m \) is a positive integer and corresponds to the order of resonance mode) [24–27]. The wavelength of the fano resonance dips will be determined by the length of the slot cavities. It can be expressed as:

\[ \lambda_m = \frac{4n_{eff} l_{eff}}{2m - \varphi / \pi} \]

3. Results and discussions

In figure 2(a), the black solid line and red circles are depicted by FDTD simulation and CMT theory, respectively. It is important to note that theoretical results correspond to FDTD method. The transmission dips are labelled as dip1 and dip2 in figure 2(a). Based on FDTD solutions, the transmission spectra are shown in figure 2(b), the inner radius \( r \) ranges from 80 nm to 180 nm, the coupling length is set as 80 nm, and the width of the bus waveguide \( h \) is chosen as 100 nm. In figure 2(b), the color curves change when \( r \) decreases steadily. As \( r \) goes from...
80 nm to 180 nm, fano resonance dips (dip1, dip2) almost disappears when $r = 180$ nm while appearing increasingly and getting deeper and deeper while $r$ rises from 120 nm to 200 nm. The size of inner radius $r$ decides the height of the fano resonance dips. What’s more, another factor which also has to be considered by designer in order to make the most decent performance of the proposed system. Initially, we set $r = 80$ nm and keep it unchangeable simultaneously, and then gradually increase $R$ from 140 nm to 220 nm. The transmission tendency is plotted in figure 3(a). It can be precisely seen that the phenomenon of fano resonance occurs at $R = 160$ nm, and the transmission valley becomes sharper as $R$ increases stage by stage. In the above simulations, the transmission valley reaches the lowest value and has the largest transmission performance when $r = 80$ nm and $R = 220$ nm. The transmission spectrum is described in figure 3(a), we marked two transmission valleys with dip1, dip2 in the figure. To analyze the theory of the produced fano resonance transmission in nature, the wavelengths of dip1 and dip2 are almost linear functions of inner radius $r$ and outer radius $R$, the lines are shown as figures 3(b) and (c). The black and red dashed lines correspond to the resonance wavelengths of dip1 and dip2, respectively. When the inner radius $r$ ranges from 80 nm to 180 nm, dip1 are plot in the wavelength of 1295 nm, 1495 nm, 1610 nm, 1732 nm and 1901 nm; Dip2 is laid in the wavelength of 682 nm, 762 nm, 815 nm, 872 nm and 954 nm. When outer radius $R$ varies from 140 nm to 220 nm, dip1 are located in 1072 nm, 1095 nm, 1131 nm, 1170 nm and 1218 nm; dip2 are stood on 549 nm, 564 nm, 585 nm, 611 nm and 642 nm. It can be seen that the wavelengths of dip1 and dip2 moderately increase with increasing radius $r$ or $R$. This tendency can also be obtained from formula (10), but the rate of increase is characteristic of finely slight. The phenomenon of fano resonance occurs when $r$ decreases from 180 nm to 160 nm or $R$ increases from 140 nm to 160 nm.

Through the above FDTD simulations, furthermore, we observe the optimal semiring cavity parameters, $r = 80$ nm and $R = 220$ nm of the semiring cavity, so that the steepest fano resonance transmission spectrum can be obtained. Moreover we change external environment in order to explore the sensitivity of nanosensor with introducing different dielectrics into the semiring cavity. Figure 4(a) shows the transmission spectra with different refractive index in the further study the sensing characteristics of plasmonic structure. We define the Sensitivity $= \Delta \lambda / \Delta n$, where the $\Delta \lambda$ and $\Delta n$ represent spectrum change and refractive index shift, respectively [28]. From the figure 4(a), it can be broadly seen that the wavelength shift of the fano resonance dip changes against the effective refractive index with the step of 0.01. The dip wavelength shifts from 1216 nm to 1269 nm, the sensitivity of the semiring structure is around 1500 nm/RIU.

Moreover, FOM as another primary parameter is used to evaluate the sensing performance of the fano resonance. The Fano resonance detects a relative intensity change $dI(\lambda)/dn(\lambda)$ at fixed wavelength $\lambda_0$, and then

![Figure 3](image1.png)

**Figure 3.** (a) Transmission spectrum when $R = 220$ nm, $r = 80$ nm. (b) Wavelength of dip1 and dip2 against different inner radius ($r$). (c) Wavelength of dip1 and dip2 against different outer radius ($R$).

![Figure 4](image2.png)

**Figure 4.** (a) Transmission spectra versus refractive index of internal intermediates. (b) Transmission spectrum and FOM as function of wavelength at $r = 180$ nm, $d = 20$ nm and $n_{eff} = 1.01$. (c) Maximum FOM against different $r$ with $d = 20$ nm and $R = 250$ nm.
FOM is defined as:

\[ FOM = \max \left| \frac{dI(\lambda)}{dn(\lambda)} \right| \]

where the \( dI(\lambda)/dn(\lambda) \) expression describes the relative intensity variation at settled wavelength introduced by a refractive index change \( dn(\lambda) \). \( I(\lambda_0) \) corresponds to the intensity where FOM achieves a maximum value.

The FOM as a function of wavelength when \( \Delta n_{\text{eff}} = 0.01 \) is plotted in red line in figure 4(b), it demonstrates that the maximum FOM rises up to about 5500 at the wavelength of 460 nm. We investigate the maximum FOM with different inner radius \( r \) for the sake of comprehensive research and the results show that max FOM is located in the point of \( r = 180 \) nm in figure 4(c) apparently.

In addition, for sake of discussing the influence of structural parameters on the sensitivity and FOM thoroughly, the coupling distance \( d \) between the semiring cavity and the main waveguide is changed step by step, and we can obtain high sensitivity and good quality factor.

Figure 5(a) shows the sensitivity of plasmonic nanosensor with different coupling distance \( d \). It is legible that the sensitivity can reach as high as 1244 nm/RIU when \( d = 15 \) nm. FOM at the dip of the transmission spectrum can reach a maximum of 1480 when \( d = 15 \) nm in figure 5(b). When the coupling distance is increasing, the corresponding FOM value is also getting higher and reach the peak value of 2880 when \( d = 30 \) nm, which is plotted in figure 5(c). In order to understand the internal physical mechanism of fano resonance thoroughly, we have analyzed the magnetic field distribution at several special dips of the transmission spectrum of this structure. For the first transmission valley at the wavelength of 717 nm, almost all the magnetic field energy is concentrated in the semiring cavity. In figure 6(a), there is hardly magnetic field distribution in the bus waveguide. For the magnetic field distribution of the second transmission valley, it is known that at the wavelength of 549 nm and the part of the electromagnetic wave is trapped under the cavity in figure 6(b), which has a very low transmittance. At the wavelength of 455 nm, the energy is dissipated in more pieces in figure 6(c).

Since the electromagnetic waves in the cavity are re-coupled and back into the bus waveguide to destructive interference, the incident wave is not trapped in the semiring cavity, the fano resonance is generated.

4. Conclusions

In summary, an arch bridge plasmonic structure, comprising of a semiring cavity coupled with a bus waveguide, has been investigated numerically and theoretically. Results of theoretical analysis based on CMT have been verified by FDTD simulation. Because of the destructive interference between broad continuum state and narrow discrete state, fano resonance has been proved in the arch bridge structure, whose sensing characteristics have also been researched in detail. Through multiple sets of numerical simulation experiments, the optimal
structural parameters are found, nanosensor has the sensitivity of 1500 nm/RIU and the maximum FOM can reach 5500 by adjusting the structural parameters. The magnetic field distribution of the structure is also a good proof of internal energy loss. The semiring cavity we proposed in plasmonic waveguide system has a simple structure and can be fabricated easily which can provide a firm cornerstone for the preparation of plasmonic nanosensor in the future.

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