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Fano Resonance Based on Multimode Interference in Symmetric Plasmonic Structures and its Applications in Plasmonic Nanosensors *

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A novel symmetric plasmonic structure consisting of a metal-insulator-metal waveguide and a rectangular cavity is proposed to investigate Fano resonance performance by adjusting the size of the structure. The Fano resonance originates from the interference between a local quadrupolar and a broad spectral line in the rectangular cavity. The tuning of the Fano profile is realized by changing the size of the rectangular cavity. The nanostructure is expected to work as an excellent plasmonic sensor with a high sensitivity of about 530 nm/RIU and a figure of merit of about 650.

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The Fano resonance in nanoplasmonic structures has aroused the attention of researchers recently because of its applications in plasmonic structures, photonics crystals, electromagnetic metamaterials, and so on. Among these nanostructure applications, one interesting aspect is that surface plasmon polaritons (SPPs) can overcome the diffraction limit and confine light in sub-wavelength dimensions.[1−21] One common way to obtain Fano resonance is by using symmetry-breaking structures, like the broken symmetry in ring or disk cavities,[1,2] plasmonic nanoclusters,[3] asymmetric T-shape single slits,[4] an asymmetric stub pair in metal-insulator-metal (MIM) waveguides,[5] and the plasmonic nanocubes in an adjacent semi-infinite dielectric.[6] The symmetry-breaking structure affects the energy distribution, thereby affecting the Fano line shape. The other ways to obtain the Fano resonance are realized by utilizing freestanding metallic gratings with narrow slits,[7] cavity-cavity interference,[8,9] strong couplings of coupled-resonator systems,[10−12] the coupling of plasmonic nanoclusters,[13,14] and so on. The Fano resonance arises directly from the coherent coupling and interference between a discrete state and a continuous state. The devices based on the Fano resonance show high sensitivity and a large figure of merit (FOM) due to the microscopic origin as an interference phenomenon and the unique line shapes of the Fano resonance, which can be used in sensors, lasing, switching, and nonlinear and slow-light devices.[22]

Researchers are generally focused on the Fano resonance in asymmetric structures or cavity-cavity interference, whereas little attention has been paid to multimode interference in a symmetric cavity. In this Letter, a novel symmetric plasmonic structure which consists of an MIM waveguide and a rectangular cavity is proposed to investigate the Fano resonance. The mechanism of Fano resonance generated by the interference between a local quadrupolar and a broad spectral line in the rectangular cavity is confirmed. The Fano profile is achieved by tuning of the size of the rectangular cavity, and the nanostructure is expected to work as an excellent plasmonic sensor with a high sensitivity of about 530 nm/RIU and an FOM of about 650.

Figure 1 shows the geometry of a two-dimensional symmetric plasmonic structure composed of an MIM waveguide and a rectangular cavity. The length and height of the rectangular cavity are denoted as L and H, respectively. The width of the waveguide is D, the insulators in the waveguide and cavity are water ($n_d = 1.33$), and the metal is silver, whose frequency-dependent complex relative permittivity is characterized by the Drude model:

$$\varepsilon_m(\omega) = \varepsilon_\infty - \omega_p^2/[\omega(\omega + i\gamma)], \tag{1}$$

where ε_∞ is the dielectric constant at the infinite frequency, γ is the electron collision frequency, ω_p is the bulk plasma frequency, and ω is the angular frequency of incident light. The parameters are $\varepsilon_\infty = 3.7$, $\omega_p = 9.1\,eV$, $\gamma = 0.018\,eV$.[23] In order to excite the SPPs, the input light is set to be transverse magnetic (TM) plane wave. The propagation direction of the electromagnetic wave is along the x-direction.

In a closed rectangular cavity, the x- and y-directional resonances can be excited. The resonant modes are classified by two integers (m, n), i.e. the x- and y-directional resonant orders, respectively. The eigenmodes of a closed rectangular cavity are researched by using a commercial software (COMSOL

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Multiphysics) of the finite-element analysis method (FEM).[6] From the eigenfrequency analysis of FEM, the magnetic field $|\boldsymbol{H}_{\mathrm{z}}|$ of eigenmodes in a rectangular cavity with $L = 220\,\mathrm{nm}$, $H = 760\,\mathrm{nm}$ are shown in Fig. 2. These eigenmodes exhibit Lorentzian-like line-shapes, which have narrow line-width resonance. In FEM, the positions and widths of the resonant modes can be estimated by $Q = \lambda_r/\mathrm{FWHM}$, $f = f_{\mathrm{re}} + if_{\mathrm{im}}$, $Q = f_{\mathrm{re}}/2f_{\mathrm{im}}$. Here, Q is the Q factor of the eigenmodes, λ_r is the position of the resonant modes, FWHM is the full width at half maximum of the transmission spectra, and the complex-valued eigenfrequency f includes the real part f_{re} and imaginary part f_{im}.

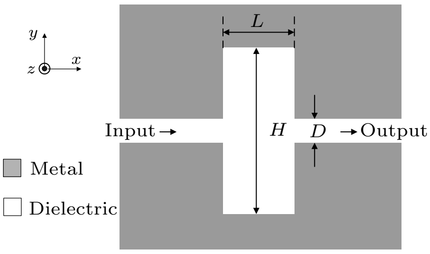

Fig. 1. Schematic diagram of the symmetric plasmonic structure.

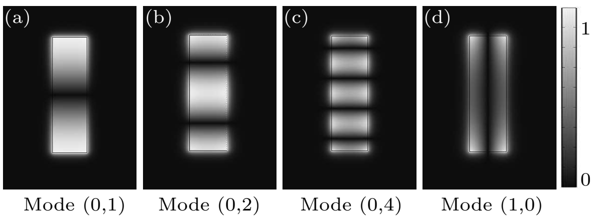

Fig. 2. The magnetic field $|\boldsymbol{H}_{\mathrm{z}}|$ of different modes in a closed rectangular cavity in the case $L = 220\,\mathrm{nm}$, $H = 760\,\mathrm{nm}$: (a) (0, 1) mode, (b) (0, 2) mode, (c) (0, 4) mode, (d) (1, 0) mode. The resonant wavelengths of these modes are 2358 nm, 1173 nm, 604 nm, and 729 nm, respectively.

However, the widths of the resonant modes are subject to change if the MIM waveguide is directly connected to the middle of the rectangular cavity in our proposed structure. For the (0, 2) and (0, 4) modes, because the magnetic field $|\boldsymbol{H}_{\mathrm{z}}|$ in the middle of the cavity ($y = 0$) is at its maximum (as shown in Figs. 2(b) and 2(c)), the power of these modes escapes from the cavity more easily, thereby leading to a broad line-width resonance. For the (1, 0) mode, the MIM waveguide has little influence on the width of the resonance, because the magnetic field $|\boldsymbol{H}_{\mathrm{z}}|$ at $y = 0$ is very small (as shown in Fig. 2(d)). Then, by utilizing the symmetric plasmonic structure shown in Fig. 1, a narrow line-width resonance with the (1, 0) mode and a broad line-width resonance with the (0, 2) or (0, 4) modes are obtained.

When a narrow discrete resonance and a broad spectral line (or continuum) are superposed together, it produces a Fano resonance.[24,25] In this study, the broad spectral line corresponds to the (0, 2) mode, and the narrow discrete state corresponds to the (1, 0) mode in the cavity.

The position of the Fano resonance is determined by the position of the narrow discrete state. The (1, 0) mode is a quadrupolar mode in the rectangular cavity. The electric fields of the quadrupolar mode are both antisymmetric along the x and y directions. The antisymmetric mode along the y direction can be excited by the antisymmetric fundamental SPPs mode in the MIM waveguide due to the longitudinal antisymmetric field $\boldsymbol{E}_x$.[26] The antisymmetric mode along the y direction in our proposed structure is only due to excitation conditions. The antisymmetric mode along the x direction corresponds to the resonant order $m = 1$. Then, the position of the Fano resonance is tuning by the length of the rectangular cavity (corresponding to $m = 1$). It should be noted that the (0, 2) mode can be excited by the antisymmetric fundamental SPPs' mode in the MIM waveguide due to the longitudinal antisymmetric field $\boldsymbol{E}_x$.

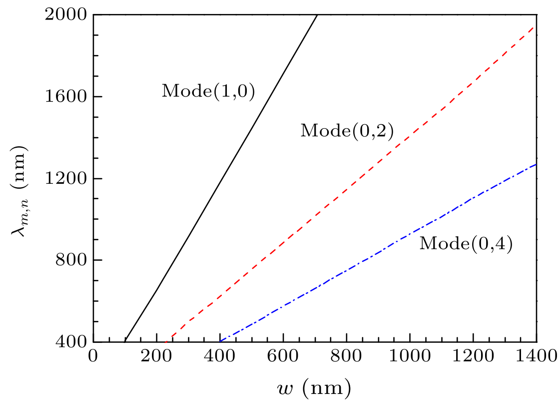

Fig. 3. The relationship between resonant wavelengths $\lambda_{m,n}$ and the width of the rectangular cavity w. The resonant wavelengths of the (1, 0) mode with a fixed $H = 760\,\mathrm{nm}$, the (0, 2) mode with a fixed $L = 220\,\mathrm{nm}$, and the (0, 4) mode with a fixed $L = 220\,\mathrm{nm}$ are presented, respectively.

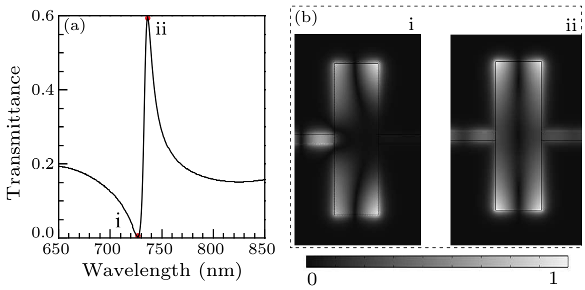

Fig. 4. (a) The transmission spectrum of the plasmonic sensor with $L = 220\,\mathrm{nm}$, $H = 760\,\mathrm{nm}$, and $D = 50\,\mathrm{nm}$. (b) The magnetic field $|\boldsymbol{H}_{\mathrm{z}}|$ of the transmittance at the minimum with $\lambda = 727\,\mathrm{nm}$ (i) and the maximum with $\lambda = 736\,\mathrm{nm}$ (ii) in the Fano profile.

When the width of the rectangular cavity in one direction is fixed, the resonant wavelengths λ_p in the other direction are expressed as[27,28]

$$\lambda_p = 2n_{\mathrm{eff}}w/(p - \varphi_r/2\pi), \tag{2}$$

where $p = m$ or n; φ_r is the phase delay of SPPs reflected on the facets of the cavity, $n_{\rm eff}$ is the effective refractive index, and w presents the L or H of the rectangular cavity. The phase shift φ_r can be calculated numerically.[29] Then, the positions of the resonant modes can be changed by adjusting the L or H.[27] Figure 3 depicts the curve of the resonant wavelengths $\lambda_{m,n}$ versus the width of the rectangular cavity w in the (1, 0), (0, 2), and (0, 4) modes.

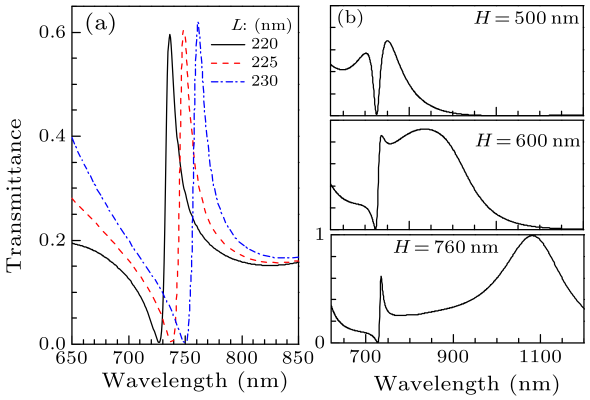

Fig. 5. The influence of the structure parameters on the transmission spectrum profile: (a) different L with fixed $H = 760$ nm and $D = 50$ nm; (b) different H with fixed $L = 220$ nm and $D = 50$ nm.

In a previous work, Fan *et al.*[16] discussed that the transmission spectra display different asymmetric line shapes when the position of the narrow discrete state is placed at different positions on the broad spectral line. In this study, when the position of the narrow discrete state is fixed, the positions of the broad spectral line are tuned by changing the height of the rectangular cavity, thereby affecting the Fano profile.

The FEM is used to calculate the transmittance of the proposed structure. The transmittance is defined as $T = |\boldsymbol{H}_{z,\rm out}|^2/|\boldsymbol{H}_{z,\rm in}|^2$, where $|\boldsymbol{H}_{z,\rm in}|$ and $|\boldsymbol{H}_{z,\rm out}|$ are the input and output amplitude of the magnetic field, respectively. The transmittance of the proposed structure is shown in Fig. 4(a), when the parameters of the structure are $L = 220$ nm, $H = 760$ nm, and $D = 50$ nm. The transmission spectrum is a typical Fano profile with one maximum and one minimum. The origin of the Fano resonance arises from the interference of a narrow discrete state (corresponding to the (1, 0) mode) with a fat continuous state (corresponding to the (0, 2) mode). Figure 4(b) displays the magnetic field $|\boldsymbol{H}_{\rm z}|$ of the transmittance at the minimum and maximum in the Fano profile.

Next, the influence of the structure parameters on the transmission spectrum profile is studied. Figure 5(a) shows that the position of the Fano resonance is tuned by the length of the rectangular cavity. According to Eq. (2), when the position of the Fano resonance is 736 nm (corresponding to $m = 1$), different H's correspond to different y-directional resonant wavelengths. The transmission spectrum profiles in Fig. 5(b) display three spectral profiles. In the case where the position of the (1, 0) mode is equal to the positions of the (0, 2) mode, the transmission spectrum possesses an electromagnetically induced transparency like (EIT-like) dip (corresponding to $H = 500$ nm); while in the case where the position of the (1, 0) mode is away from the positions of the (0, 2) mode, the transmission spectrum profile shows a steep drop (corresponding to $H = 600$ nm); and in the case where the position of the (1, 0) mode is far away from the positions of the (0, 2) mode, the transmission spectrum profile has a maximum and a minimum (corresponding to $H = 760$ nm). The physical mechanism is the coupling and interference between modes (1, 0) and (0, 2). The transmission spectrum shows an EIT-like dip due to the Fabry-Pérot oscillations.[16]

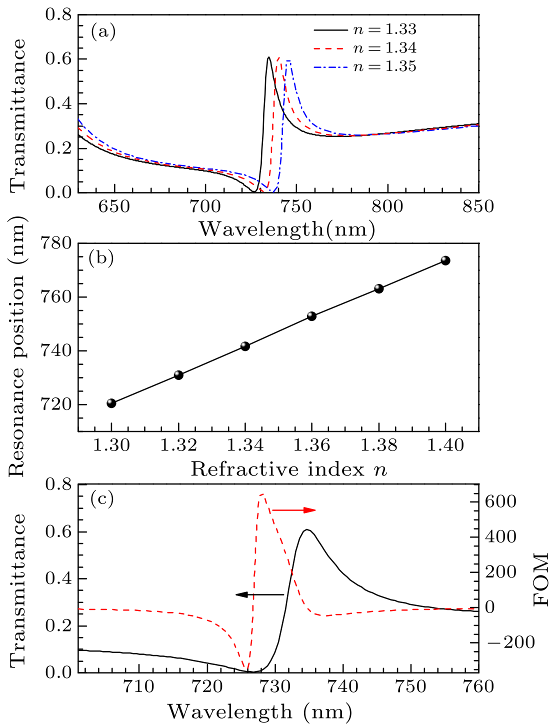

Fig. 6. (a) The transmission spectrum for different refractive indexes n, when $L = 220$ nm, $H = 760$ nm, and $D = 50$ nm. (b) The relationship between the Fano resonance position and the refractive index n. (c) The FOM and the transmission spectrum.

By utilizing the asymmetric Fano transmission spectrum, we now study the performance of our structure as a plasmonic nanosensor. The resonant wavelength is a redshift when increasing the refractive index filled in the cavity. Figure 6(a) depicts the transmission spectrum for different refractive indexes (n) when $L = 220$ nm, $H = 760$ nm, and $D = 50$ nm. The sensitivity (nm/RIU) is defined as the shift in the resonant wavelength per unit change of refractive index. Figure 6(b) shows the linear relationship between the Fano resonance position and the refractive index n. The sensitivity of the proposed plasmonic sensor is about 530 nm/RIU. FOM is another key parameter for the sensor. Our plasmonic sensor detects a relative intensity change $dI(\lambda)/dn(\lambda)$ at the fixed wavelength λ_0. An FOM, which is introduced by Becker *et al.*, is defined as[30]

$$\mathrm{FOM} = \max\left|\frac{dI(\lambda)/dn(\lambda)}{I(\lambda)}\right|, \quad (3)$$

where $dI(\lambda)/dn(\lambda)$ is the relative intensity change at a fixed wavelength induced by a refractive index change dn. $I(\lambda_0)$ corresponds to the intensity when the FOM reaches a maximum value. Figure 6(c) presents the transmission spectrum and the FOM for water at different wavelengths. The FOM of our plasmonic nanosensor is about 650.

In summary, a symmetric plasmonic structure consisting of an MIM waveguide and a rectangular cavity is proposed and investigated. By utilizing the x-directional resonance ($m = 1$) in the rectangular cavity and the fundamental antisymmetric SPPs mode in the MIM waveguide, the quadrupolar mode is constructed. The mechanism of Fano resonance generated by the interference between a local quadrupolar and a broad spectral line in the rectangular cavity is confirmed. Our research shows that the position of the Fano resonance is tuned by the length of the rectangular cavity and the Fano profile by the height of the rectangular cavity. The proposed nanostructure is expected to work as an excellent plasmonic sensor with a sensitivity of about 530 nm/RIU and an FOM of about 650.

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