Dual Fano Resonances Induced by Rectangle-based Plasmonic Resonator for Refractive Index Nano-sensor

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Abstract. A tunable dual Fano-like plasmonic structure consisting of metal-insulator-metal (MIM), baffle and a rectangular cavity containing two identical rectangular metal blocks is obtained. Numerical simulation results show that there are dual Fano resonances in the transmission spectrum of the structure, which can be tuned by changing the geometric parameters of the structure. In addition, due to the apparent asymmetry of the Fano resonances, the system was developed as an effective refractive index sensor (RIS) with a sensitivity of 853 nm/RIU and figure of merit (FOM) of 1631. It is considered that this structure has important application value in high integrated photonic circuit.

1. Introduction
Fano resonance is a phenomenon of resonance scattering that produces sharp asymmetric line-shape [1]. In recent years, it has become increasingly popular due to its numerous potential applications in highly integrated photonic circuits such as plasmonic filters [2], nano-sensors [3], and broadband nonlinear processes [4]. Multiple Fano resonances have attracted extra consideration by reason of the progress of highly integrated photonic circuits and the advantages of multi-color spectra and broadband nonlinear processes. Additionally, supporting multiple channels and detection points, they perform well in nano-sensors. Due to the deep-sub-wavelength confinement of light, MIM (metal-insulator-metal) waveguides are more suitable for integrated photonic circuits. However, it is still under-reported in this area. Therefore, it is meaningful to design various plasmonic structures based on the MIM waveguide to induce Fano resonances for nano-sensors.

In this paper, a tunable dual Fano-like plasmonic structure which is made up of baffle, metal-insulator-metal (MIM) and a rectangular cavity containing two identical rectangular metal blocks is obtained. According to numerical simulation, multiple Fano resonances appear in its transmission spectrum, which are perchance tuned by changing the geometric parameters of the structure. In addition, due to the sharp asymmetry of the Fano resonance, the system was developed as a productive refractive index sensor (RIS) with a sensitivity of 853 nm/RIU and a quality factor (FOM) of 1631. It is regarded that it has essential application value in highly integrated photonic circuits for this structure.

2. Structure Model and Simulation Results
The structure diagram is shown in figure 1a, where a rectangular cavity containing two rectangular metal blocks is placed in the rectangle structure of the MIM waveguide. This is a two-dimensional model, with gray and white representing Ag and Air, respectively. In this paper, a two-dimensional simulation method based on COMSOL multi-physics is adopted. Therefore, the Z-axis length is neglected. figure 1a shows the other parameters. Specifically, the total length of the structure is 5um, corresponding to...
the x-axis, while the height is 3um, corresponding to the y-axis. The width of the insulator is fixed at 50nm, the distance between the rectangular cavity and the edge of the rectangular metal block is indicated by the fixed value of 50nm, and the coupling distance g is indicated by the fixed 25 nm. What’s more, t represents the width of the baffle. h represents the width of the cavity, which is set to be 200nm. In order to keep the distance between the rectangular metal block and the rectangular cavity as a constant of 50nm, the center distance of the two rectangular metal blocks is set to be D, the length of the cavity is set to be 2D, and the length of the metal block is set to be (D - 100). Based on the COMSOL multi-physical model, the transmission spectrum of the system is numerically calculated, and the optical characteristics of the system are determined.

Here, we define the transmission of SPP as the result of dividing the SPP power flows of the system by the SPP power flows with only MIM waveguides. In addition, the dielectric constant of Ag can be obtained from Drude model [5]:

$$\varepsilon_m = \varepsilon_\infty - \frac{w_P^2}{(w^2 + i\omega \gamma)}$$  \(\text{(1)}\)

Where \(\varepsilon_\infty = 3.7, w_P = 9.1 eV, and \gamma = 0.018 eV.\)
Figure 1. (a) The obtained plasmonic structure which is made up of metal-insulator-metal (MIM), baffle and a rectangular cavity containing two identical rectangular metal blocks. (b) The transmission spectra of the system (the red solid line), the structure with no baffle (the blue dotted line) and the MIM waveguide with only baffle (the green dotted line) with t=10nm, D=250 and g=10 nm. (c)-(d) The electric field intensity distributions at $\lambda=796$nm (c) and $\lambda=873$nm (d).

As shown in Figure 1b, the transmission spectra of the system, the structure with no baffle and the MIM waveguide with only baffle, correspond to the red solid line, the blue dotted line, and the green dotted line, respectively. As can be seen from Figure 1b, two explicit Fano resonances appear in the transmission spectrum, which are named as FR1 and FR2 in sequence. Bright mode is from the baffle as the curve with only baffle shown. Inversely, the rectangular cavity containing two identical rectangular metal blocks induces two dark modes as the curve with no baffle displayed. The coupling and interference between the dark modes with the bright modes produce the two sharp Fano resonances. For the sake of further clarify the basic physical properties of the dual Fano resonance, Fig. 1c-d show the electric field intensity distribution at the peaks of FR1($\lambda=796$nm) and FR2($\lambda=873$nm), respectively. One can see that the FR1 and FR2 are derived from TM12 and TM11, respectively.

3. The Analysis of Tunable Characteristic and Application on Refractive Index Nano-sensor

3.1 The tuning characteristics of the obtained structure.
Due to the different mechanisms of realizing multiple Fano resonances, the structure’s transmission spectrum can be tuned by changing the structural parameters. Fig. 2a shows the variation of the transmission spectrum with t while keeping other parameters unchanged. The detailed relationship between the peak value of Fano resonance and the parameter t is shown in Fig. 2b. With changing t, the resonance wavelengths of FR1 and FR2 stay almost unchanged. But the linear shape of the transmission spectrum is obviously different, which means that the shape of the transmission can be adjusted by modifying the parameter t. The result is consistent with the result of figure 1b, that is, the baffle plays a role of wide continuum state in the formation of multiple Fano resonances. Similarly, the rectangular parameter D is adjusted, and the results are shown in Fig. 2c. Fig. 2d show the relationship between the resonant peaks and variable D. When D changes linearly, the peaks of FR1 and FR2 also change linearly, which is called red shift. Therefore, the calculated results imply that the induced Fano resonances can be adjusted so that the system can be well controlled.
3.2 Refractive Index Sensing Based on the quintuple Fano Resonances

When the refractive index of the medium around the structure changes [6], the extremely sharp Fano resonance can produce the highly sensitive spectral response. Therefore, different refractive index materials are be used to replace media to have further study on spectral response. The shift of the resonant wavelength per unit variation of the refractive index is used to define the sensitivity (nm/RIU) of the sensor. [7]. The transmission spectra of the changed refractive index is shown in Fig. 3a. Fig. 3b displays the linear relation between the resonant peaks and the different refractive index n, which is perfectly linear. As shown in Fig.3b, the sensitivity of FR1 and FR2 can be calculated as 748 nm/RIU and 853 nm/RIU, respectively.

In addition, the FOM is also akey parameter to express the performance of the sensor. It is identified as

$$FOM = \frac{\Delta T}{T_{br}}$$

(2)

Where T represents the transmittance in the obtained structure and the transmittance variation at the rigid wavelength caused by the variation of refractive index [ ]. It is recommended that the FOM of various refractive index n of the system is shown in figure 3b, and the calculation formula is as follows:

$$FOM = \frac{|T_{n=1.10} - T_{n=1.00}|}{\Delta n T_{n=1.00}}$$

(3)

According to figure 3c, the maximum value of FOM=1631 is obtained, which corresponds to the FR2 when the n=1.1. The refractive index sensor based on Fano resonance has high performance and can support two sensing detection points, so it has a good application prospect in the field of sensing.
Figure 3. (a) the transmission spectrum of the Fano resonant structure with $n$ varying between 1.00 and 1.20. (b) the linear relation between the resonant peaks and the different refractive index $n$. (c) the FOM values calculated by the equation 3.

4. Conclusion

In summary, dual Fano resonances have been obtained and investigated in the plasmonic system according to the finite element method. The simulation results illustrate that due to the coupling and interference between the cramped discrete state sustained by rectangular cavity containing two identical rectangular metal blocks and the wide continuous state excited by the baffle, the dual Fano resonance are obtained in the transmission spectrum. In addition, the Fano resonance is able to be easily tuned by changing the structure’s geometric parameters. The system is applied to the refractive index sensor, and the sensitivity of 853nm/RIU and the FOM of 1631 are obtained. Due to the enhancement of highly integrated photonic circuits, it is regarded that this structure will perform well in the optical sensing and optical communication field.

References

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