Research on coupling property of side-coupled asymmetric square-ring resonator in a plasmonic waveguide

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Abstract. The characteristics of resonant modes in the side-coupled asymmetric square-ring resonator based on a plasmonic waveguide are investigated. The 1-order modes and 2-order modes can be manipulated by adjusting the longitudinal distance $\Delta z$ and transversal distance $\Delta x$ of the metal block in the square air cavity. The coupling and splitting effect of the resonant modes in the asymmetric square ring resonator are exploring. The proposed structure is potential in sensing and filtering.

1. Introduction
The plasmonic waveguide structures have been exploring extensively due to their ability to manipulate light at the subwavelength scale. In recent years, various plasmonic resonator based on the metal-insulator-metal (MIM) waveguide have been proposed and studied, such as ring resonator [1, 2], nanodisk resonator [3, 4], rectangular-ring resonator [5-11], nonlinear resonator [12, 13] and other resonators [14, 15], which are potential in the photonic integrated circuits and high sensitive sensing. Among them, the side-coupled rectangular-ring resonator based on the MIM plasmonic waveguide proposed by Hosseini and Massoud [5] has attracted considerable attentions. By modulating the dimension of the rectangular-ring resonator, multiple integer modes can be excited in the structure and the mode splitting of even modes is observed. Then, aperture-coupled square-ring resonator [8] and the complementary split-ring resonator [9] have been proposed and it is observed that non-integer modes are excited.

In fact, it is inferred in the past years that only even modes can witness the splitting, until in ref. [8], it is observed that the odd order resonance also can be splitting in the square ring resonator with a special dimension. However, it is difficult to modulate the splitting of the odd order resonance. In this paper, an asymmetric square-ring resonator based on a plasmonic MIM waveguide is proposed. By adjusting the longitudinal distance $\Delta z$ and transversal distance $\Delta x$ of the metal block in the square air cavity, we can manipulate the resonant modes in the asymmetric square ring resonator, therefore, the coupling and splitting effect of the odd modes and even modes can be controlled.

2. Model and method
The finite difference time-domain method (FDTD) is used to numerically explore characteristics of the asymmetric square ring resonator based on the MIM waveguide. In the simulation, the permittivity of the metal is modelled with the Lorentzian function
\[ \varepsilon(\omega) = \varepsilon_\infty + \sum_{k=1}^{6} \Delta \varepsilon_k \left[ a_k (i\omega)^2 - b_k (i\omega) + c_k \right], \]  

(1)

Where \( \varepsilon_\infty \) is the value of permittivity in the limit of infinite frequency, \( \Delta \varepsilon_k \) is the strength of each resonance, and \( a_k, b_k \) and \( c_k \) are fitting coefficients. For the metal of silver (Ag) used in this work, six terms of fitting were applied with \( \varepsilon_\infty = 1 \), \( \Delta \varepsilon_k = (1.759471, 135.344, 258.1946, 22.90436, 1.74906, 11.75618) \), \( a_k = 1 \) for all, \( b_k = (0.243097, 19.68071, 2.289161, 0.329194, 4.639097, 12.25) \), and \( c_k = (0, 17.07876, 515.022, 1,718.357, 2,116.092, 10,559.42) \).

Figure 1. Schematic and geometrical parameters of the asymmetric square-ring resonator side-coupled with an MIM waveguide.

Figure 1 shows the schematic of the proposed structure, which consists of a MIM waveguide with width of 50 nm and side-coupled asymmetric square ring resonator. The distance \( g \) between the waveguide and asymmetric square ring resonator is set to be 20 nm. The wall width of the outer square air resonator whose centre is the cyan dot is \( L_{x1} = L_{z1} = 300 \) nm. The wall width of the inner square metal block whose centre is denoted as the black dot is \( L_{x2} = L_{z2} = 200 \) nm. The longitudinal and transversal distances between the cyan dot and black dot are denoted as \( \Delta z \) and \( \Delta x \), respectively. Here we modulate the \( \Delta z \) and \( \Delta x \) to modulate the resonant modes in the asymmetric ring resonator.

3. Simulation results and discussion

The simulated transmission spectra of the asymmetric ring resonator based on MIM waveguide with positive longitude distance \( \Delta z \) at \( \Delta x = 0 \) are shown in Figure 2 and the magnetic-field distributions at the resonant wavelengths are shown as insets. The resonance condition for the square ring cavity is

\[ L = N \frac{\lambda}{n_{\text{eff}}} \]  

(2)

Where \( N \) is the mode number, \( n_{\text{eff}} \) is the effective refractive index, and \( L \) is the total length of the ring-resonator. For symmetric case of \( \Delta x = 0, \Delta z = 0 \) shown in Figure 2(a), it is observed that 1-order \((N = 1)\) and 2-order \((N = 2)\) of the resonant modes can be excited in the square ring cavity. Meanwhile, the 2-order mode is splitting into two modes denoted as \( TM_{2y} \) (the four magnetic antinodes are posed at the face) and \( TM_{2x} \) (the four magnetic antinodes are posed at the corners) [9]. The transmittance and the resonant wavelengths slightly differs from ref. [9] because the permittivity of the metal in this paper is characterized by the Lorentz model which is more consistent with the experimental data rather than the Drude model.

For asymmetric case of \( \Delta x = 0, \Delta z = 15 \) nm shown in Figure 2(b), it is observed that the \( TM_{2y} \) mode is redshifted and approaching the \( TM_{2x} \) mode as the \( TM_{2x} \) mode shifts slightly. Increasing the \( \Delta z \) to 25 nm shown in Figure 2(c), the \( TM_{2y} \) mode and \( TM_{2x} \) mode are coupling and enhancing the absorption. The magnetic field distribution of the coupling mode is similar to the field of \( TM_{2y} \), but the antinodes are posed near the corner. The coupling between the two modes is absolutely trapped the light at 724 nm and results in the near-null transmittance. In fact, the resonance coupling in the nano-structure is belonging to the fano resonance, the destructive interference between two neighbored overlapping...
Resonance modes with equal magnitude can achieve the perfect absorption. The asymmetry in the square ring resonator can modulate the field distributions of $TM_{2f}$ mode and $TM_{2c}$ mode, when the two modes are modulated with almost equal magnitude in the overlapping frequency, the nearly-null absorption is achieved. From the Figure 2(c), it is interesting that the 1-order resonant mode also occurs splitting into the $TM_{1f}$ mode and $TM_{1c}$ mode. From the magnetic field, the magnetic antinodes of $TM_{1f}$ are posed in the face of the upper side and lower side, and the field is distributed in the whole square ring resonator except a small part face of left and right sides. The magnetic antinodes of $TM_{1c}$ are posed in diagonal corners and the field is distributed in the whole resonator except a small part of the other diagonal corners. If we furtherly increasing $\Delta z$, the 1-order and 2-order would occur splitting, shown in Figure 2(d). The splitting of the resonances is possible attributed to the role of corners of the square-ring resonator. If the corners are positioned in a large magnetic field, the corner modes ($TM_{1c}$ and $TM_{2c}$) are formed and presented in the spectra. However, the frequencies of $TM_{1f}$ and $TM_{1c}$ are close and it is difficult to distinguish them. In order to distinguish them, large asymmetry (with large $\Delta z$) should be introduced to split the 1-order resonance.

Figure 2. The transmission spectra of the proposed structure with positive longitude distance $\Delta z$ where $\Delta x = 0$. The magnetic distributions are shown as insets.

For clarity, the relationship between the resonant wavelength and the positive longitude distance $\Delta z$ is plotted in Figure 3. As $\Delta z$ varies from 0 nm to 20 nm, the 1-order resonant mode would not split and shifts little because the frequencies of $TM_{1f}$ and $TM_{1c}$ are close and it is difficult to distinguish them for small $\Delta z$. While for 2-order resonant modes, the $TM_{2f}$ mode exhibits a red shift and the $TM_{2c}$ mode shifts slightly, this is because the field of $TM_{2f}$ mode is distributed in the face of the four sides of the square ring resonator, the asymmetry due to the small value of $\Delta z$ has a major effect on the face of the resonator, it is easily affecting the distribution of $TM_{2c}$. However, the value of $\Delta z$ has a minor effect on the asymmetry of the corners, therefore, the $TM_{2c}$ mode shifts slightly. Increasing $\Delta z$ to the range of 25~30 nm, the 1-order resonant mode is splitting into $TM_{1f}$ mode and $TM_{1c}$ mode. The fields of $TM_{1f}$ mode and $TM_{1c}$ mode are nearly distributed in the whole resonator, the asymmetry of the square ring resonator due to $\Delta z$ can modulate $TM_{1f}$ mode and $TM_{1c}$ mode, so the two modes exhibit a redshift. However, the $TM_{1c}$ mode is more sensitive to the asymmetry and moves more quickly, therefore, the 1-order resonant mode occurs splitting. While for 2-order resonant mode, $TM_{2f}$ mode is red shifting continually and the $TM_{2c}$ mode is still not sensitive to the asymmetry, so the $TM_{2f}$ mode and $TM_{2c}$ mode can be overlapping and enhancing the absorption. Increasing $\Delta z$ furtherly, the 1-order mode and 2-order mode both exhibit splitting and four dips can be recognized in the spectrum.
The negative longitude distance $\Delta z$ is also investigated in Figure 4. From the transmission spectra, the similar effect of the positive longitude distance is observed, the 1-order and 2-order resonances can be modulating with increasing the $|\Delta z|$. However, the coupling condition between the waveguide and the side coupled square ring resonator is differed from the case of positive longitude distance, therefore, the transmittance and resonant positions of the 1-order and 2-order resonant modes are varied slightly. Hence, the $TM_{2f}$ mode and $TM_{2c}$ mode are overlapping at a different value $|\Delta z| = 30 \text{ nm}$ shown in Figure 4(c) other than the value $\Delta z = 25 \text{ nm}$ in the case of positive longitude distance. It is also observed with increasing $|\Delta z|$ that the 1-order resonance is splitting and the corner mode $TM_{1c}$ can be distinguished in the spectrum.

The property of the transversal distance $\Delta x$ is shown in Figure 5. As the structure is bilateral symmetrical, we only discuss the case when $\Delta x$ is positive. It is known that $\Delta x$ is introducing the asymmetry of square ring resonator, the 1-order and 2-order resonances can be modulating with varying $\Delta x$. The effect of 2-order resonances is similar to the case of $\Delta z$. When $\Delta x = 30 \text{ nm}$, the $TM_{2f}$ mode and $TM_{2c}$ mode are coupling and enhancing the absorption. However, the perfect absorption is not achieved because the fields are not modulated with almost equal magnitudes and not cancelled.
completely in the far field. To achieve the perfect absorption, the dimension should be designed more accurately to reallocate the field distributions of the coupled modes. With increasing $\Delta x$, the 1-order resonance $TM_1$ is splitting into $TM_{1c}$ mode and $TM_{1f}$ mode. Because the field distributions of the $TM_{1c}$ mode and $TM_{1f}$ mode are a little different from the case of $\Delta z$, it is observed that the $TM_{1c}$ mode is located at a shorter wavelength while the $TM_{1f}$ mode is located at a longer wavelength, that is different from the case of varying $\Delta z$.

![Figure 5](image_url)

**Figure 5.** The transmission spectra of the proposed structure with different transversal distance $\Delta x$ where $\Delta z = 0$.

4. **Conclusions**

In this paper, we investigate the resonant modes in the side-coupled asymmetric square ring resonator based on a plasmonic waveguide. The results show that the 1-order modes and 2-order modes can be manipulated by adjusting the longitudinal distance $\Delta z$ and transversal distance $\Delta x$ of the metal block in the square air cavity. With increasing $\Delta z$ or $\Delta x$, the 2-order modes can be coupling and enhancing the absorption, meanwhile, the 1-order resonant mode occurs splitting in the asymmetric square ring resonator. The proposed structure is potential in sensing and filtering.

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