Polarization-Insensitive Magnetic Quadrupole-Shaped and Electric Quadrupole-Shaped Fano Resonances Based on a Plasmonic Composite Structure *

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A combined structure with the unit cell consisting of four sub-units with 90° rotation in turn is designed. Each of sub-units is composed of two gold rods in transverse arrangement and one gold rod in longitudinal arrangement. Simulating electromagnetic responses of the structure, we verify that the structure exhibits the double Fano resonances, which originate from the coupling between magnetic quadrupoles and electric dipoles and the coupling between electric quadrupoles and electric dipoles. Simulation results also demonstrate that the structure is polarization-insensitive and shows an analogue of electromagnetically induced transparency at the two Fano resonances. Such a plasmonic structure has potential applications in photoelectric elements.

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Since the Fano resonances[1] were proposed, researchers have made great efforts in their realization utilizing different systems. The Fano resonances based on metamaterial and plasmonic structures have become a hot topic in recent years.[2] Much attention to them lies in their many potential applications in electromagnetically induced transparency,[3] high-sensitive sensing,[4–6] and slow light.[7]

Analyzing the production mechanisms of the Fano resonances, we can divide the structures into electric plasmonic structures and magnetic plasmonic ones. One of the electric plasmonic structures was first proposed by Zhang *et al.*[8] It is composed of an array of two metal rods in transverse arrangement which form a mode of electric quadrupole oscillation (dark mode) and one metal rod in longitudinal arrangement which composes a mode of electric dipole oscillation (bright mode). The coupling between the two modes causes a Fano resonance. After that, Liu *et al.*[9] proposed a similar structure and experimentally confirmed the Fano resonance. Subsequently, ring/disk cavities[10,11] were considered to produce the Fano resonance. Under an external electric field, the disks form a mode of electric dipole oscillation, while the rings compose a mode of electric multipole oscillation. The coupling between the two modes leads to the Fano resonance. In addition, an array of metal nanoparticle clusters[12,13] is also a typical electric plasmonic structure. The nanoparticle in the middle of the nanoparticle clusters acts as an electric dipole and the surrounding nanoparticles are equivalent to a linear combination of electric dipoles under suitable excitation. However, the two kinds of electric dipoles are inverse in phase and unequal in magnitude. Their generated electric dipole moments bring about the Fano resonance. Frimmer *et al.*[14] also investigated a similar structure. A magnetic plasmonic structure was first demonstrated to produce the Fano resonance by Zheludev *et al.*[15,16] Its unit cell consists of two sections of weakly asymmetric concentric metallic arcs, in which antisymmetric currents can be formed under suitable polarization. The antisymmetric currents are regarded as a mode of non-radiative magnetic dipole oscillation. As the currents in the two metallic arcs are unequal, an electric dipole mode can be formed. The coupling between the two modes results in the Fano resonance. Following this idea, many magnetic plasmonic structures[17,18] have been proposed.

However, the Fano resonances generated in the two types of plasmonic structures are generally dependent on the polarization directions of the incident waves. Meanwhile, it is seldom for a given structure that electric plasmonic-shaped and magnetic plasmonic-shaped Fano resonances are simultaneously produced.

In this Letter, we introduce a combined structure with the unit cell consisting of four sub-units with 90° rotation in turn. Each of the sub-units is composed of two gold rods in transverse arrangement and one gold rod in longitudinal arrangement. The shape of the structure is different from that in Ref. [9], where each of the sub-units is placed in the same direction. Simulations show that our structure exhibits double Fano resonances originating from the coupling between magnetic quadrupoles and electric dipoles and the coupling between electric quadrupoles and electric dipoles, respectively, as well as the resonances are

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polarization-insensitive. The simulation results indicate that though each of the sub-units is regarded as a typical electric plasmonic structure, their proper combination still leads to a magnetic plasmonic structure.

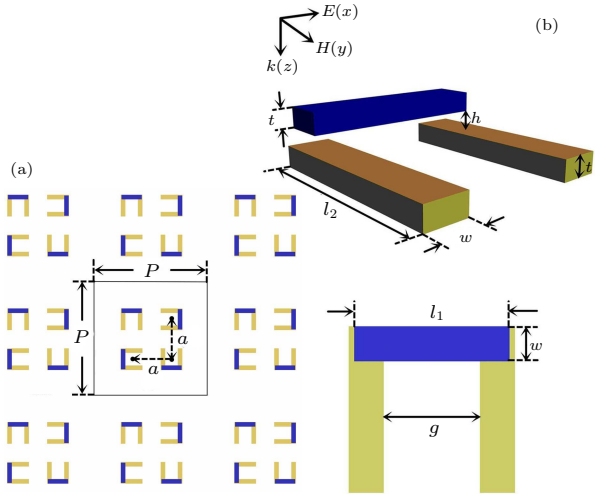

Fig. 1. (a) Schematic diagram of several unit cells, each of which is composed of four sub-units. The period of the structure is $P = 2000\,\text{nm}$ and the center distance between the two adjacent sub-units is $a = 700\,\text{nm}$. (b) Schematic diagram of one sub-unit consisting of two gold rods in transverse arrangement and one gold rod in longitudinal arrangement. The geometric parameters are $l_1 = 355\,\text{nm}$, $l_2 = 380\,\text{nm}$, $w = 80\,\text{nm}$, $g = 220\,\text{nm}$, $t = 40\,\text{nm}$, and $h = 30\,\text{nm}$, respectively.

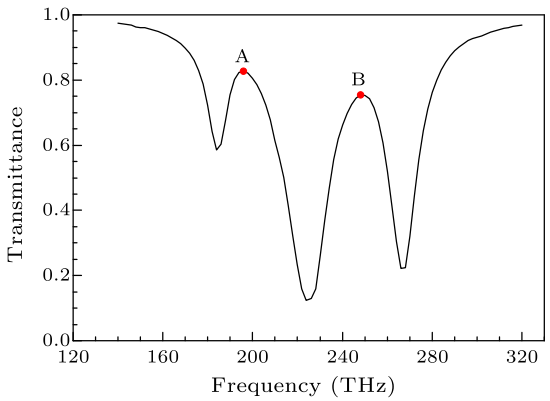

Fig. 2. Transmittance as a function of the frequency.

As shown in Fig. 1, a unit cell of the structure contains four sub-units, each of which consists of two gold rods in transverse arrangement and one gold rod in longitudinal arrangement. The four sub-units make a clockwise rotation of 0°, 90°, 180°, and 270°. The structure is surrounded by air. The detailed dimensions of the unit cell are described in the figure caption. Figure 1(b) shows that a plane wave is supposed to be incident normally onto the top surface of the structure, with its electric field E, magnetic field H, and wave vector k along the x, y, and z directions, respectively. In the following simulations, only one unit cell is considered due to the periodicity of the structure. Definitively, the two-paired surfaces of the unit cell in the two periodic arrangement directions are set to periodic boundary conditions, while the two surfaces of the unit cell in the propagation direction of the electromagnetic wave are set to ports. The permittivity of gold comes from the experimental dispersion data which can be found in Ref. [19].

In the simulations, the Ansoft high frequency structure simulator (HFSS) software was used. The simulated transmittance as a function of frequency is shown in Fig. 2. It is found that there are two resonance peaks, which are located at the frequencies of 196 THz and 248 THz, respectively. The two corresponding peak values are 0.826 and 0.753, which are called point A and point B, respectively.

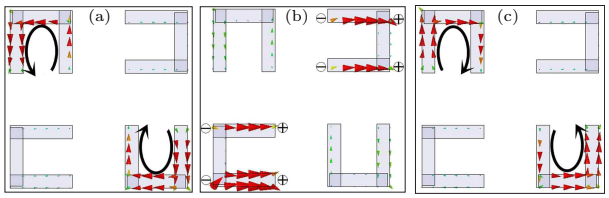

Fig. 3. Current and charge distributions in the unit cell at the resonance frequency of 196 THz (point A) with the phases of (a) 0°, (b) 100°, and (c) 180°.

To investigate the mechanism of the two resonances generated by the structure, we simulated the current distributions with 0° to 360° phases in the structure at the two resonances of points A and B in Fig. 2. Since the components of the rods in the structure are metallic, the current fields with the phases in them can be induced under the excitation of the incident wave and can be stored in the simulation software. The corresponding results with several phases are shown in Figs. 3 and 4, where charge distributions can be drawn based on the current distributions, respectively.

It can be observed from Fig. 3(a) that there are almost no currents flowing in the top right and bottom left sub-units, while currents are mainly distributed in the top left and bottom right ones. With the increase of the phase from 0° to 100°, the current distributions convert to the two other sub-units, as shown in Fig. 3(b), signifying that the top right and bottom left sub-units take part in oscillation at the phase. When the phase reaches 180°, the current distributions are similar to those in Fig. 3(a) and only occur in the top left and bottom right sub-units, as shown in Fig. 3(c). Their differences are a reversal of the currents.

Analyzing the current distributions in Figs. 3(a) and 3(c), we take the toroidal currents as magnetic dipoles. Each sub-unit with a toroidal current can be seen as a magnetic dipole. Therefore, the top left and bottom right sub-units can be regarded as two magnetic dipoles, and their phases are reversed. The two reverse magnetic dipoles play the role of a magnetic quadrupole. Its radiation is obviously restrained, and then a dark mode is formed in the sub-units. Following the current distributions in Fig. 3(b), the charge dis-

tributions are marked in this figure. Evidently, each metal rod with the existence of currents can be known as an electric dipole. Hence, there are four electric dipoles in the top right and the bottom left sub-units, and they are parallel and in phase. Since an electric dipole is radiative, the sub-units can be considered as a bright mode. The coupling between the dark mode and the bright mode leads to the Fano resonance at the frequency of 196 THz.

Figure 4(a) shows that currents flow in all the sub-units. It is clear that these sub-units contribute to oscillation. When the phase converts from 70° to 160°, currents mainly concentrate on the top left and bottom right sub-units, which indicates that the two sub-units play a decisive role in oscillation. Similar to Fig. 4(a), all sub-units participate in oscillation at the phase of 250° since currents also flow in these sub-units, as shown in Fig. 4(c).

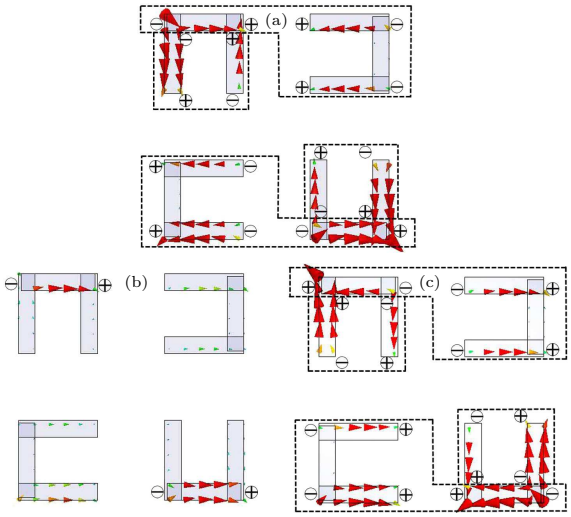

Fig. 4. Current and charge distributions in the gold rods at the resonance frequency of 248 THz (point B) with the phases of (a) 70°, (b) 160°, and (c) 250°.

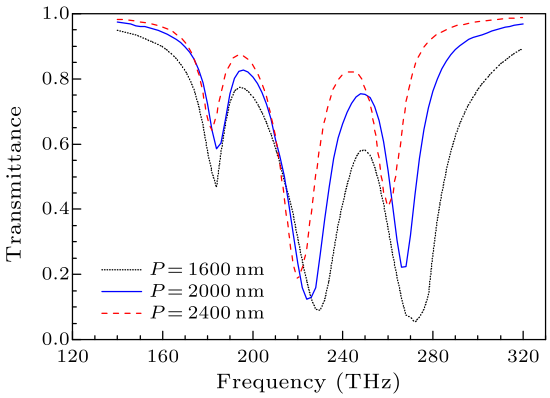

Fig. 5. Transmittance as a function of frequency for different periods.

From the current distributions in Fig. 4, we can draw the corresponding charge distributions in the sub-units, as also shown in the figure. From Figs. 4(a) and 4(c), we can see that each figure exhibits four electric quadrupoles, any of which is marked in dashed lines. These quadrupoles have a characteristic of non-radiation, forming a dark mode. In Fig. 4(b), the electric dipoles with the same direction emerge in the top left and bottom right sub-units. The electric dipoles are viewed as a bright mode. The coupling between the dark mode and the bright one induces the Fano resonance at the frequency of 248 THz.

To investigate influences of different parameters of the structure on resonances, we first simulated transmittance as a function of frequency for different periods. The corresponding results are shown in Fig. 5. Evidently, when the period of the plasmonic structure becomes longer, the two Fano resonances show slight red-shift. The reason is that the effective plasmonic density of the structure decreases with the increase of the period, resulting in such a red-shift phenomenon.

Figure 6 shows the transmittance as a function of frequency for different a. Following the above analysis, the Fano resonance at the low frequency comes from the coupling between the magnetic quadrupoles and the electric dipoles. The two reverse magnetic dipoles forming a magnetic quadrupole attract each other. This means that when the center distance between the two adjacent sub-units becomes shorter, the currents in the sub-units will flow more slowly due to stronger attraction between the sub-units. Hence, we observe the red-shift phenomenon with decreasing a. Differently, the Fano resonance at the high frequency originates from the coupling between electric quadrupoles and electric dipoles. These electric quadrupoles do not constitute electric octupoles, which indicates that they interact weakly. Therefore, the resonance at the high frequency almost does not change with the decrease of a.

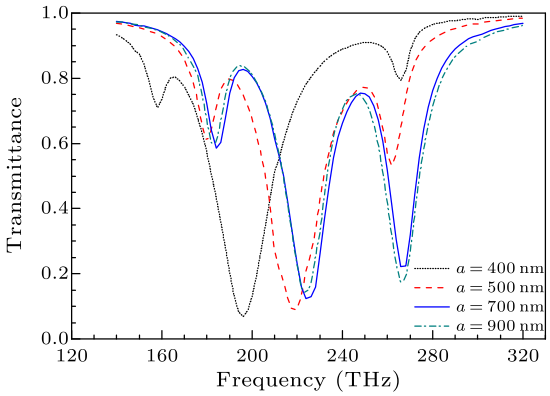

Fig. 6. Transmittance as a function of frequency for different center distances between the two adjacent sub-units.

Next, the polarization behavior of the structure will be investigated. As shown in Fig. 7, the combined structure is rotated 15°, 30°, 45°, 60°, and 75° with the polarization directions of the incident electromagnetic wave unchanged (due to the symmetry of structure, it is unnecessary to consider the case of rotation greater than 90°). It may also be considered that the structure is fixed and the polarization direc-

tions of the incident wave are rotated in the opposite directions. We simulated transmittance as a function of frequency for the different rotation angles and the simulation results are shown in Fig. 7(b). Evidently, the transmittance is independent of structure's rotation, which means that the double Fano resonances are irrelative to the polarization directions of the incident wave. Therefore, it is believed that the structure is polarization-insensitive.

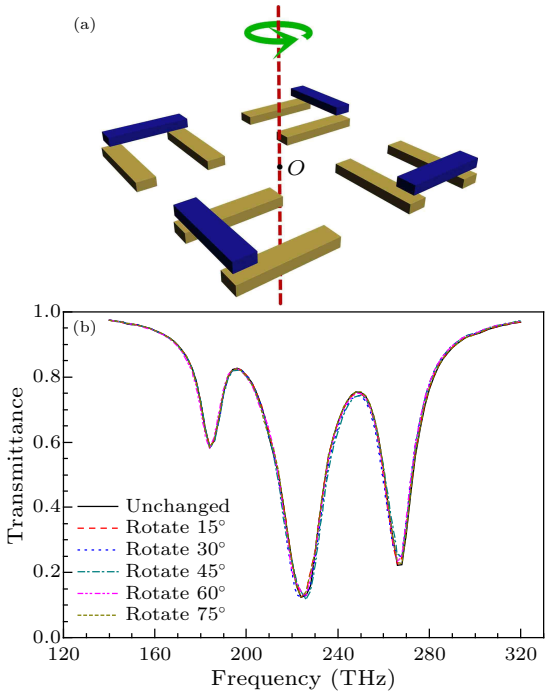

Fig. 7. (a) Schematic diagram of structure's rotation. (b) Transmittance as a function of frequency for different rotation angles.

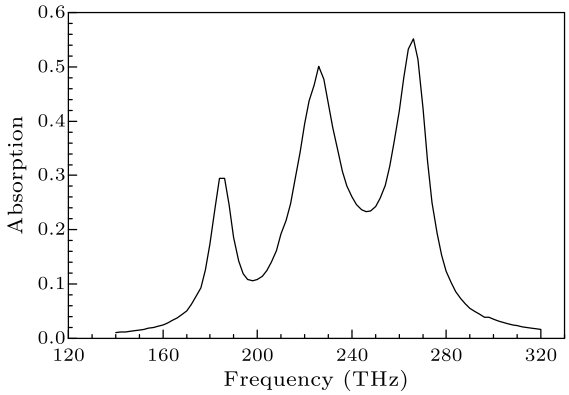

Fig. 8. Absorption as a function of frequency for the structure shown in Fig. 1.

The Fano resonances are often accompanied by an analogue of electromagnetically induced transparency. To verify it, we computed the electromagnetic absorption of the structure by 1–T–R, where T is transmittance, and R is reflectance. The result is plotted in Fig. 8. From the figure we can find that the absorptions decrease evidently at the frequencies of 196 THz and 248 THz and are equal to 0.109 and 0.234, respectively. It indicates that the Fano resonances cause an analogue of electromagnetically induced transparency at the two resonance frequencies.

In summary, we have proposed a combined structure which comprises an array of two gold rods in transverse arrangement and one gold rod in longitudinal arrangement. The simulation results demonstrate that the structure exhibits a phenomenon of two types of Fano resonances and an analogue of electromagnetically induced transparency at the resonances. We disclose that the two Fano resonances originate from the coupling between magnetic quadrupoles and electric dipoles at the low-frequency position and the coupling between electric quadrupoles and electric dipoles at the high-frequency position by analyzing the current distributions of the metal rods. Additionally, the simulation results also demonstrate that the double Fano resonances are insensitive to the polarization directions of the incident wave. Such a polarization-insensitive structure has more potential applications in optoelectronics.

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