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Multiple Fano Resonances Structure for Terahertz Applications

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Abstract—A new planar engineered material structure, which has multiple Fano resonances at the terahertz range of frequency, is presented. Starting with a double Fano resonance structure, it is shown that by considering several unit cells as a larger unit cell and creating new asymmetries in the super-cell, we can have five Fano resonances in one structure. Analysis of current distributions at resonance frequencies clarifies the origin of different resonances. We show that all of these resonances come from different arrangement of magnetic dipoles.

1. INTRODUCTION

Engineered materials have found many important applications in all ranges of frequencies. A large number of reported structures use split ring resonator (SRR) and double-split ring resonator (DSRR) as their main building block. Having an asymmetry in the two gaps of a DSRR can excite a resonance mode with asymmetric line shape, which is called Fano resonance. But DSRR is not the only structure which can support Fano resonance. Many other structures have been shown to exhibit Fano resonances at microwave [1] and terahertz [2–5] and optical [6–9] range of frequencies. Because of its asymmetry in the line shape, Fano resonance has higher quality factor as compared with the ordinary Lorentz resonance. A structure which shows several Fano resonances at different frequencies is very useful for multi-frequency sensing applications. While single Fano resonance comes from combination of one bright mode and one dark mode, combining a bright mode with several dark modes can result in several Fano resonances [10–15]. Here, we propose a new planar structure which shows five Fano resonances at the terahertz frequencies. The proposed structure has evolved from simple configurations. Figure 1 shows the starting structure, which consists of a rod and two U shape segments around it. In [14] a single element of this structure is proposed and considered at the optical regime for double plasmonic Fano resonances. Here, we use an array of this structure at the terahertz range, and try to create more Fano resonances by introducing new asymmetries in a planar periodic structure.

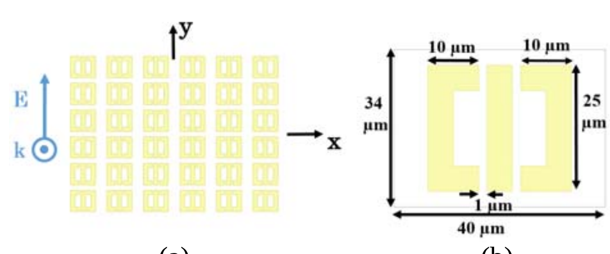

Figure 1. (a) Planar periodic structure. (b) One unit cell.

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2. CONFIGURATION

Let us consider a typical structure, shown in Figure 1, wherein metallic parts are made of gold, and high resistive silicon is used as the substrate. Gold has very high conductivity at THz frequencies, and HFSS model of gold is used for metallic parts. High resistive silicon is a very low loss material at the THz range, and has permittivity of 11.7 for a very wide range, including THz frequencies. The structure is excited by a normal incident plane wave with vertical polarization, as shown in Figure 1. Using periodic boundary conditions in HFSS software, one can study the whole structure by analyzing just one unit cell. Floquet port in HFSS is used for top and bottom of the unit cell to model the plane wave excitation of this periodic structure. Figure 2(a) shows the plane wave transmission spectrum, which is normalized to that of the bare silicon substrate. Two Fano resonances, with asymmetric line shapes, can be seen at 1.55 and 2.35 THz. To find the origin of these resonances, Figure 2(b) shows the current distribution at resonance frequencies. The resonance at 1.55 THz is mainly due to the coupling of the incident wave to the U-shape sections and the resonance at 2.35 THz comes from coupling of the incident wave to the rod. These can be seen from the current distribution in Figure 2(b). Also, the ratio of the wavelength at 1.55 THz to that of 2.35 THz is very close to the ratio of the length of the U-shape section to that of the rod. Current induced in each U-shape section, combined with that in the middle straight section, forms a closed loop. These current loops are equivalent to two magnetic dipoles in the opposite directions (z and $-z$). In the rest of this paper the evolution of a new and highly asymmetrical structure with up to five Fano resonances is presented.

Starting with a fully symmetric structure, the first asymmetry can be generated by making L_1 and L_2 different, as shown in Figure 3(b). In this case, two loops have different sizes, so magnetic dipoles will be excited at different frequencies. Figure 3(a) shows the transmission spectrum for this case. Another

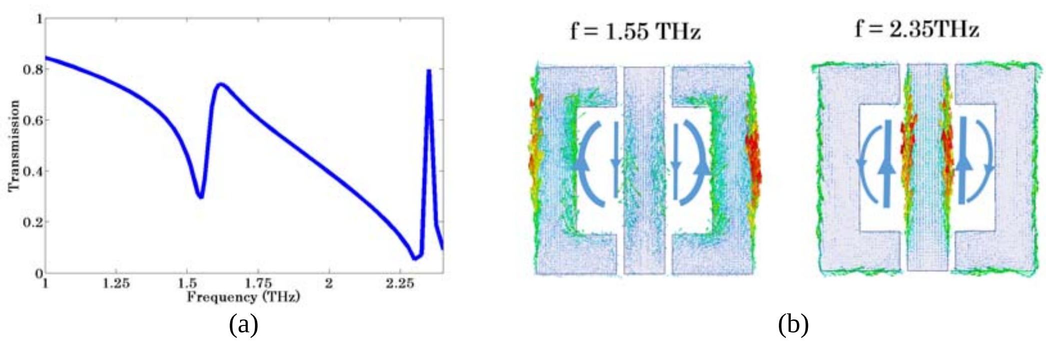


Figure 2. (a) Transmission spectrum through the structure shown in Figure 1. (b) Current distribution at resonance frequencies.

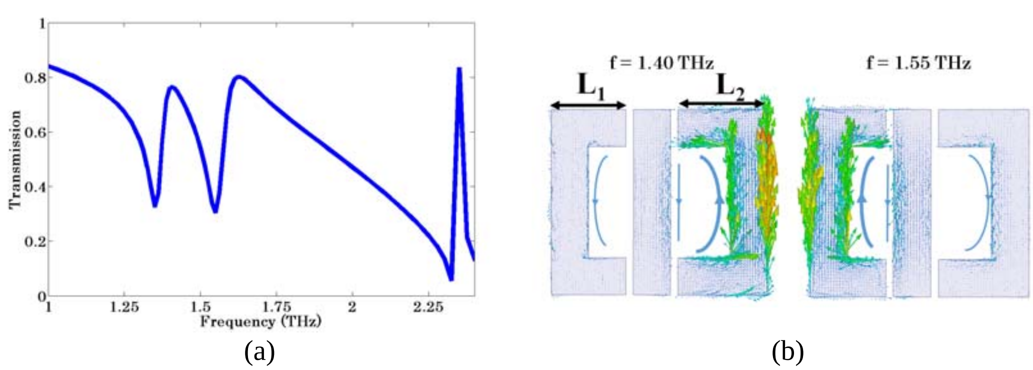


Figure 3. (a) Transmission spectrum. (b) Current distributions on the structure with $L_1 = 10\,\mu\text{m}$ and $L_2 = 13\,\mu\text{m}$.

Fano resonance is added at 1.40 THz. Figure 3(b) shows current distribution for 1.40 and 1.55 THz (current distribution at 2.35 THz is similar to the previous case). From current distributions, it can be concluded that two magnetic dipoles are also excited in this case, but at different frequencies, since the loop sizes are different. At 1.40 THz the larger loop is excited, whereas at 1.55 THz the smaller loop is excited.

3. NEW FANO RESONANCES USING ASYMMETRIES IN SUPER-CELL

The structure proposed in previous section is based on asymmetric cells. In order to increase the number of Fano resonances, if we consider two adjacent unit cells as one super-cell, as shown in Figure 4, by interchanging the positions of L_1 and L_2 in the bottom cell, another asymmetry will be created. Figure 5(a) shows the transmission through this structure. As can be seen there are four Fano resonances in this structure. Figure 5(b) shows the current distribution at 1.38, 1.53 and 1.63 THz (current at 2.35, the last resonance, is similar to the previous case). As can be seen in Figure 5(b), the resonance at 1.38 THz, the lowest resonance frequency, is from the loop current in the U-shape sections (the current in the middle section is very small). The top loop and the bottom loop have opposite current directions because of the last second introduced asymmetry (exchanging the position of L_1 and L_2 in the bottom cell). The resonances at 1.53 and 1.63 THz come from coupling to the loop current in the larger loop and

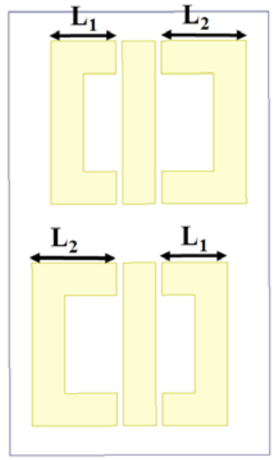
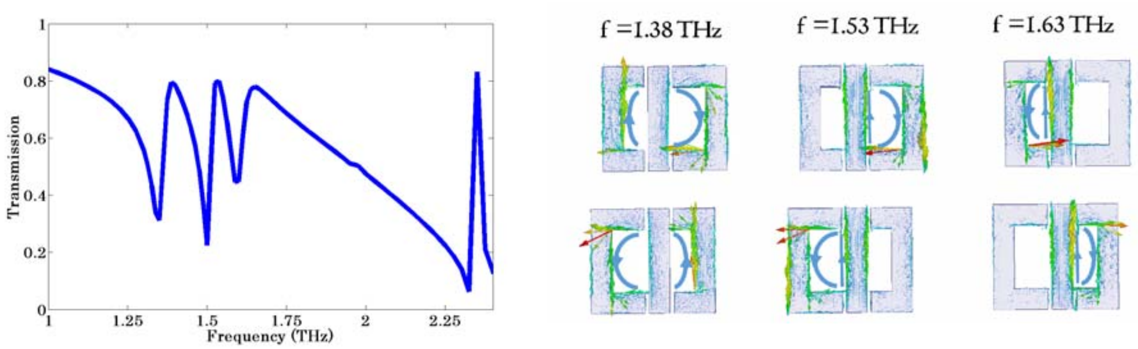


Figure 4. Proposed structure (super-cell), combining two adjacent unit cells defined in Figure 1(b) with interchanged positions of L_1 and L_2 sections in the bottom half of the asymmetrical super-cell.



(a) (b)

Figure 5. (a) Transmission spectrum through structure with unit cell shown in Figure 4. (b) Current distributions at resonance frequencies of structure with unit cell shown in Figure 4.

smaller loop respectively. Interestingly, the new resonance does not reduce the quality factor of previous resonances, and even increase it. This can be described as the equivalent magnetic dipoles, for the large loop at 1.53 THz and that for the small loop at 1.63, have opposite directions for top and bottom cells in the super-cell, while they had same direction in the previous structure. Each two magnetic dipoles with opposite directions will make a magnetic quadruple, which is less radiative than magnetic dipole and therefore it will have higher quality factor. The resonances at 1.38 THz and 2.35 THz are also from two magnetic dipoles with opposite directions.

In the last step, a new resonance is generated by making the two unit cells in each super-cell closer to each other in the vertical direction (y axis) as shown in Figure 6. In this way, they can couple more efficiently and higher order mode can be excited as well. One more resonances is added at 1.78 THz, as shown in Figure 7. Figure 8 shows current distribution for the newly added resonance at 1.78 THz. As the current distribution shows, this mode is higher order mode for each metallic section.

Higher order diffraction orders can be excited when the periodicity is smaller than the effective wavelength. The average refractive index between subtract and air is 2.21, and the largest periodicity in the super-cell is 68 µm. So the smallest wavelength without exciting higher diffraction orders is $68 * 2.21 = 150.28$ µm, which corresponds to the frequency of 2 THz. The resonance at 2.35 THz can

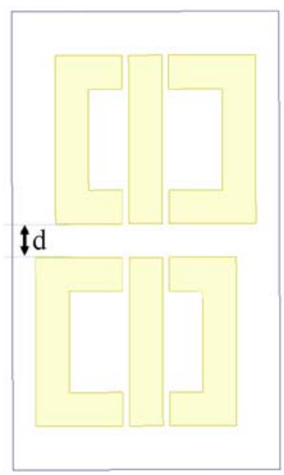


Figure 6. Decreasing the value of d, from 9 µm in the previous structure to 5 µm, to increase coupling between two cells in each super-cell.

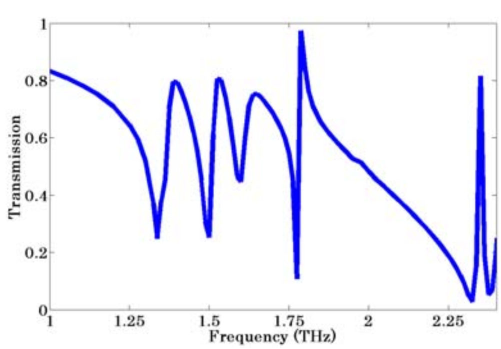


Figure 7. Transmission spectrum through the structure shown in Figure 6.

Figure 8. Current distributions at two added resonances at 1.78 and 1.42 THz.

not be from higher diffraction orders, because this resonance also exists in the structure of Figure 1, in which the largest periodicity is 40 μm, and the higher diffraction orders will not be excited until up to 3.39 THz.

Since Fano resonance has asymmetric line-shape, its quality factor (Q) can be defined as: $(f_2 + f_1)/(2(f_2 - f_1))$, in which f_1 is the frequency of the minimum transmission point and f_2 is that of the maximum transmission point. A useful figure of merit, FOM, to compare the resonances is FOM $= Q * A$, in which A is the resonance amplitude defined as the maximum transmission minus minimum transmission (all transmission values are normalized to the transmission through bare silicon substrate). FOM for the five Fano resonances in the last structure, Figure 7, are 10, 22, 8, 104, and 62, from lowest frequency to the higher frequencies. The first and second highest FOM values (104 and 62) are larger than any FOM for Fano resonances at THz range reported so far. The number of Fano resonances excited in the proposed structure is five, which is the highest value reported so far.

4. CONCLUSION

We have shown that up to five Fano resonances can be achieved in a single planar structure by introducing several asymmetries. If we consider several unit cells as a super-cell, new possibilities for having more asymmetries will emerge. We have shown that new resonances do not reduce the quality factor of previous resonances and can even increase it through alternating magnetic dipoles with same direction to the magnetic dipoles with opposite directions, (magnetic quadruple). Existence of several sharp Fano resonances can be very useful for multi-frequency sensing and spectroscopy applications.

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