Tuning Trapped-mode Resonances in a Planar Metamaterial

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Abstract— We demonstrate tuning of trapped-mode resonances in a symmetric planar metamaterial both experimentally and theoretically. By controlling the excitation of the Fano-type trapped-mode resonance via the angle of incidence, its quality factor is controlled and the resonance is red-shifted by up to 21%.

1. INTRODUCTION

The asymmetric Fano resonance, which has long been known as a characteristic feature of interacting quantum systems, has more recently been found in plasmonic nanostructures and metamaterials [1, 2]. The steep dispersion of the Fano resonance profile promises applications in slow light [3–9], sensor [10, 11], nonlinear [12] and switching [13] applications. Fano resonances in metamaterials were first observed in arrays of asymmetrically split rings [14], consisting of two wire arcs of different lengths. Incident electromagnetic waves with the electric polarization parallel to these asymmetric wires can excite a high-Q mode formed by counter-propagating currents, i.e., a so-called trapped mode resonance that is associated with an asymmetric Fano-type line shape [14]. The quality factor of such trapped-mode resonances is mainly limited by losses and attempts to compensate or eliminate Joule losses using optically-pumped gain media such as semiconductor quantum dots [15, 16] and superconducting metamaterials [17] have been reported. The tunability of Fano resonances is another key issue. Tuning of a Fano resonance was observed when crossing the superconducting transition temperature of a superconducting metamaterial [17]. Most generally, the properties of Fano resonances can be controlled by the metamaterial design [14, 18–20]. However, it is extremely difficult to change the geometrical size of elements once they are fabricated. Therefore, a practical way of controlling Fano resonances is of great importance for developing metamaterials for real applications [21].

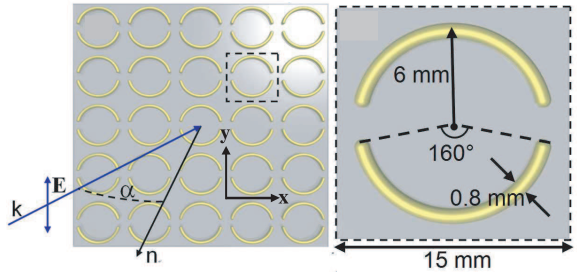
In this paper, we report that trapped-mode Fano-type resonances in a planar metamaterial can be efficiently controlled via the angle of incidence, offering an easy-to-implement way of achieving local field tunability in metamaterials. We demonstrate tuning of the trapped-mode quality factor and its spectral localization experimentally and numerically.

2. EXPERIMENTAL AND SIMULATED RESULTS

We investigate resonance tuning in a meta-surface based on symmetrically split rings (SSR), see Fig. 1. The SSR consists of two identical wire arcs corresponding to 160° and each copper split ring has a radius of 6 mm and a width of 0.8 mm. Due to its high symmetry, this structure does not allow the excitation of anti-symmetric currents at normal incidence. The metamaterial consists of a square meta-molecule array with a period of 15 mm and an overall size of about $200 \times 200\,\text{mm}^2$. It was etched from 35 μm copper cladding covering FR4 PCB substrate of 1.6 mm thickness. Detailed dimensions of the SSR unit cell are given in Fig. 1(b). The SSR metamaterial transmission was measured at angles of incidence from 0° to 50° in the 9–14 GHz frequency range. The experiments were carried out in an anechoic chamber using broadband horn antennas (Schwarzbeck BBHA9120D) equipped with dielectric lens concentrators and a vector network analyzer (Agilent E8364B).

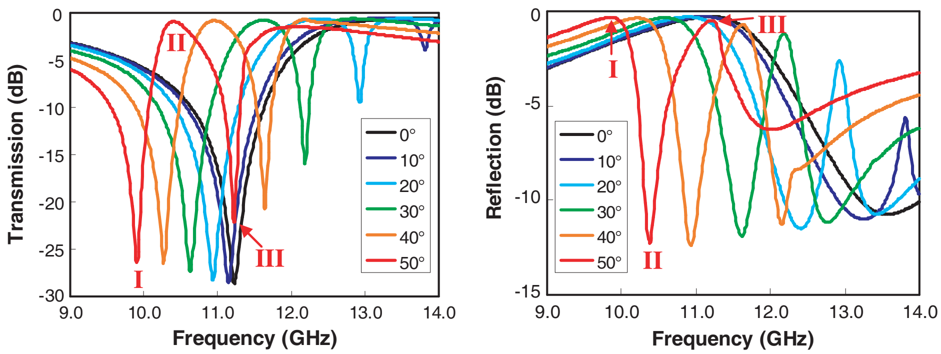
The electromagnetic response of the SSR metamaterial was also simulated using a full three-dimensional Maxwell finite element method solver in the frequency domain, where copper was treated as a perfect electric conductor and a permittivity $\varepsilon = 4.05 - i0.05$ was assumed for the lossy dielectric substrate. For the results presented below, both the polarization of the incident wave and the axis around which the metamaterial was tilted to achieve oblique incidence were perpendicular to the SSR wires (i.e., the y-axis), see Fig. 1.

Figures 2 and 3(a) show simulated and measured transmission and reflection spectra of the SSR metamaterial as a function of the angle of incidence α. At normal incidence onto the metamaterial y-polarized electromagnetic waves can only excite one electric dipole resonance at about 11.3 GHz.



(a) (b)

Figure 1: Metamaterial structure. (a) The angle of incidence α is measured between the incident wave vector k and the metamaterial's surface normal n. Here metamaterial transmission and reflection are studied for y-polarized electromagnetic waves at oblique incidence which is realized by tilting the metamaterial around its y-axis. (b) Symmetrically split ring (SSR) unit cell.



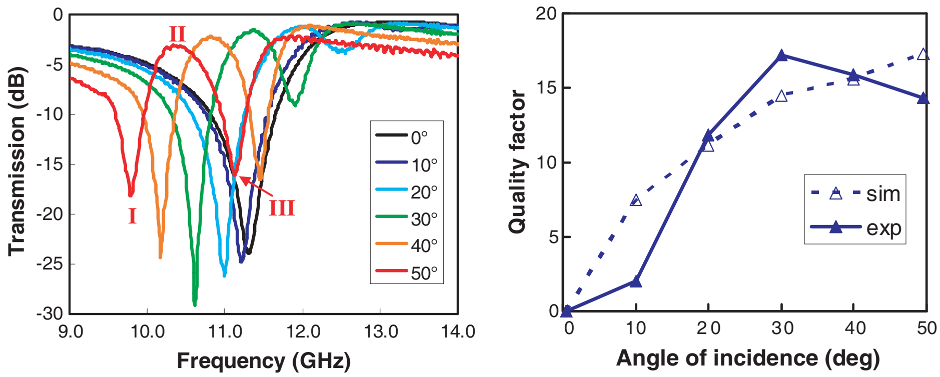
(a) (b)

Figure 2: Simulated transmission and reflection of the SSR metamaterial for various angles of incidence. The resonant modes corresponding to resonances I, II, and III are shown in Fig. 4 for $\alpha = 50°$.

The excitation of the trapped mode, which consists of anti-symmetric current oscillations in opposite wire arcs, is prohibited by the high experimental symmetry in this case. However, when the metamaterial pattern is tilted around the y-axis, the trapped-mode resonance appears: a narrow pass band (reflectivity minimum) which may also be discussed in terms of electromagnetically induced transparency (EIT) [3] forms between two transmission minima. It is obvious from Figs. 2 and 3(a) that the SSR metamaterial exhibits large frequency tunability of the trapped-mode resonance. With increasing α, the pass band II becomes more pronounced and as illustrated by Fig. 3(b) its quality factor measured as $Q = f/\Delta f$ increases to about 18 at $\alpha = 50°$ (peak width $\Delta f = 0.6$ GHz at 3 dB below maximum). Simulations [Fig. 2(a)] and experimental results [Fig. 3(a)] agree well with each other, however, the resonant feature II is more pronounced in the simulations. This deviation is linked to scattering from the edges of the experimental sample, which was assumed to be an infinite periodic structure in the simulations.

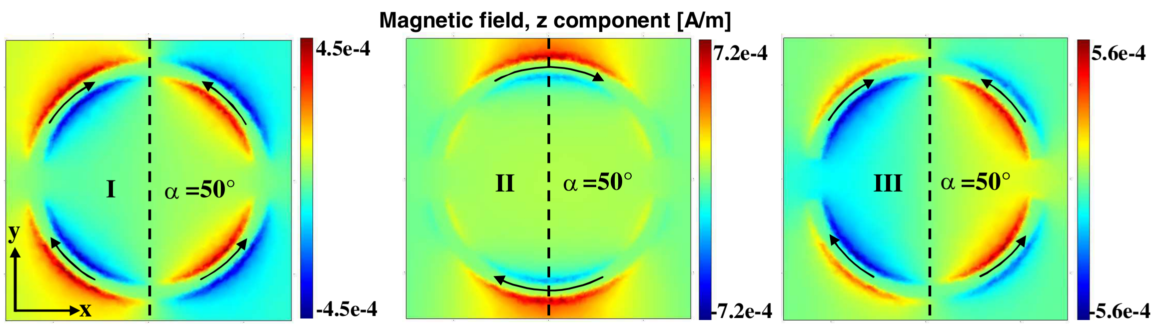
Oblique incidence leads to a small delay between the excitation of the two arcs of the SSR. This delay is sufficient to allow the excitation of an antisymmetric trapped current mode associated with transmission maximum (reflection minimum) II, which gives rise to a strong magnetic dipole [see Fig. 4(b)]. In contrast to this magnetic dipole mode, resonances I and III are electric dipole resonances with no significant net magnetic field [see Figs. 4(a) and (c)]. At normal incidence, the excited magnetic fields show perfect symmetry with respect to the mirror line of the SSR and completely cancel each other, leading to a vanishing magnetic dipole moment.

The anti-symmetric current oscillations of the trapped-mode resonance II are largely dominated by the x-directional surface currents propagating along the wire arcs. Fig. 5 shows the frequency dependence of the x-directional surface current density at different angles of incidence. At normal incidence, the net x-component of the surface current is zero in each arc. As the angle of incidence increases, currents of equal magnitude oscillating in anti-phase in the two wire arcs appear. In particular the increasing angle of incidence results in a 10-fold enhancement of the magnitude of the excited currents and a remarkably large red-shift of the trapped-mode resonance, which can be tuned from 13.2 GHz to 10.4 GHz. The large magnitude of the anti-symmetric currents results from



(a) (b)

Figure 3: Measured transmission and quality factor. (a) Measured transmission spectra for various angles of incidence. (b) Quality factor for the pass band II as a function of the angle of incidence (dashed line: simulation, solid line: experiment).



(a) (b) (c)

Figure 4: Snapshots of the normal magnetic field at resonances I-III at $\alpha = 50°$, compare Fig. 2. All field maps show the field amplitude at its maximum. The arrows indicate the instantaneous direction of the excited currents and the dashed lines correspond to the SSR mirror line along the y-axis.

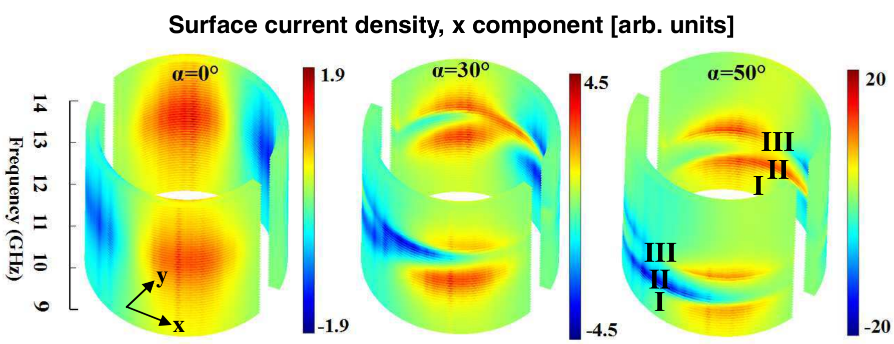


Figure 5: X-component of the instantaneous surface current density as a function of frequency at 0°, 30° and 50° oblique incidence.

the fact that any fields emitted from opposite arcs would destructively interfere in the far-field and therefore the electromagnetic energy is trapped at the meta-surface, ensuring a high quality factor of the pass band.

3. CONCLUSIONS

In summary, we experimentally and numerically demonstrate that the excitation of trapped-mode resonances in SSR metamaterials can be controlled via the angle of incidence. In particular, we have realized trapped mode on/off switching, tuning of the resonance quality factor and a 21% red-shift of the trapped-mode resonance via the angle of incidence for a simple, planar model structure based on symmetrically split rings. The structure is well-suited for existing micro-and nanofabrication technologies and tuning via the incidence angle can be easily applied anywhere in the electromagnetic spectrum. The EIT-like behavior of the SSR metamaterial makes it a promising candidate for "slow light" applications, while local energy confinement provides in interesting platform for nonlinear and gain metamaterials and the lasing spaser.

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