3-Dimensional Anisotropic Split Resonant Cavity

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Abstract. An innovative 3-Dimensional split resonant cavity (SRC) is introduced here as an enhancement of planar split-ring resonators (SRRs), which could overcome the strong dependence of SRRs on polarization. Numerical simulations demonstrate that multiple resonances, including electric dipole mode, magnetic dipole mode and interaction of both modes, can be excited by three different polarized incident electromagnetic (EM) waves. Fano resonance characterized by asymmetric transmission line shape due to interference of multiple modes is observed in the simulation.

Keywords: split resonant cavity, Fano resonance, asymmetric, polarization.

1. Introduction
Metamaterial with negative refraction index was theoretically investigated by Veselago [1] in 1968, and extraordinary phenomena due to the simultaneously negative permeability and permittivity were predicted, including negative refraction, inverse Doppler effect and reversed Cherenkov radiation. In order to couple magnetic dipole resonance with electric dipole resonance, D. R Smith et al. put forward a periodic array of interspaced conducting nonmagnetic split ring resonators and continuous wires [2], and successfully realized a negative refraction index metamaterial [3]. Since then, metamaterials have spurred intense discussions and various structures have been proposed over the last several decades as evolvements of SRRs to diversify metamaterial elements [4~9]. Most of these designs, however, are planar structures and strongly dependent on polarization [10], which means resonance can be excited only by incident electromagnetic (EM) waves with the designated polarization.

Recently, some 3-Dimensional designs have been reported to overcome the polarization dependence barrier. On another hand, the coupling between electric dipole mode and magnetic dipole mode can generate a complex interaction that leads to asymmetric transmission lineshape, the so-called Fano resonance [11], which was first discovered by Ugo Fano in 1961. Fano resonance has been observed in asymmetric split-ring arrays [7], and widely found in metamaterials since then, from radio frequency to optical region [7~8]. Due to the high-Q character and sensitivity to input parameters, Fano resonances have been applied to chemical and biological sensing [12], surface enhanced spectroscopy [13], active plasmonic switching [14], and slow light devices [15~16].

In this paper, we introduce an innovative 3-Dimensional split resonant cavity (SRC), in which multiple resonances including strong magnetic dipole mode, electric dipole mode, and interaction of both modes, can be excited by EM waves with different polarization modes. This SRC is highly sensitive
to the incident angle, at a certain angle with proper polarization it can behave as a multiband filter or a magnetic field confiner.

2. Design of Split Resonant Cavity and Simulation Setup
As we can see from Fig. 1, a 3-dimensional split resonant cavity (SRC) contains two metal hemispherical shells adjoined by a metal pillar located at the center of the cavity.

Fig. 1 Schematic representations of the SRC with different polarizations. (a) A possible arrangement of SRC arrays, which is not necessarily adopted by all of the following measurements. Inset is the cross-section of the SRC. (b)-(d) Representations of three different polarizations.

Fig. 1(a) reveals the cross section of the cavity, where $r_1$ denotes the outer radius of the shell and $r_2$ the inner radius. The diameter of the pillar and the width of the split gap are denoted as $d$ and $g$ respectively. Numerical simulations demonstrate that EM waves of different polarization can cause multiple resonant modes in the introduced SRC. Fig. 1(b) represents an incident wave directed at an azimuthal angle of $\theta$ to the $z$-axis (along with the pillar) while magnetic field set along $x$-axis or $y$-axis. Figs. 1(c) and 1(d) indicate the incident wave directed at an azimuthal angle of $\theta$ to the new $z$-axis (perpendicular to the pillar) with magnetic field oscillating along $x$-axis and $y$-axis, respectively. Hence, with the identical wave direction and $H$ field oscillation, Figs. 1(b) to (d) represent three different polarizations. In the rest of this paper, we refer to the polarizations depicted in Fig. 1(b)-(d) as PB, PC and PD respectively. To analyze the performance of SRC excited by electromagnetic wave with different polarizations, we use Comsol software to investigate numerically its spectral properties. Floquet periodic boundary conditions are adopted with periodicities set along $x$-axis and $y$-axis. The calculations are performed on a copper SRC with $r_1 = 2.0\text{mm}$, $r_2 = 1.8\text{mm}$, $g = 0.4\text{mm}$ and $d = 0.8\text{mm}$.

3. Results
Fig. 2(a), 2(b) and 2(c) show the transmission properties corresponding to PB, PC and PD respectively with $\theta = 0$ (normal incidences). As we can see, all three polarizations can contribute resonant transmission properties, and different polarizations lead to distinctive transmission lineshapes. When the incident EM wave is parallel to the pillar with magnetic field oscillating along $y$-axis (PB condition), two resonances are excited in the SRC (Fig. 2(a)). The first dip of the transmission curve at the lower frequency comprises a centrosymmetric imaginary part and a symmetric real part, resulting in a symmetric transmission lineshape. Fig. 2(d) shows the field and current distribution of the first resonance. One can see that electric field concentrates at the +x and -x sides of SRC, while magnetic field is localized at +y and -y sides. Current mainly exists on the outer spherical surface of SRC, flowing...
in -x direction, and current on the inner surface is relatively negligible. Thus it can be concluded that an electric dipole mode is excited [17].

![Fig. 2](image)

**Fig. 2** Transmission properties of SRC corresponding to PB, PC and PD. (d)-(h) Electric field distributions (color map in i & ii), magnetic field distributions (color map in iii & iv), and surface currents (red arrows) in yx-plane (i & iv) and xz-plane (ii & iii) corresponding to resonances marked as d-h in (a)-(c).

However, a centrosymmetric imaginary part and an asymmetric real part compose the second nadir of the transmission curve, resulting in a Fano resonance-like asymmetric transmission lineshape. This asymmetric lineshape results from coupling of different resonance modes. Within a narrow spectral range, this interaction between different modes changes dramatically from constructive interference to destructive interference, causing a sharp dive and steep rise to the transmission curve. Electric field distribution and magnetic field distribution of the second resonance mode appear like two orthogonal pairs of bananas inside the split gap, with electric pair along the x-axis and magnetic pair along the y-axis (Fig. 2(e)). The current flow distribution is more complex compared with that of the first resonance. On the outer spherical surface of the SRC’s +z half, current flows from -x side to +x side, then goes back to -x side along edge of the split gap, while on the -z half current flows in the exactly opposite direction. On the inner spherical surface of SRC, current magnitude is relatively smaller and flows oppositely in contrast with outside currents. On the pillar surface, the currents flow counterclockwise observed from +y direction (Fig. 2(e)). Both electric dipole and magnetic dipole nature of current distribution are observed.

From 20.042 GHz to 20.044 GHz, electric field and magnetic field further condense into the banana pair area, resulting in a rise of maximum electric and magnetic magnitude (Fig. 3). However, this subtle frequency increase causes magnetic field to invert while electric field stays the same, indicating a reversion of magnetic dipole. On the other hand, maximum Hy magnitude experiences two peaks respectively at 20.042 GHz and 20.044 GHz (Fig. 3(e)), validating a phase shift of $\pi$. Hence we can conclude this resonance is an interaction of a wide spread flat electric dipole mode and a magnetic dipole mode with high quality factor that takes place within the range of the former electric dipole mode [7] dramatic reversion of magnetic dipole changes the coupling of two resonances from constructive interference to destructive interference, causing a Fano resonance.
When PC is taken into consideration, only one Lorentzian resonance with centrosymmetric imaginary part and symmetric real part is observed (Fig. 2(b)). 3-dB bandwidth is around 0.225 GHz, and by dividing a resonant frequency of 10.14 GHz, a quality factor higher than 45 is obtained. Strong electric field and magnetic field are generated. Electric energy fills in the split gap, forming a doughnut-like electric field distribution, and magnetic field is confined inside the cavity, suggesting a strong magnetic dipole [15, 17] (Fig. 2(f)). Currents mostly exist on the inner surface of SRC, looping in a circle formed by the pillar and the inner spherical surface.

Two resonances can also be excited by EM wave with propagating direction orthogonal to the pillar and magnetic field parallel to the pillar (for PC condition). The transmission lineshape has a symmetric nadir and an asymmetric one, which is quite analogous to that of PB. The first resonance occurs at 19.98 GHz, near to 19.978 GHz of PB. Notice that in the cases of PB and PD, electric polarizations of the incident wave are perpendicular to the pillar, but parallel to the pillar in the case of PC. We can safely conclude that the polarization of electric field plays an important role in determining the spectral properties of SRC, while magnetic field exerts less but certain influences. Field distribution as well as current density distribution is reveals the electric dipole nature of the first resonance mode (Fig. 2(g)). The second resonance takes place at 20.074 GHz, higher than that of PB. Compared with the second resonance of PB, this one seems to have a more complex nature. Judging by the eccentric current loops, a weak magnetic dipole accompanied by electric dipole is excited (Fig. 2(h)).

4. Summary

In conclusion, an innovative anisotropic split resonant cavity is introduced. Distinctive transmission curves marked by multiple resonant modes, including strong magnetic dipole, electric dipole, and interaction of both modes, can be excited by EM waves with different polarization. Fano resonance is observed. Due to the interesting characteristics discussed above, this structure can be very promising to various applications.

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