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TRAPPED MODE RESONANCES IN METALO-DIELECTRIC STRUCTURES WITH ELECTRIC ASYMMETRY

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***Abstract* - The excitation of an anti-symmetric trapped mode on a symmetric resonator structure is demonstrated through numerical simulation. The electrical symmetry is broken by using different dielectric substrates leading to trapped modes being excited onto a geometrically symmetric metallic structure. These modes are weakly coupled to free space, therefore their resonant response yields a high quality factor.**

I. INTRODUCTION

Electromagnetic metamaterials and their potential applications have attracted significant attention from the scientific community in recent years. The research is driven by the opportunity to achieve electromagnetic properties that lead to new phenomena such as negative refraction, perfect magnetic surface or cloaking [1], which have no equivalents in natural world.

Most of such 'exotic' electromagnetic response of metamaterials is due to their resonant behaviour, hence achieving a high-quality factor resonance is essential to obtain an efficient metamaterial based device. Typically, a metamaterial cell comprises a metallic structure – on which currents can be induced – and a supporting dielectric substrate. Depending on the induced current distribution in the conducting region, different resonance modes can be excited within these cells. Most of these resonant structures do not have a very high resonant quality factor because they suffer significant radiation losses. Moreover, due to their relative small size with respect to the wavelength of operation, the metamaterial cell structures are not able to provide a large enough volume for the confinement of electromagnetic field necessary to support high quality factor resonances. However, most recent theoretical analysis and experimental results have shown that high quality factor resonances involving trapped modes are possible in metamaterials, providing a certain small structural (geometrical) asymmetry is introduced to the shape of their structural conducting elements [2, 3, 4, 5].

In this work it is shown through numerical simulation that similar effects can be achieved without breaking the geometrical symmetry of the resonator but instead by introducing an electrical asymmetry through a combination of substrates with different dielectric properties.

II. ELECTRICAL ASYMMETRIC TRAPPED MODE RESONATOR

The structures studied in this work are based on a split ring configuration arranged in a periodic array (Fig. 1). The split rings are assumed to be made of copper, with a radius of 6mm, 0.8mm width and 35μm thickness. The substrate thickness is 1.5mm and cell dimensions are 15×15mm. The ring is split along the *y* direction. By removing the conducting material within the two 20^o angles as illustrated in Fig. 1, two equal conducting arcs are obtained. The array is considered to be infinitely long in the *x* and *y* directions, therefore this arrangement can be simulated under periodic boundary condition assumption. Such an arrangement will not normally diffract a normal incident electromagnetic wave for frequencies lower than 15GHz.

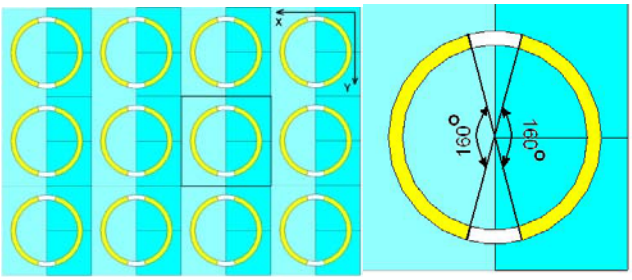

Fig. 1. Planar array of split ring resonators and elemental cell

To confirm this behaviour a 'full wave' simulation using commercially available software (CST Microwave Studio) was undertaken. The periodic array from Fig. 1 was illuminated with a transverse electromagnetic wave for two polarizations, in *x* and *y* directions respectively. A frequency sweep between 3 and 15 GHz was then simulated and the transmission and reflection through and from the split rings array were calculated. As expected, no diffraction was observed in this band.

As mentioned in Introduction this behaviour can be changed by breaking the symmetry of the metallization and asymmetrically split rings have been shown to diffract normal incident waves at relatively low frequencies [2]. For asymmetric split ring structures the transmission and reflection properties depend strongly on polarization of the incident wave. For our numerical experiment we have kept the split rings symmetrical but changed the substrate in such a way that half of it has a different value of the dielectric constant to the other half. Taking into account the two wave polarizations described above, two possibilities have been considered of how the substrate could be partitioned. Our simulations, however, have shown that only one situation (Fig. 1) creates a response similar to the asymmetric split rings arrangement. In this case, for an electromagnetic wave incident to the array with a polarization normal to the mirror line (*y* polarization in Fig.1), the reflection and transmission responses create a very different situation than the symmetric split rings with homogenous substrate (Fig. 2). The reflection plot for the new electrically asymmetric case reveals a very sharp resonance just bellow 6GHz (Fig. 2). Two weaker resonances, corresponding to peaks in the reflection response, are also present at 5.8 and 7.3GHz respectively. The transmission plot shows a very narrow peak reaching −4.78dB. Its width is only 0.36 GHz as measured at 3dB below the maximum. The quality factor of such response can be calculated as the ratio between the bandwidth at 3dB, as mentioned above, and the centre frequency that is 5.85GHz. The resultant value of 16 is larger by at least one order of magnitude than for most metamaterials based on lossy PCB substrates. This set of results was obtained for the following material combination: half of cell substrate had $\varepsilon_r = 4.07$ and $\tan\delta = 0.012$ and the other half $\varepsilon_r = 5$ and $\tan\delta = 0.012$.

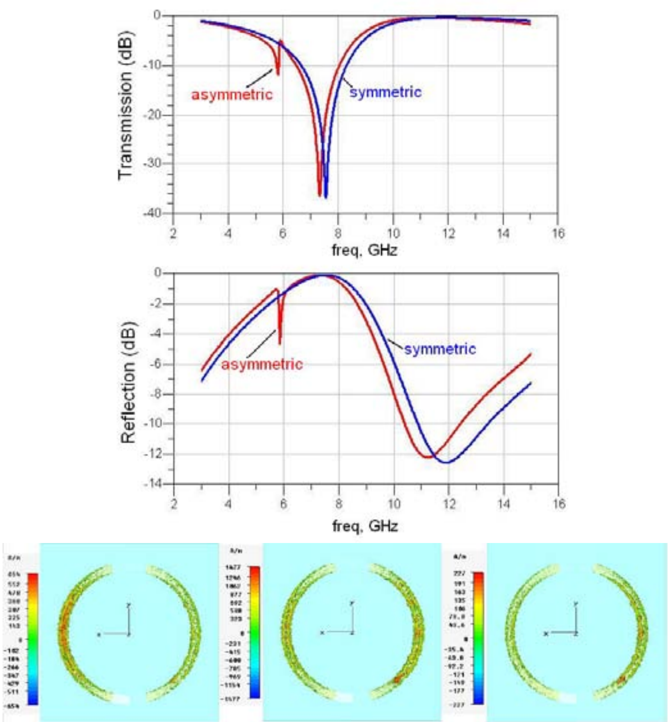

Fig. 2. Transmission and reflection of normal incident wave for *y*-polarization. Current density distributions at 5.8, 5.856 and 7.3 GHz

To understand the resonant nature of the response of the electrically asymmetric structure the distribution of the current density within the cell has been be analysed. It can be observed (Fig. 2) that an asymmetric current mode dominates the usual symmetric mode (dipole mode). At 5.856GHz the currents flowing in the two parts of the ring are in anti-phase while having almost the same amplitude. In this configuration the dipole radiation of the two oscillating currents in the arcs cancel each other. The magnitudes of the induced currents reach very high values which results in a very high quality factor response. This type of response is not accessible in a symmetrical structure and the high quality resonant mode excited is said to be trapped within the structure; hence the name “trapped mode”. At 5.8GHz, the two currents are not in anti-phase anymore and the current in the left hand arc has higher amplitude than the current in the right hand arc. In this configuration a dipole mode is excited. At 7.3GHz the right had side current will dominate and the two currents are now almost in phase. Again a dipole mode response is observed. Importantly, the amplitudes of the currents for the dipole mode cases are significantly smaller than for the trapped mode which yields lower quality factor for this type of response. For further analysis we have defined an asymmetry factor ξ as a ratio between ε_r of the substrate for the two halves of the cell ($0<\xi<1$). Our numerical simulations have shown that by reducing ξ the resonances, including the trapped mode resonance, shift towards lower frequencies (Fig. 3). We have also noted that the quality factor has a maximum of about 17 for $\xi = 0.68$.

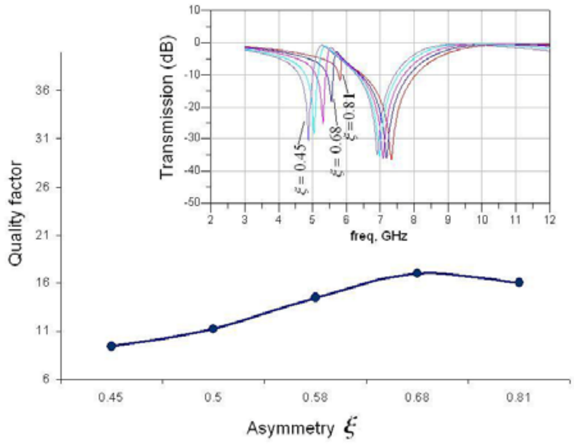

Fig. 3. Quality factor of the trapped-mode for different asymmetry factors

III. CONCLUSIONS

In this work we have studied through numerical simulation the possibility of exciting trapped modes in structures with geometrical symmetry but with electrical asymmetry. The asymmetry is achieved by using simultaneously substrates of different dielectric properties within the cell of the resonator. The new structures exhibit high quality resonances due to the excitation of trapped modes providing extremely narrow transmission and reflection pass and stop bands.

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