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Tightly Coupled Resonant Pairs as Metamaterial Constituents

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Abstract **− The distinctive features and properties of metamaterials containing the constitutive particles composed of tightly coupled pairs of the dogbone shaped conductors and planar spirals are discussed. The results of the full-wave simulations and measurements of the scattering characteristics of such arrays will be presented to illustrate the main concepts of such artificial media.**

1 INTRODUCTION

Artificial electromagnetic media with the engineered properties attract considerable interest driven by their exciting potential applications at microwave and optical frequencies. Metamaterials with negative effective refractive index (NRI) are in the centre of these developments. NRI is usually associated with the medium exhibiting simultaneously negative dielectric permittivity ε(ω) and magnetic permeability μ(ω). However certain conceptual issues arise in the description of such a medium because μ(ω)→1 in natural materials at optical frequencies, and thus μ(ω) loses its connection to magnetic moment of the unit volume [1]. As argued in [2], the latter feature does not imply negligible magnetic response of macroscopic media to electromagnetic fields at high frequencies but, rather, that full response can be rendered by the effects different from the traditional magnetic-dipole-type resonances. For example, according to [3], the light scattering by a pair of metallic bars demonstrates comparable magnetic-dipole and electric-quadrupole contributions to the scattered intensity at the frequency of electric-quadrupole resonance. This suggests that the higher order resonances in complex lattice arrangements can qualitatively alter the effective parameters of the artificial medium. Indeed, several arrayed structures such as split-ring resonators, pairs of finite-length wires, fishnet and their derivatives exhibit the effective NRI response in different frequency bands.

The experimental demonstration of the NRI effect has inspired search of new metamaterial architectures scalable to various frequency bands. The constitutive particle geometry and the lattice configuration proved to play a crucial role in the array collective response. When the size and separation of the constituent particles are small as compared with the wavelength, the effective medium can be often described in terms of ε(ω) and μ(ω). On the other hand, the dielectric response of structures with spatial dispersion provides an alternative framework that accommodates majority of situations described within the conventional ε(ω)–μ(ω) formalism [2]. In such spatially dispersive medium the electric dipole moment of a reference particle is determined not only by the local fields in a close proximity of the particle, but also depends on the field distribution in the whole periodic structure. This phenomenon has recently been demonstrated in [4] for anomalous refraction of light by the wire-medium prism.

In this paper we will discuss the properties of metamaterials whose constitutive particles are composed of tightly coupled pairs of the dogbone shaped conductors [5] and planar spirals [6, 7]. The concepts of controlling the artificial media response will be illustrated by the results of the full-wave simulations of the scattering characteristics of the arrays at different polarisations of incident fields. The distinctive features of the metamaterials based upon these types of constitutive particles will be discussed in presentation.

2 DOGBONE SHAPED CONDUCTOR PAIRS

A comprehensive parametric study [5] of the arrays of dogbone shaped conductor pairs (Figure 1) has demonstrated that the particle geometry determines the relative positions of the "magnetic" and "electric" types of the resonances. The simulation results also indicated that the magnetic resonance mode, being confined to a conductor pair, is strongly influenced by

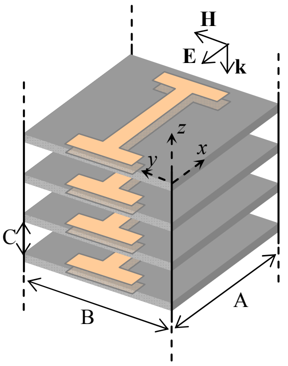

Figure 1: A unit cell of doubly periodic array of stacked dogbone shaped conductor pairs.

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the particles in the adjacent cells. These non-local interactions manifest themselves as spatial dispersion of the homogenised medium which, as mentioned above, may qualitatively alter its response, cf. [2, 4].

An example of the extreme case of the electric and magnetic resonances occurring at the same frequency is displayed in Figure 3 for a single layer array of dogbone shaped conductor pairs. The simulation results show that the frequencies of both magnetic and electric resonances are practically invariant for both polarisations of the incident wave, TM_x (field E_x, H_y, H_z) and TE_y (field E_x, H_y, E_z). The incidence angle weakly affects the magnetic resonance, while the electric resonance shifts to higher frequencies at slant angles. These unique features of the dogbone shaped particles are also present in the stacked arrays. The simulation and measurement results for the multilayered arrangements have shown that the layer separation, C (cf. Figure 1), has significant impact on the transmittance characteristics. In particular, it has been observed that transmittance at the magnetic resonance frequency rapidly decreases with the number of layers when $A \geq C >> W$ (W is width of the dogbone central conductor). Alternatively, for the closer spaced layers with $C \sim W$, strong coupling between the particles in different layers leads to higher transmittance, albeit the magnetic resonance widens and may even split.

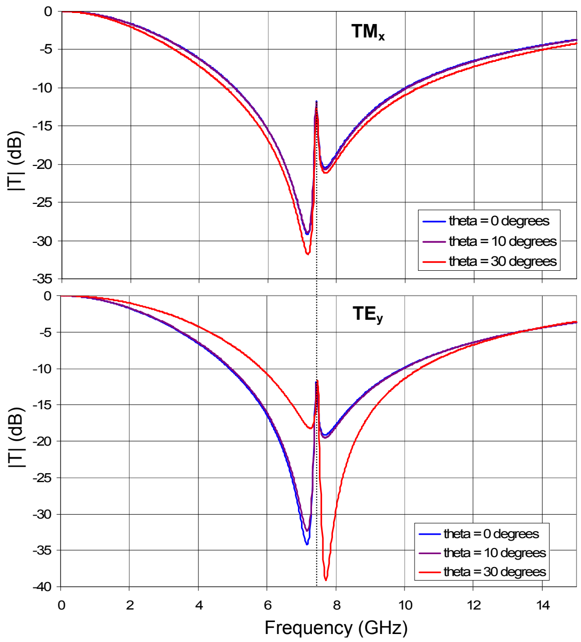

Figure 3: Transmission coefficient for a single layer doubly periodic array of dogbone pairs illuminated by TM_y and TE_x waves incident at $\theta = 0°$, 10°, 30°. The magnetic resonance frequency is shown by dotted line.

3 ARRAYS OF PAIRED PLANAR SPIRALS

An array of stacked tightly coupled pairs of spiral resonators printed on opposite sides of a dielectric substrate has been simulated using CST Microwave Studio. The layouts of the typical reference unit cells are shown in Figure 2 for the spirals with the aligned parallel conductors and for the spirals rotated about the unit cell centre.

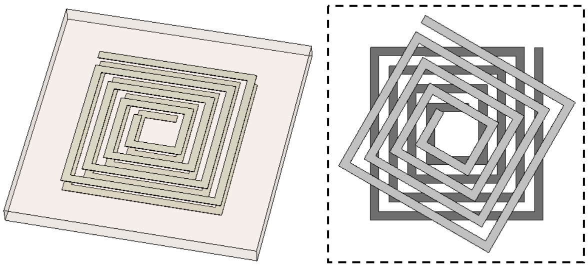
(a) (b)

Figure 2: A unit cell of doubly periodic array of stacked pair of planar spirals (single layer): (a) - aligned spirals; (b) - rotated spirals (top view).

The results of initial simulations indicate that the response of the spiral pairs is strongly affected by the self-resonances of a single spiral. Such behaviour of the pairs of closely spaced spirals is particularly noticeable for the aligned spirals shown in Figure 2(a). Variations of the mutual orientation and winding directions of the spirals in the unit cell enable the selective enhancement and suppression of the particular resonance modes that provides an efficient control of the array response. The characteristics and features of the specific arrangements of the arrays of paired planar spiral resonators will be demonstrated and discussed in the presentation.

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