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A compact dual, triple band resonators for negative permittivity metamaterial

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ABSTRACT

We report, two different dual and triple-band designs of single negative meta-atoms based on combination of individual Z-shaped and S-shaped inclusions. The multi-band responses for proposed resonators are obtained based on combination of individual resonant structures which exhibit electric resonances at different frequencies in microwave region. Numerical simulations and parameter extractions using retrieval method for normally incident wave demonstrate negative permittivity response over frequencies 3.27–4.5 GHz and 7.37–9 GHz for metamaterial made of dual-resonant meta-atom (DRMA). Further, metamaterial made of modified version i.e., triple-resonant meta-atom (TRMA) has negative values for permittivity over frequencies 2.79–3.5 GHz, 6.4–7.5 GHz and 8.93–11.0 GHz. The magnitude of reflection and transmission coefficient obtained from numerical simulations are further validated with microwave free space measurements. The equivalent circuit model developed for TRMA is validated with numerically simulated results. The effective medium ratio (λ_0/p) for proposed resonators is compared with various other metamaterial resonators to indicate compact nature. The proposed DRMA/TRMA resonators can find applications in performance improvement of multiband devices such as antennas, antenna arrays, filters and in realization of microwave sensors, detectors at microwave frequency regime.

1. Introduction

Metamaterials are artificially structured composites made of array of metal or dielectric inclusions that exhibit unique electromagnetic properties not found in individual constituent components. Metamaterials are classified accordingly as epsilon-negative (ENG), mu-negative (MNG) or double-negative (DNG) based on negative values for either permittivity, permeability or both [1]. The ENG ($\varepsilon < 0$) and MNG ($\mu < 0$) metamaterials are constituent in the formation of negative refractive index left handed media [2]. Various types of resonators for ENG/MNG metamaterials are investigated for their use in antenna performance improvement at microwave regime by embedding below patch to ensure miniaturization [3], placing between the closely spaced antenna array elements for suppression of mutual coupling [4], side lobe reduction in antenna arrays [5] and gain enhancement in antennas [6]. Metamaterials made of these resonators are further optimized for ENZ (epsilon-near zero) or MNZ (mu-near zero) characteristics and widely used for gain enhancement in broadside direction for patch antenna [7,8], endfire direction for [9] and Vivaldi antenna [10]. They are coupled with mictrostrip lines to inhibit propagation of narrowband interfering signal [11]. This property is found to be useful in sensor applications [12], dielectric characterization of materials [13] and filter applications [14]. Multiband operations for microwave device such as antenna requires multiband characteristics for metamaterial resonators without affecting the size [15]. To solve these problems several resonators for metamaterial with ENG or MNG responses were reported in the literature [16–20]. Most of above reported resonators have mixed responses with MNG and ENG regions in non overlapping frequencies (refer Table 3). Moreover, little attention has been paid to metamaterials with ENG characteristics for multiband operations (refer Table 3).

The conventional resonators for ENG characteristics include thin wire structure [21] and complementary SRR [22]. The prime disadvantage with this structures is that they have inter-metallic continuity between adjacent cells and that imposes difficulty in fabricating countered objects like lenses etc. Improvement over this were proposed in the form of E-LC resonators [23,24] and their variants such as I-shaped, Z-shaped [25], S-shaped [26] and meander-shaped resonators [27]. However, these resonators have single band response and low value of λ_0/p indicating large electrical size. Recent research interest in this area includes electrical size reduction, improvement in effective medium ratio [28], achieving dual-band characteristics [29–31].

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However, these designs have inherent shortfalls. A poor coupling to external field at higher resonant frequency is observed in [29] whereas, in [30], a high permittivity substrate is used to achieve a compact size. A dual-band negative permittivity meta-atom based on the delta loop resonator integrated with square closed ring resonator was proposed in [31]. However, loading meanders in the delta loop adds significant complexity to the design.

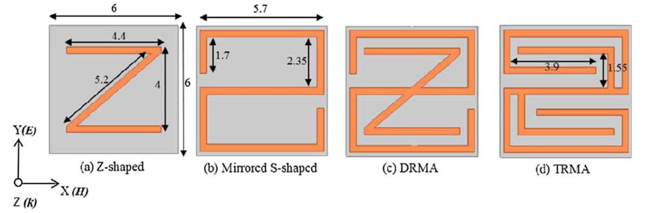
To address above issue, we have proposed resonators for metamaterials having purely epsilon-negative ($\varepsilon < 0$) response with dual and triple-band characteristics. The multi-band responses for these meta-atoms are obtained based on combining individual resonant inclusions with single or dual band characteristics. The resultant structure retains responses of individual inclusions without affecting the dimensions of the unit cell. The combined element method for generating multiband responses has been applied earlier in designing of left-handed metamaterials [32], SNG metamaterials [19,16]by stacking unit cells with different geometrical dimensions and shapes. These resonators are combined in concentric [19,16]or non-concentric way [32] and multiband responses obtained by these approaches are at the expense of increased electrical size [32] and/ or increased structural complexity [19,16].

The metamaterial made of array of proposed DRMA/TRMA resonators exhibit ENG property ($\varepsilon < 0$) having dual/triple band response. They attain high value of λ_0/p ratio which indicates miniaturization and improved homogeneity. Multiband responses are generated by combining individual resonant inclusions in concentric way on one side of the substrate without affecting the size. Moreover, proposed resonators make use of FR-4 dielectric substrate as against use of very high permittivity substrate to achieve miniaturization [19]. Single sided design printed on one face of substrate offers ease in fabrication and feasibility to incorporate lumped elements like Varactors for frequency controllability [33]. The multiband responses, highly compact size, single sided design and use of low permittivity dielectric board are prime advantages of our proposed resonators.

2. Numerical simulations of electric-LC resonators

In this communication, dual and triple band resonators are introduced and studied which couple strongly to electric component of the incident field. Designs of these resonators are based on combining two different meta-atoms having single or dual-band response. For performance comparison, individual and proposed resonators are printed on single sided copper cladded FR-4 epoxy board having permittivity $\varepsilon_r = 4.4$, loss tangent $\tan\delta = 0.02$ and height $h = 1.6$ mm. The lattice constant for all the unit cells has same dimensions of 6 mm × 6 mm. Metallic strips in all designs are made of copper material having conductivity of 5.8×10^7 S/m and thickness of 35 μm. Minimum copper trace width considered is 0.3 mm for fabrication tolerances. The electromagnetic performances of these resonators are characterized using Finite element method based Ansys HFSS Version 14. Simulations are performed on single unit cell using PEC, PMC boundary conditions. These PEC, PMC boundaries along with wave ports model source of plane wave excitation. PEC, PMC boundaries are assigned to the planes parallel to XZ and YZ so that, electric field is oriented along Y-direction and magnetic field is oriented along X-direction as shown in Fig. 1. Wave ports used for the excitation are de-embedded at the edges of the cubic unit cell. From unit cell simulation, we obtained complex S-parameters S_{11} and S_{21} in the frequency range of 2–12 GHz. At a higher value of frequency sweep i.e. 12 GHz, the ratio of wavelength to unit cell ratio is 4.1 in compliance with the limit of 4. This ensures that unit cell dimensions are much smaller than operating wavelength without introducing undesired effects of spatial dispersion [34].

2.1. Transmission, reflection coefficient analysis



(a) Z-shaped (b) Mirrored S-shaped (c) DRMA (d) TRMA

Fig. 1. Geometry and design parameters of (a) Z-shaped resonator (b) Mirrored S-shaped resonator (c) proposed dual-resonant meta-atom (DRMA) (d) proposed triple-resonant meta-atom (TRMA). Note that, all the dimensions are in mm and lattice constant of the unit cells is 6 mm × 6 mm. Width of metallic strips for all resonators is w = 0.3 mm.

We started with individual Z-shaped [25] and S-shaped [26] resonators, that are already reported in the literature (refer Fig. 1(a) and (b)). The Z-shaped [25] and S-shaped [26] resonator derived from conventional E-LC resonator by geometrical transformation was shown to have electric response having a single band of negative permittivity for normally incident wave. Note that we have considered mirrored geometry of S-shaped resonator and for the sake of brevity we drop use of word ‘mirror’ while refereeing structure shown in Fig. 1(b). When Z-shaped and S-shaped resonators are combined, a composite metamaterial structure is formed for which a dual stop band response is obtained. The size of Z-shaped resonator we considered is smaller so that it completely fits within larger S-shaped resonator. We name this structure as dual-resonant meta-atom referred hereafter as DRMA as shown in Fig. 1(c). The responses of both the resonators are accumulated in the composite DRMA structure with slight variations in the resonant frequencies.

From the magnitude of transmission coefficient as shown in Fig. 2(a), two distinct resonances can be identified for the DRMA resonator at frequencies $f_{01} = 3.43$ GHz and $f_{02} = 8.03$ GHz. To introduce additional stop band, we made modifications to geometry of DRMA. This modified structure as shown in Fig. 1(d) is referred as triple resonant meta-atom TRMA throughout the article. First, additional metallic strips are added to modify outer S-shaped geometry. Second modification is performed to inner Z-shaped resonator. The inclined strip of Z-shaped is twisted appropriately to get S-shaped like pattern. In all, three distinct resonances are obtained for proposed TRMA at frequencies $f_{0A} = 2.81$ GHz, $f_{0B} = 6.8$ GHz and $f_{0C} = 9.66$ GHz as shown in

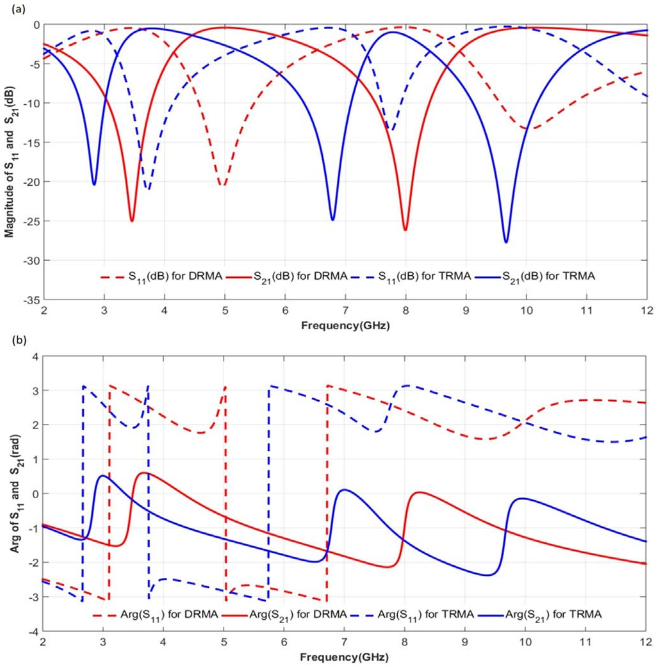


Fig. 2. (a) Magnitude and (b) phase spectra of the simulated reflection (S_{11}) and transmission (S_{21}) coefficients for proposed DRMA and TRMA resonators as shown in Fig. 1.