PARTICLE FOR AN ISOTROPIC METAMATERIAL WITH NEGATIVE PERMITTIVITY

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Abstract: A particle showing negative effective permittivity in some frequency band is presented in this paper. This particle is suitable for making up an isotropic epsilon-negative metamaterial. The unit cell of this metamaterial consists of a cube bearing the proposed particle on its faces with specific orientations. An experiment verified that this unit cell shows an isotropic response. The particle is also proposed in a reduced size. Its dimensions are now three times smaller than those of the original particle.

INTRODUCTION

The basic problem of most metamaterials proposed up to now is their anisotropy. Isotropy can be assured by the specific form of a cell and by arranging the particles within this cell to meet the symmetry of selected crystallographic groups. An isotropic mu-negative (MNG) metamaterial was presented in [1] as a uniform 3D structure of cube cells with split-ring resonators (SRR) appropriately located on their faces. No similar epsilon-negative (ENG) metamaterial has yet been proposed. The ENG particles, applied in the same concept as in [1], have to be planar, like, e.g., those reported in [2].

This paper deals with the evolution of an isotropic ENG metamaterial, and presents a new planar ENG particle. The particle is composed of a planar electric dipole loaded by an inductor. The interaction of the exciting field with the particle results in negative permittivity in a narrow frequency band above its resonant frequency. The layout of this particle is shown in Fig. 1a. The dipole is sensitive only to the electric field parallel to its arms, and the response to a homogeneous magnetic field vanishes due to the particle symmetry. The six particles deposited on dielectric substrates are assembled to form a cube, as described in [1], in order to obtain an ENG cell with an isotropic response. The original particle was redesigned as a dipole loaded by an inductor consisting of two turns, Figs. 1b, c. Due to the substantial increase in inductance the particle dimensions were reduced by a factor of three.

The particles were designed by the CST Microwave Studio, then fabricated and measured. The effective permittivity and permeability were calculated according to [3], though it is senseless to define these quantities for a single particle. Our code therefore provides the effective parameters of the volume between the ports where the particle is located, so that they serve as some measure of the electric and magnetic polarizability of the particle.

ENG PARTICLE, DESIGN AND EXPERIMENT

The particles were designed and fabricated on a ROGERS RT/duroid 5870 substrate with permittivity 2.33 and thickness 0.508 mm, tan$d$ = 0.0012 at 10 GHz and metallization thickness 0.035 mm. The dipole arm is 13.8 mm in length and 2 mm in width, and d = 28.8 mm, Fig. 1a. It is deposited on a substrate 30x30 mm in area. The rear substrate side is without metallization. The strips representing an inductor are 0.2 mm in width. The measured and calculated transmissions of this particle are plotted in Fig. 2 when the particle was transversally located in the R18 waveguide at the center of its cross-section, so that the electric field is parallel to the dipole. The CST Microwave Studio uses a rectangular mesh and is therefore not able precisely to discretize the circularly bent strips of the inductor. This causes the difference between the measured and simulated patterns, as shown in Fig. 2. This particle behaves anisotropically, as its response depends on the incident electric field direction. Fig. 3 shows the calculated real and imaginary parts of the effective permittivity.

The dipole particle, Fig. 1a, was designed for a resonant frequency of about 1.85 GHz, the center frequency of the R18 waveguide band. Taking into account its size *d* = 28.8 mm, we get the ratio $l_0/d = 5.6$, where l_0 is the free space wavelength at the resonant frequency. Such a particle is not small enough to produce a real homogeneous metamaterial. The size of this particle is limited mainly by the area occupied by the planar loops. This area can be reduced by making use of the rear side of the substrate and using an inductor with two turns, see Figs. 1b, c. The penalty for this, however, is the presence of two vias. The dipole arms are now located on the opposite surfaces of the substrate. The reduced size particle was designed again for a resonant frequency of 1.85 GHz on the above defined substrate. The dipole arm is now 4.65 mm in length and 1 mm in width and *d* = 9.6 mm. Its calculated transmission characteristic is shown in Fig. 2, and the calculated effective permittivity is plotted in Fig. 3. The frequency band of the negative permittivity is now 20 MHz wider than that of the original particle. The reduced size particle is suitable for making up the homogeneous metamaterial, as now the ratio $l_0/d = 16.8$.

The 3D isotropic unit cell providing negative permittivity can be made by placing the planar particles on the faces of a cube, observing the appropriate crystallographic groups of symmetry [1]. The particles located on the walls of the cube create a tetrahedral symmetrical system [1], see Fig. 4a. The cube composed of particular planar particles is a complex system with many internal couplings. Moreover, the presence of the waveguide walls, the existence of the TE_{10} mode longitudinal magnetic field component and the non-homogeneity of the field influence its electromagnetic response. These effects result in a response of the cube that is different from the response of a single planar particle.

Fig. 5 shows the transmissions of the cube from Fig. 4a, inserted into the R18 waveguide and measured for several orientations. In this plot, figure 1 marks the basic orientation of the cube shown in Fig. 4.a, where the electric field is parallel with the *y* axis and the waveguide axis is parallel to the *z* axis. 8_i and 4_i represent the rotation around the *i* axis by the angle 2π/8, i.e., 45°, and by 2π/4, i.e., 90°, where *i* = *x*, *y*, *z*. The transmissions of this cube calculated by the CST Microwave Studio differ from the measured patterns, similarly as in Fig. 2. The cube response around the resonance at 1.82 GHz, as shown in Fig. 5, is almost insensitive to the particle orientation, consequently, this cube cell is isotropic. The calculated real part of the complex effective permittivity *e*’ and permeability *m*’ of this cube for its basic orientation is depicted in Fig. 6. Tightly above this resonance, the cube behaves as an isotropic ENG particle. The response round the lower resonance at 1.71 GHz depends slightly on the orientation of the cube, as documented in Fig. 5. The cube is an anisotropic MNG particle. Fig. 4b shows the cube constituted from reduced size particles drawn in the same scale as the cube in Fig. 4a. The size reduction is remarkable.

CONCLUSION

An ENG particle consisting of a planar dipole loaded by an inducting loop is presented in this paper. This planar particle was tested for the assembly of an isotropic ENG metamaterial. It served as the walls of a cube and fulfilled constraints ensuring the required crystallographic symmetries. There are two resonances in the response of the cube cell, as compared to the one resonance in the response of the single planar particle. At the higher resonance the cube cell has an isotropic response with negative permittivity, while at the lower resonance it exhibits an anisotropic MNG response. The particle with dimensions three times smaller than those of the original was designed for applications in homogeneous metamaterials.

ACKNOWLEDGEMENT

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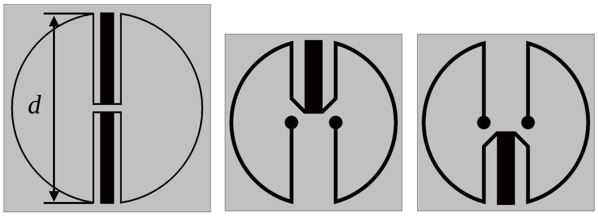


(a) (b) (c)

Fig. 1 Layout of a dipole particle (a), a reduced size particle, top layout (b), and bottom layout (c), not on the same scale as (a). The two vias are located at the two circles.

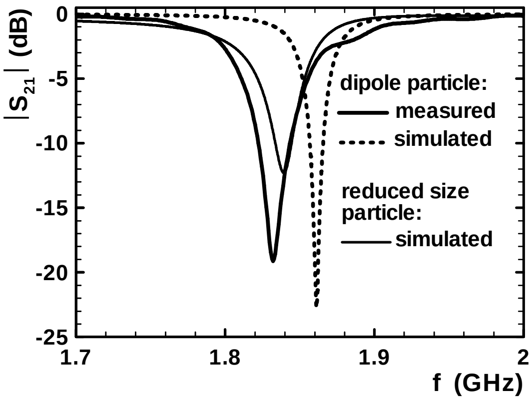


Fig. 2 Transmission of the R18 waveguide with the particles from Fig. 1 located in the waveguide center.

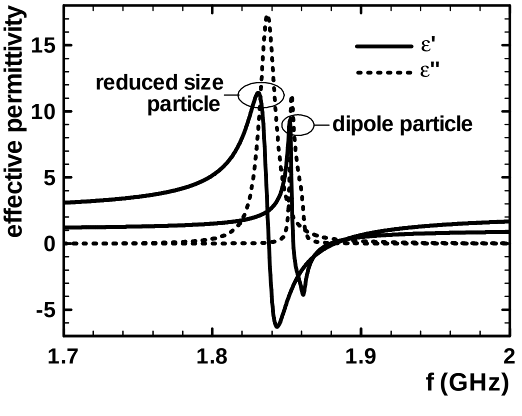
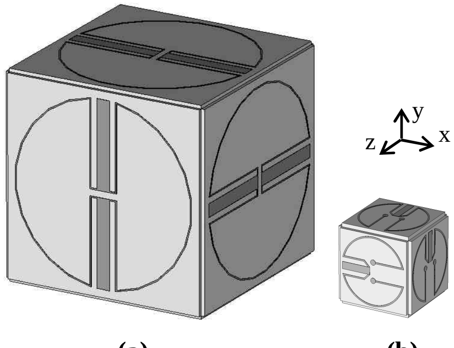


Fig. 3 Calculated effective permittivity of the particles from Fig. 1.



(a) (b)

Fig. 4 Volumetric ENG cube cell composed of particles from Fig. 1a (a), and composed of reduced-size particles (b).

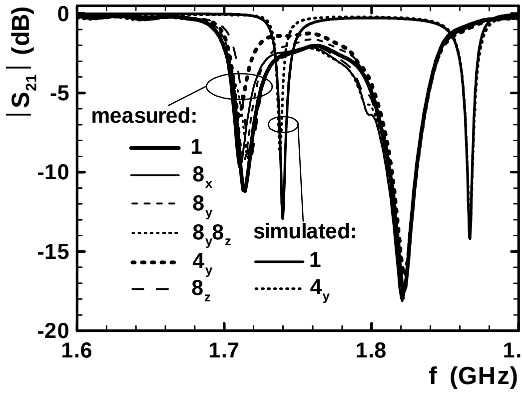


Fig. 5 Transmissions of the R18 waveguide with the cube from Fig. 4a for its different orientations.

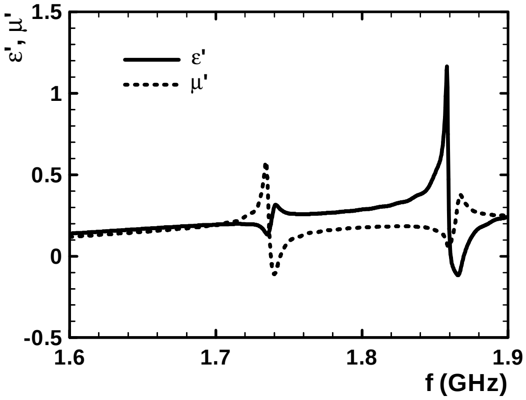


Fig. 6 The calculated effective parameters of the cube from Fig.5.