Volumetric single negative metamaterials

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Abstract

This paper presents the results of a study of bulk single negative isotropic metamaterials. Magnetic and electric metamaterials are treated separately. The same approach was used for developing anisotropic particles with magnetic or electric responses. A volumetric isotropic medium was made up consecutively from unit cells with cubic symmetry of the particles, and in parallel by random or quasi-periodic location of particles in the host medium. The consequences of periodic and random distributions of the unit cells in the host medium are given. The experiments confirmed the rightness of the concepts selected here, and have provided media for microwave applications that can be manufactured using inexpensive, currently-available technology.

1. Introduction

In the last seven years there has been a renaissance in the efforts of researchers to obtain a practically utilizable medium with negative permittivity and/or permeability. These artificial composites have evolved in two forms, depending on their intended applications. They are either so-called 1D Left-Handed (LH) transmission lines, or 2D and 3D bulk composites. Their evolution until now and the results that have been achieved are well summed up in [1-3]. This paper will deal with 2D and 3D single negative (SNG) magnetic and electric metamaterials (MTM).

Volumetric MTM consists of a host medium in which insertions such as unit cells are located. Either a single specifically-shaped element, also known as a particle, or a suitably spatially-arranged set of particles forms the unit cell. The particles are anisotropic. Consequently, the medium composed by them is generally also anisotropic. Our objective is to design and fabricate a volumetric isotropic SNG MTM. The particles that are used are of a resonant nature, and consequently their operation is frequency selective. The second objective is thus to widen their frequency band. This involves designing the structure of a particle, analyzing its responses to exciting an electromagnetic wave, fabricating a medium and measuring its electrical parameters. In the first stage, and also in this paper, we investigate in parallel but separately the birth of a magnetic and electric SNG MTM. These new composites may then be combined, resulting in an LH, i.e., double negative (DNG), isotropic medium.

There are two ways leading to isotropy of an MTM. The first way utilizes a specific form of the unit cell satisfying symmetry of the selected crystallographic group, and its periodical arrangement in space. The correctness of this concept has been proven true in the case of the cells belonging to the cubic crystallographic group, each composed of one kind of resonator. The second way is based on randomly located unit cells in the volume of the host. We adopted both these concepts for producing 2D and 3D isotropic MTMs by making contemporary use of inexpensive, easily-accessible technology. Our results offer a real medium for designers of microwave devices and systems. It is only necessary to recalculate the proportions of the particle and unit cell by scaling in order to meet the specific requirements for each application.

The unit cell is isotropic if its polarizability tensor is invariant to any rotation. This fact, expressed in terms of the scattering parameters, means that the transmission of such a unit cell does not depend on the angle at which the illuminating wave is incident on the cell. Using this method, we evaluate the degree of isotropy of the final products of both concepts mentioned above. The procedure outlined here will be applied to both magnetic and electric MTMs.

2. Magnetic single negative metamaterials

Until now, various modifications of split ring resonators (SRR) have been used for making up an SNG MTM. SRR is an anisotropic element. These elements are therefore configured in such way that the whole unit meets the conditions of symmetry of a cubic group. A 3D isotropic unit cell consisting of three SRRs with spherical geometry also belongs in this group, Fig. 1 [4]. Hereafter 8_i and 4_i stand for the rotation around the i-axis by the

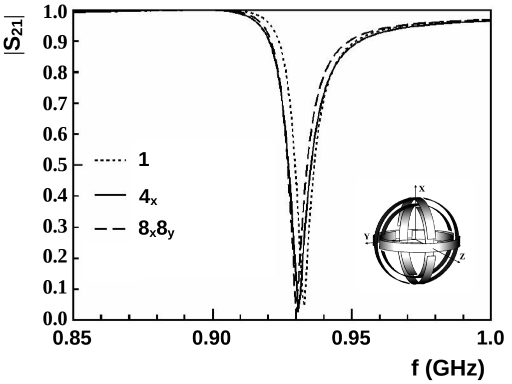

Fig. 1 Transmission through the waveguide loaded by the spherical unit cell [4]

angle $2\pi/8$ and by $2\pi/4$, respectively, where i=x, y, z. However, from the fabrication point of view its geometry is not suitable for mass production. A cubic geometry, with planar SRRs located on the six walls of the cube, is therefore more popular, and is preferred here. In the second experiment, a cubic cell was investigated, Fig. 2 [5]. The space periodic location of such unit cells enables the emergence of 3D isotropic SNG media. Our design, production and measurements of the 3D unit cells with a double or quaternary of spiral SRRs confirmed the rightness of this concept.

The second way of making up volumetric isotropic MTMs utilizes random location and orientation of simple anisotropic particles in the host medium. As it turned out, 3D random location of these particles was a great technological problem. The concept of randomly distributed particles was therefore checked first on 2D and then on 3D structures. Broad side coupled SRRs (BC-SRR) were used as particles. The experiments showed that better isotropy and a wider frequency band of the MTM could be achieved by quasi-periodic location and higher density of the particles Fig. 3 [6]. The isotropy is very sensitive to the particle distribution. The actual 3D MTM with quasi-periodic location and randomly oriented unit cells was achieved by BC-SRRs boxed in polystyrene spherical shells filling up the volume of a cube with the edge 70 mm in length Fig. 4 [6].

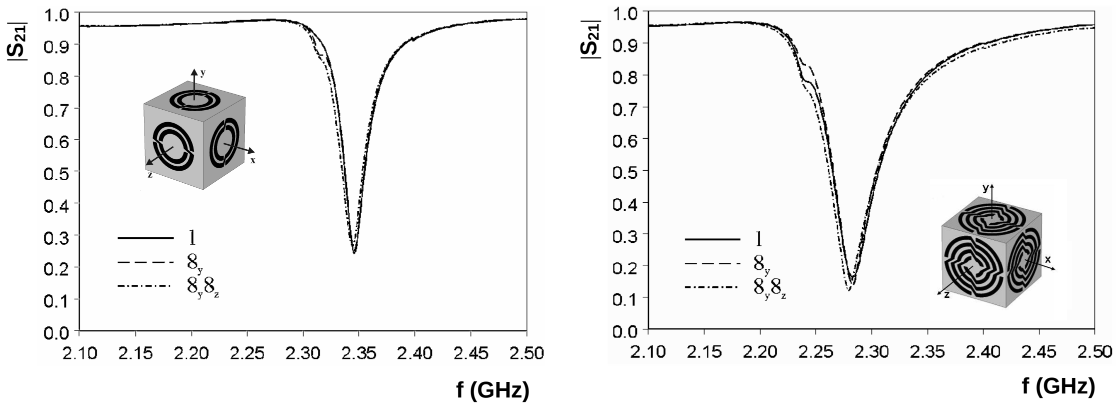

Fig. 2 Transmission through the waveguide loaded by double and quaternary split spirals [5]

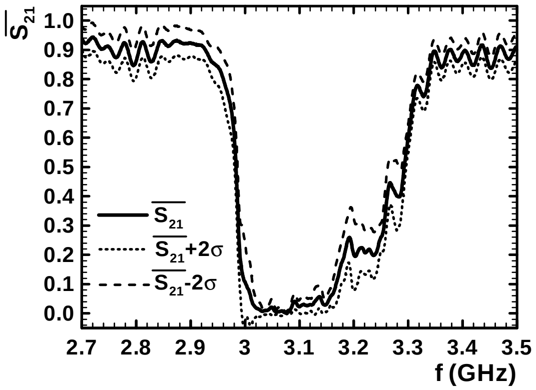

Fig. 3 Arithmetic mean value of the transmission through 64 cubic samples in the R32 waveguide with 243 BC-SRRs and its disperse when the resonators are in the nodes of the squared net and are randomly oriented [6].

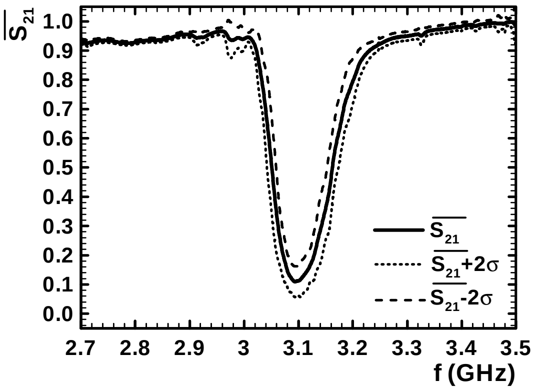

Fig. 4 Arithmetic mean value of the transmission through 63 cubic samples in the squared R32 waveguide with 246 BC-SRRs and its disperse when the resonators in the shells are randomly distributed [6].

3. Electric single negative metamaterials

It is known that negative permittivity is a characteristic of wire media. A 3D set of straight thin wires is unacceptable from the fabrication point of view for assembling isotropic volumetric MTMs. Consequently, miniature resonators with a dominant response to the electric field of the exciting wave have again come into consideration. We have therefore designed a new anisotropic particle with a distinct electrical response. The electrical dipole loaded by a loop inductance, shown in Fig. 5, is the first such particle. It turned out that the particle is anisotropic, as documented by Fig. 6 [7], since its measured response depends on the angle between the axis of the dipole and the direction of the electric field of the incident wave. The transmission of the waveguide R18 loaded with this particle simulated in CST Microwave Studio differs from the measured transmission, because the rectangular mesh of the Studio is not compatible with the semicircular conductor of the inductance. Rotation of the particle round the longitudinal dipole axis does not influence its response to the incident electric field.

To obtain a particle with the response independent from the angle of incidence of the wave, we modified its layout which resulted in the quadruple particle drawn in Fig. 7. Now its response, measured either in the R18 waveguide or in the parallel plate guide, is isotropic as follows from Fig. 8.

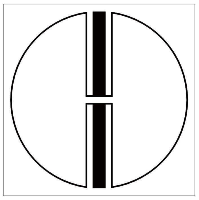

Fig. 5 Single dipole inductively loaded.

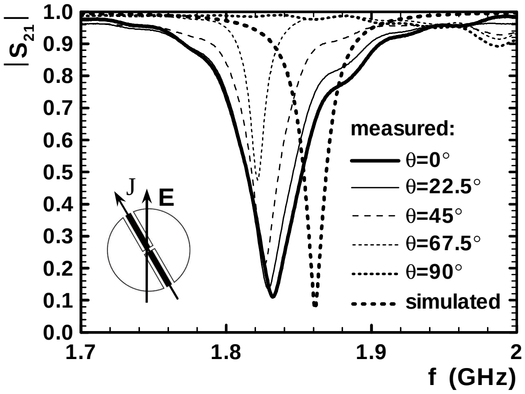

Fig.6 Transmission of one particle measured and simulated in the R18 waveguide [7].

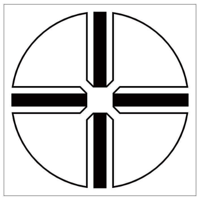

Fig. 7 Inductively loaded quadruple.

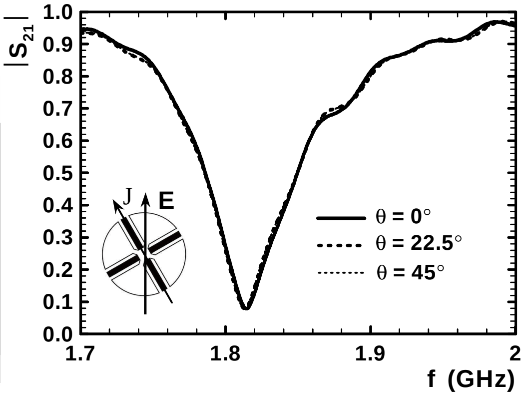

Fig. 8 Transmission of one quadruple particle measured in the R18 waveguide [7].

Particles with their greatest dimensions negligible in comparison to the wavelength are required for homogenization. In our case the wavelength was only six times greater than the length of the dipole. The single dipole particle was therefore redesigned with enhanced inductance for the frequency about 3.3 GHz. One half of the layout is located on the front side of the substrate while the second half is deposited on the opposite, rear side of the substrate. Both parts are connected through vias as shown in Fig. 9. The rectangular shape of the inductance loop was chosen in order to utilize the substrate area as much as possible. The measurement confirmed the isotropy of these particles as regards rotation round the longitudinal axis of the dipole.

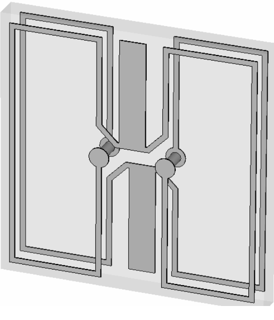

Fig. 9 Miniaturized single dipole particle.

The isotropy of one 3D cubic unit cell with single dipoles is documented by its measured transmission in Fig. 10 [7]. The cubic unit cell with quadrupoles did not meet this expectation, most probably due to the higher multipole couplings inside the cube. We proved that it is possible to produce a bulk medium with an isotropic electric response consisting of periodically distributed isotropic unit cells, each of them assembling six 2D anisotropic particles, as follows from the single dipole particle behavior.

Experiments with random distribution of particles also provided promising results. 64 measured transmissions of 147 particles inserted in the polystyrene slices consecutively rotated by 90E provided very good isotropy of the cubic sample, as follows from the small disperse shown in Fig. 11. An experiment with particles boxed in polystyrene spherical shells has been set up in the laboratory and is ready to begin.

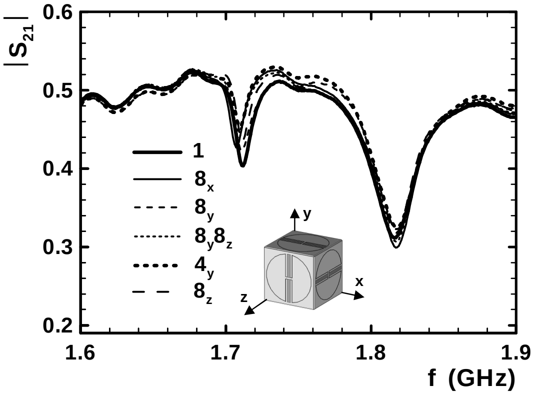

Fig. 10 Measured transmission of one cubic unit cell in the parallel plate waveguide

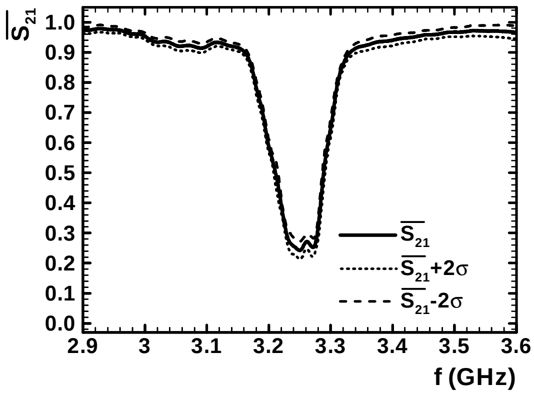

Fig. 11 Transmission through 147 periodically distributed and randomly oriented particles

4. Conclusion

We now have available unit cells with a distinct magnetic or electric SNG response. Their space periodical location provides bulk isotropic magnetic or electric MTMs. The concept of manufacturing isotropic 3D MTMs with randomly distributed anisotropic particles has been proved practicable in the case of a magnetic and also electric SNG medium. Particles that respond to an electric or magnetic field are planar and easy to manufacture. Negative permeability/permittivity of the single magnetic/electric particle was calculated from their scattering coefficients when inserted in the rectangular waveguide. The frequency band of composites with randomly located unit cells is wider than the band of a single particle. We are ready to react to impulses and requirements from the domain of practical applications which would demarcate the further development of SNG or DNG media utilizing typical features of both of the SNG media introduced here.

Acknowledgement

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