

Isotropic Single Negative Metamaterials

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Abstract. *This paper presents the application of simple, and therefore cheap, planar resonators for building 3D isotropic metamaterials. These resonators are: a broad-side-coupled split ring resonator with a magnetic response providing negative permeability; an electric dipole terminated by a loop inductor together with a double H-shaped resonator with an electric response providing negative permittivity. Two kinds of 3D isotropic single negative metamaterials are reported. The first material consists of unit cells in the form of a cube bearing on its faces six equal planar resonators with tetrahedral symmetry. In the second material, the planar resonators boxed into spherical plastic shells and randomly distributed in a hosting material compose a real 3D volumetric metamaterial with an isotropic response. In both cases the metamaterial shows negative permittivity or permeability, according to the type of resonators that are used. The experiments prove the isotropic behavior of the cells and of the metamaterial specimens.*

Keywords

Electric dipole, isotropic metamaterial, single negative metamaterial, split ring resonator.

1. Introduction

Artificial materials known as metamaterials have attracted great attention in the scientific and technical community in recent years [1], [2]. This very rapidly growing interdisciplinary field combines contributions from a wide range of areas, e.g., physics, microwave technology, optics, and nanotechnology. The goal is to design and fabricate new kinds of materials with electrical properties not found in natural materials, and that can be tailored for special applications. The main characteristics of these metamaterials, such as left-handed behavior of the waves, negative permeability, negative permittivity and negative index of refraction, can be observed in bulk media and also in periodically loaded transmission lines from microwaves up to optics. The concept of a left-handed transmission line is well known [3]. A volumetric metamaterial consists of a host medium in which insertions such as unit cells are located. Either a single specifically-shaped resonant element or a suitably spatially-arranged set of resonators

forms the unit cell. The planar resonant elements themselves are anisotropic. Consequently, the medium composed by them is generally also anisotropic.

There are several ways leading to isotropy of a metamaterial. A specific form of the unit cell satisfying symmetry of the selected crystallographic group [4], and its periodical arrangement in space were utilized in [4-7]. Another way leading to isotropy is based on randomly located unit cells in the volume of the host [8]. A double-negative isotropic medium can be designed as a 3D structure consisting of a set of dielectric spheres of high permittivity, having two different radii located periodically [9-11] or randomly [12] in a hosting material. A single sphere can be used, but it has to consist of a core and a casing of different materials [13]. Dielectric spheres of one kind can be used for building an isotropic double-negative metamaterial using mutual coupling between them, or they are placed in an epsilon-negative medium [14]. An isotropic epsilon-negative metamaterial was achieved by a 3D triple wire medium consisting of connected wires just below the plasma frequency, as presented in [15]. The authors of [16] prepared an isotropic metamaterial in the optical region, consisting of a matrix of magnesium diboride performing negative permittivity. This served as a host material for spherical inclusions of silicon carbide performing negative permeability. An isotropic metamaterial was designed using a circuit approach as a rotated transmission line matrix scheme [17], [18].

Our objective is to design and fabricate a 2D or 3D volumetric single-negative metamaterial using inexpensive, easily-accessible technology. We have adopted the concept of a cubic unit cell consisting of six planar resonant elements on its faces, or alternatively the concept of single resonant elements randomly placed in a hosting material. This involves designing the structure of the resonant element, analyzing its responses to excitation by an electromagnetic wave, fabricating the medium and measuring its electrical parameters. A unit cell of this medium 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. In the first stage, and also in this paper, we investigate a magnetic single-negative metamaterial and an electric single-negative

metamaterial in parallel, but separately. These new composites may then be combined, resulting in a left-handed, i.e., a double-negative isotropic medium. Our results offer a real medium for designers of microwave devices and systems. It is only necessary to recalculate the proportions of the resonant element and unit cell by scaling in order to meet the specific requirements for each application. Technological limitations must, however, be taken into account here.

The planar resonators were designed by the CST Microwave Studio, then fabricated and measured. The effective permittivity and permeability were calculated according to [19], though it is senseless to define these quantities for a single resonant element. Our code therefore provides the effective parameters of the volume between the ports where the resonant element is located, so that they serve as some measure of the electric and magnetic polarizability of the element.

2. Planar Resonators

The aim of our work is to design and fabricate a real 3D isotropic single-negative metamaterial with negative permittivity or permeability using cheap, easily accessible technology. This can be achieved by using planar resonators on a dielectric substrate provided by standard planar technology. For a μ -negative metamaterial we have used broadside-coupled split ring resonators, as presented in [20], see Fig. 1a. The resonant elements consisting of a planar electric dipole terminated by two loop inductors connected in parallel to provide symmetry were proposed in [6] as good candidates for building an isotropic epsilon-negative metamaterial. The layout is shown in Fig. 1b. The dipole with minimized dimensions is shown in Figs. 1c-e. It was necessary to use vias in these resonators, but this drawback was removed by using a double H-shaped resonator, as shown in Fig. 1f.

2.1 Split Ring Resonator

The broadside-coupled split ring resonator was designed on a Rogers RT/duroid 5880 substrate 0.127 mm in thickness with permittivity 2.20 and 0.017 mm copper cladding. Each resonator resides on a squared leaf with a 7 mm edge [8]. We measured the transmission of the R32 waveguide with this resonator located in the middle of its cross-section. The resonant response was found at around 3.1 GHz. The resonant frequencies of the individual resonators differed in a 50 MHz interval due to manufacturing imperfections. The resonator is about 13.8 times smaller in size than the resonant wavelength in free space, so a metamaterial consisting of these resonators can be assumed to be homogeneous.

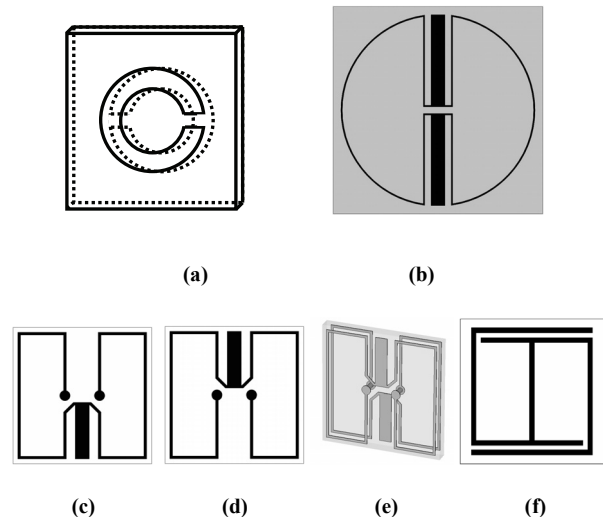


Fig. 1. Sketch of the planar resonators, not drawn to scale. Broadside-coupled SRR (a), layout of the electric dipole (b), the reduced size dipole terminated by two loop inductors, top layout (c), rear layout (d), view (e), layout of the double H-shaped resonator (f).

2.2 Electric Dipole

An electric dipole terminated by a planar loop inductor [6] is a resonant element sensitive to an electric field. This element effectively modifies the permittivity of the hosting material under irradiation by an electromagnetic wave. The originally designed resonator has a resonant frequency around 1.86 GHz, and the R18 waveguide was used to measure its transmission. For this resonator we obtained the ratio of the free space wavelength at resonant frequency to its total size of 28.8 mm, equal to 5.6. Such a resonant element is not small enough to produce a real homogeneous metamaterial. The size of this resonant ele-

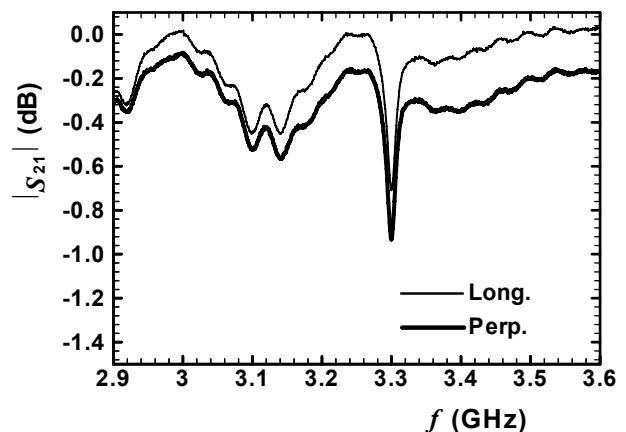


Fig. 2. Measured transmission of the R32 waveguide with one reduced-size dipole (Long: oriented parallel to the waveguide longitudinal axis, Perp: located perpendicular to the waveguide axis). The resonant element is located at the center of the waveguide.

ment is limited mainly by the area occupied by the planar loops. We reduced this area by making use of the rear side of the substrate and using an inductor with two turns, see Figs. 1c,d,e. The penalty for this, however, is the presence of two vias. The dipole arms are now located on the opposite surfaces of the substrate. This reduced-size dipole resonator measured in the R32 waveguide gives a resonant-like response with resonant frequency about 3.3 GHz. The spread of the resonant frequencies of the particular resonant elements is similar as in the case of broadside-coupled split ring resonators, reported above. An example of the transmission of a single dipole located in the R32 waveguide is shown in Fig. 2.

2.3 Double H-shaped Resonator

Our aim was to find a new planar resonant element for composing an epsilon-negative metamaterial able to resonate at a satisfactorily low frequency and therefore compatible in size with our broadside-coupled split ring resonators. A solution was found after several iterations with a planar resonant element in the form of a folded dipole. We obtained a double H-shaped resonator, the layout of which is shown in Fig. 1f.

The double H-shaped resonator was optimized by the CST Microwave Studio using a substrate 0.2 mm in thickness, with permittivity 2.3, loss factor 0.001, and metal cladding 17 μm thick, finally obtaining an area of 6x6 mm and an outer strip 5.25 mm in length. Fig. 3 shows the transmission characteristics of the double H-shaped resonator located in three positions in the middle of the TEM waveguide calculated by the CST Microwave Studio. The resonant frequency is around 3.8 GHz. The ratio of the free space wavelength at resonance and the resonator size is about 13, so a metamaterial consisting of these resonant elements can be assumed to be a homogeneous medium. Position 1 denotes a double H-shaped resonator perpendicular to the side walls of the waveguide, and the central strip is in the vertical position, so there is no interaction with the magnetic field in the TEM waveguide. We have only one basic resonance at which the element shows negative effective permittivity. In positions 2 and 3, the double H-shaped resonator is located parallel to the waveguide side walls with the vertical position and with the horizontal position of the central strip, respectively. The magnetic field now interacts with the resonant element. This results in the appearance of the second magnetic resonance, Fig. 3, at which the double H-shaped resonator shows negative effective permeability, see Fig. 4. This additional resonance is, however, well separated from the basic resonance aimed as the metamaterial working resonance. The calculated effective permittivity of the TEM waveguide section with the double H-shaped resonator located in position 2 is shown in Fig. 4.

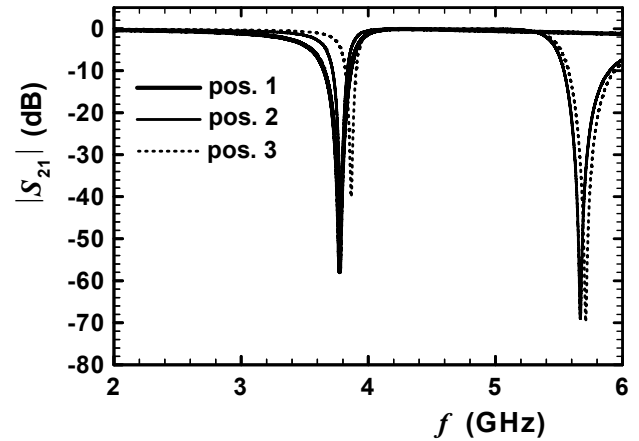


Fig. 3. Simulated transmission of the double H-shaped resonator located at the center of the TEM waveguide in three positions defined in the text.

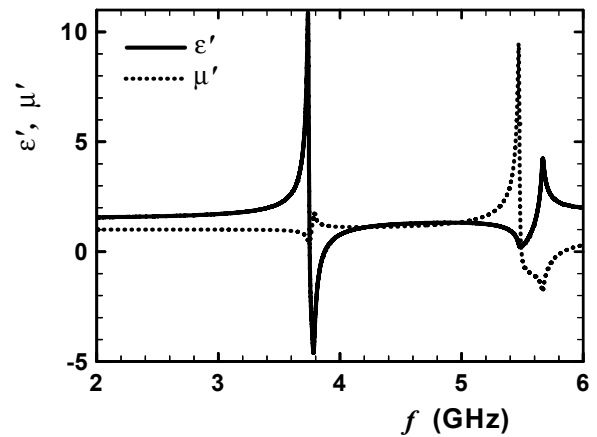


Fig. 4. Calculated [4] real parts of the effective permittivity and permeability of the double H-shaped resonator located in the TEM waveguide in position 2.

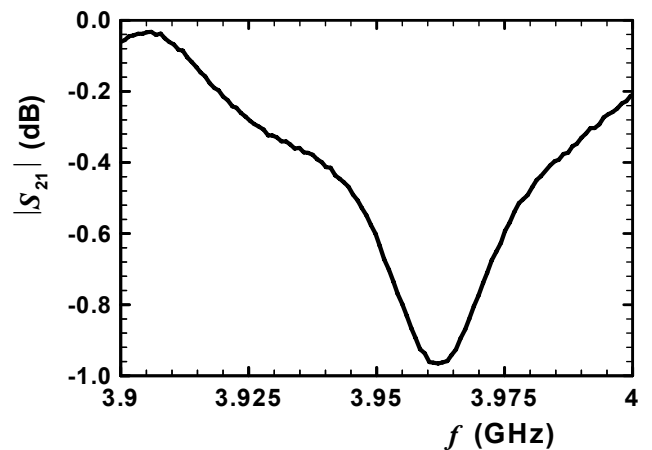


Fig. 5. Measured transmissions of the double H-shaped resonator located at the center of the R32 waveguide.

The double H-shaped resonator was fabricated on ROGERS RT/duroid 5880 substrate with permittivity 2.22

and thickness 0.254 mm, loss factor 0.0012 at 10 GHz and metallization thickness 0.017 mm. The outer strip is 5.25 mm in length and 0.2 mm in width, the same as the slot width. The resonator is deposited on a substrate 6x6 mm in area. The double H-shaped resonator was located in the R32 waveguide at the center of its cross-section in position 1.

The measured transmission characteristic is plotted in Fig. 5. As expected, the response is weak since we have only one tiny resonant element 6x6 mm located in the R32 waveguide with a rectangular cross section of 72.14x34.04 millimeters.

3. Cubic Cells with an Isotropic Response

A 3D isotropic unit cell providing negative permittivity or permeability can be designed by placing the planar resonant elements on the faces of a cube, observing the appropriate crystallographic groups of symmetry [4], [5]. The cells composed of a tetrahedral symmetrical system are shown in Fig. 6. The cube with particular planar resonant elements 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 the electromagnetic response of the cube.

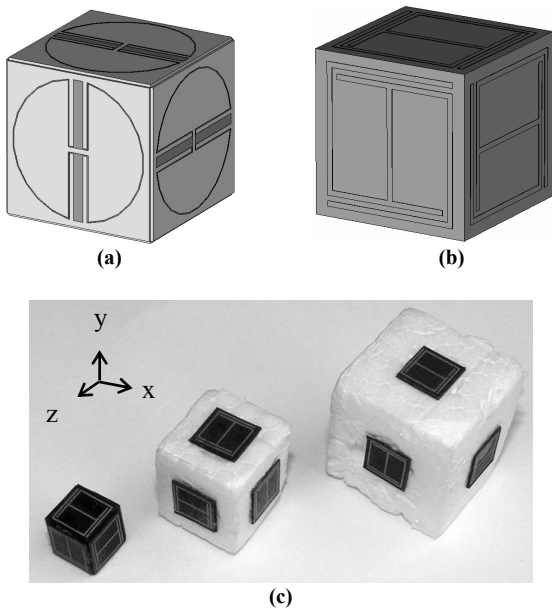


Fig. 6. Cubic-like cells, not drawn to scale, composed of electric dipoles (a), and double H-shaped resonators (b). Fabricated cubes with double H-shaped resonators (c).

These effects result in a response of the cube that is different from the response of a single planar resonator. Cubes composed of various versions of split-ring resonators have already been proposed and studied in [4], [5]. Cubes composed of electric resonant elements are shown in Fig. 6. The transmission characteristics of these cells with electric

dipoles, both calculated and measured, have been presented in [6] for their different positions in the waveguide of the rectangular cross-section and the TEM waveguide. For the main resonance at which these metamaterials are aimed to work, the response of the cell does not depend on its orientation. This proves that these unit cells behave isotropically.

Fig. 6b is a sketch of the CST Microwave model of the cube cell composed of double H-shaped resonators. The three fabricated versions of this cube, with dimensions 6x6x6, 12x12x12, and 15x15x15 mm, are shown in Fig. 6c. They are composed of planar double H-shaped resonators, see Fig. 1f, stuck on to polystyrene cubes of given dimensions. The isotropy of these cells was tested by measuring the transmission through the R32 waveguide with the cube located in its center in different positions, see Fig. 7 for the cube with dimensions 15x15x15 mm. Position 1 refers to the cube located as shown in Fig. 6c, assuming that z is the waveguide axis and the waveguide side walls are parallel to the yz plane. The cube is rotated by 45 deg around the x axis in position 2, while in position 3 the cube is additionally rotated by 45 deg around the y axis. The cell response depends only slightly on its chosen position. We can therefore conclude that this cube-like unit cell behaves isotropically, and is a suitable building block for an isotropic epsilon-negative metamaterial.

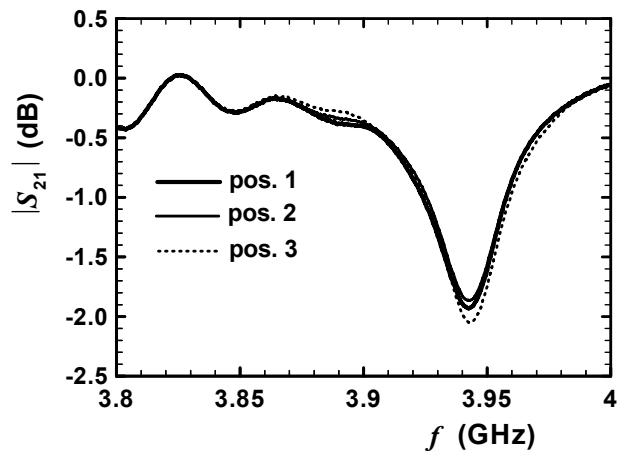


Fig. 7. Measured transmissions of the R32 waveguide with a cube of dimensions 15x15x15 mm assembled from six double H-shaped resonators for its different positions.

4. 2D Random Distribution of Elements in Space

The 2D random system consists of the host material - polystyrene - in the shape of a parallelepiped with the base 50x50 mm cut into three slices that are equal in height 10 mm, Fig. 8a. In each slice, an equal number of planar resonant elements of any kind from Fig. 1a,e,f are inserted with random orientation. Two different random arrangements were used and tested, as depicted in Figs. 8b,c, representing the top view of a slice [8]. The surface normals

of the elements, and thus also the magnetic moments, lie only in the xz plane, forming the desired 2D system. The centers of the particular resonators are either positioned periodically in the nodes of a squared net, Fig. 8b, or their position varies randomly, Fig. 8c. Randomness is obtained by choosing random angles between the normals of the resonators and the x axis. The distribution of these angles and also the distribution of the resonator positions on each slice were generated independently. Consequently, by changing the mutual orientations of the slices in the parallelepiped by 90-degree rotations, there are 64 different parallelepipeds with randomly distributed resonators inside, assuming that the vertical order of the slices is kept. Interchanging the vertical order of the slices, with their three rotations, we obtain a total of 384 combinations of resonator locations. However, we utilized only the first 64 combinations in the experiment.

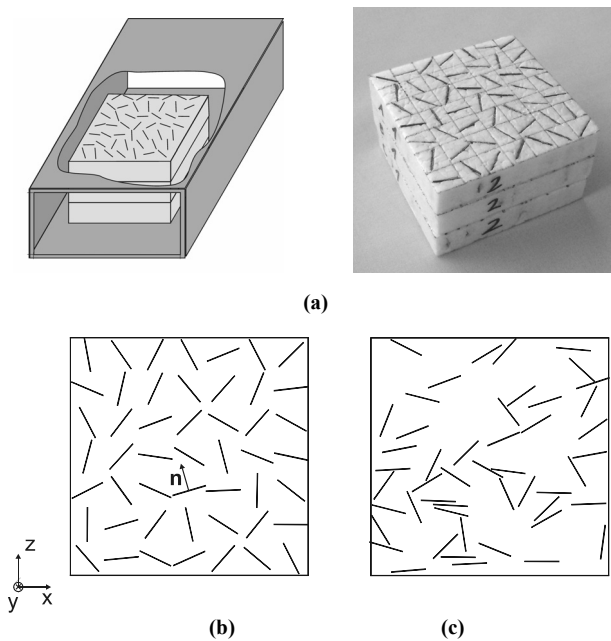


Fig. 8. Waveguide loaded with a parallelepiped composed of three slices with randomly distributed planar resonators (a), periodic positions of resonators with randomly chosen angles (b), doubly random distribution (c).

An experiment performed with the use of a μ -negative metamaterial consisting of broadside-coupled split ring resonators was reported in [8]. The parallelepiped with doubly randomly distributed resonant elements, see Fig. 8c, proved not to be suitable for fabrication of isotropic metamaterials [8], while the distribution from Fig. 8b provides a material with acceptable isotropy.

Here we report the results of two epsilon-negative metamaterials composed of single dipoles, Fig. 1e, and double H-shaped resonators, Fig. 1f. Sixty-four measured transmissions of 147 resonators inserted in the polystyrene slices consecutively rotated by 90 deg provided very good isotropy of the cubic sample. This follows from the small disperse shown in Fig. 9 for the electric dipoles and in Fig. 10 for the double H-shaped resonators. Both measurements

were performed in the R32 waveguide and show a small dispersion. The measured metamaterial specimens can therefore be considered as isotropic, assuming that the electromagnetic wave propagates in the xz plane and the electric field is parallel to the y axis, Fig. 8b.

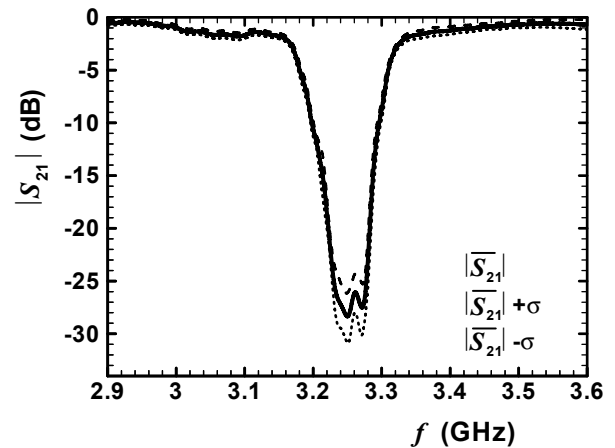


Fig. 9. Arithmetic mean value of the transmission through the sample with 147 planar reduced size electric dipoles, and the disperse when the resonators are in the nodes of the squared net, Fig. 8b.

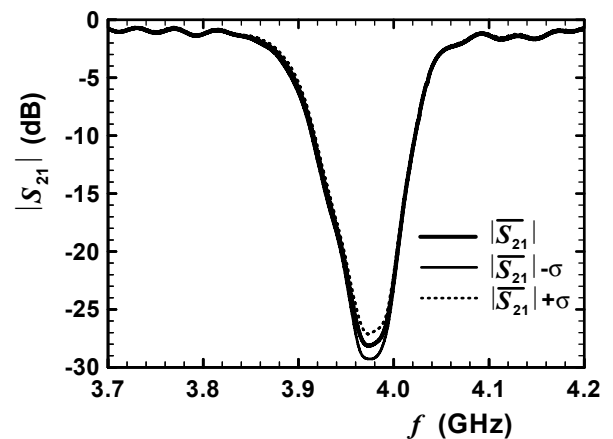


Fig. 10. The same plot as in Fig. 9, but for double H-shaped resonators.

5. 3D Isotropic Single-Negative Metamaterials

Real volumetric isotropic metamaterials cannot be based on the 2D distributions presented in the previous paragraph. The planar resonant elements have to be distributed with a real 3D random location and orientation in the host medium. As it turned out, 3D random location of the planar resonant elements was a great technological problem. Finally, the actual 3D metamaterial with randomly distributed and oriented resonant elements was achieved by boxing the planar resonant elements into polystyrene spherical shells, Fig. 11a. The shells with an outer diameter of 11 mm consist of two yoked hemispheres with inside slots for inserting the resonant element. About 256

shells are placed in the cube with the edge 72 mm in length, Fig. 11b. These specimens of the single-negative metamaterial were measured in the squared R32 waveguide, Fig. 11b.

The transmission characteristics of the prepared single-negative metamaterials were measured repeatedly, changing the positions of the shells each time. Finally, the dispersion of these characteristics was calculated and plotted. Fig. 12 shows the behavior of the mu-negative metamaterial composed of broadside-coupled split ring resonators. The response of the reduced size electric dipoles is plotted in Fig. 13, and Fig. 14 shows the results of measurements of the epsilon-negative metamaterial consisting of boxed double H-shaped resonators.

The characteristics plotted in Figs. 12 – 14 show dispersion that is slightly higher than in the case of 2D metamaterials, see Figs. 9, 10. Nevertheless, single-negative metamaterials composed of boxed planar resonant elements can be viewed as real 3D isotropic metamaterials.

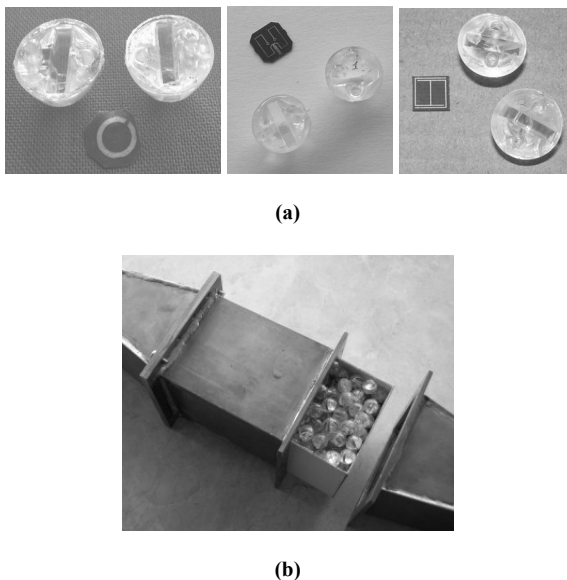


Fig. 11. Planar resonant elements boxed in plastic spherical shells (a), the partly disassembled measuring setup (b).

6. Conclusion

This paper presents two ways of designing a bulk isotropic metamaterial with a single negative response. Simple and consequently cheap planar resonant elements are proposed as the building blocks of these metamaterials. Broadside-coupled split ring resonators are used. When irradiated by an electromagnetic wave these resonators show negative effective permeability. Two different resonant elements sensitive to an electric field are used to show negative effective permittivity, assuming they are irradiated by an electromagnetic wave. These are: an electric dipole loaded by a loop inductor, and a double H-shaped resonator. The behavior of these two resonant elements is similar. In comparison with the electric dipole using a two-loop

inductor, the double H-shaped resonator has the advantage of a simpler structure with no vias. Consequently, it can be produced more cheaply and more reliably.

An isotropic response with both negative permittivity and negative permeability was proved in the case of a unit cell in the form of a cube with six identical planar resonant elements located with tetrahedral symmetry on its faces.

To test a simple way of manufacturing an isotropic single negative metamaterial, we placed the planar resonators in a 2D system with their periodic positions, but with random orientations. This system measured in the R32 waveguide showed good isotropy.

The concept of manufacturing real isotropic 3D metamaterials with randomly distributed resonant elements has been proved practicable in the case of a magnetic single negative medium and also an electric single negative medium. The resonant elements are boxed into plastic spherical shells, preserving their random positions in space

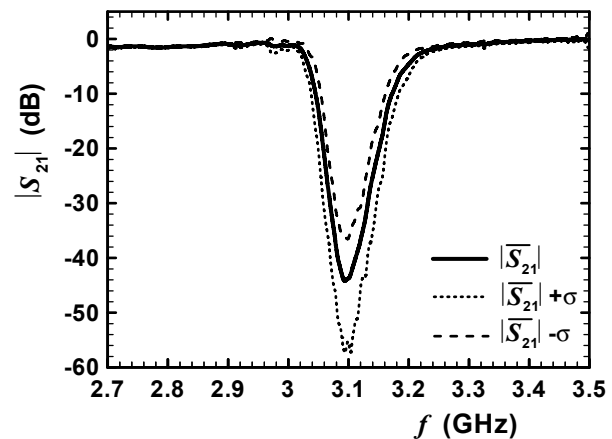


Fig. 12. The arithmetic mean value and its disperse for 25 measurements of transmission through the 3D mu-negative metamaterial in the raised R32 waveguide with 256 boxed broadside-coupled split ring resonators randomly located in the volume of a cube with the side 72 mm in length [8].

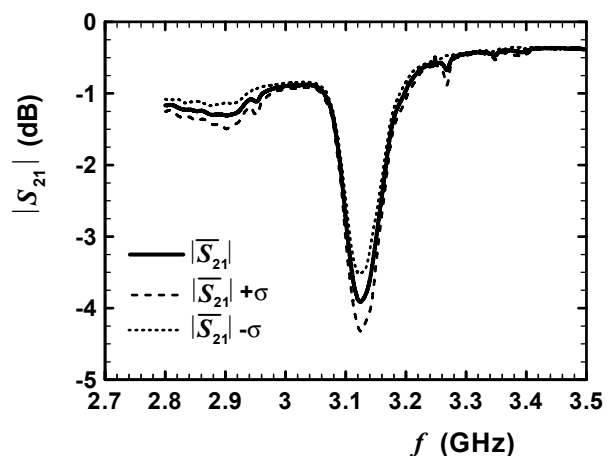


Fig. 13. The same dependence as in Fig. 12, but for the epsilon-negative metamaterial consisting of 256 boxed reduced-size electric dipoles.

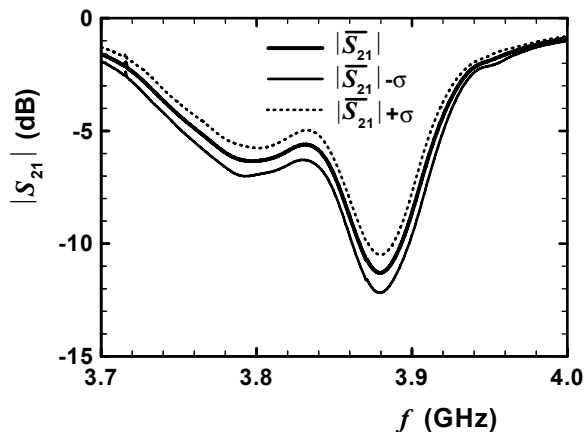


Fig. 14. The same dependence as in Fig. 12, but for the epsilon-negative metamaterial consisting of 256 boxed double H-shaped resonators.

together with random orientation. The frequency band of composites with randomly located unit cells is wider than the band of a single resonant element. This medium can fill a volume of any shape, and can therefore be used in a wide range of applications.

The designed planar resonant elements showing effective negative permittivity or permeability under irradiation by an electromagnetic wave can be simply scaled down or up for application in a different frequency band. In combination, these elements provide the material with a negative refractive index. To achieve this, the cubic cells can be alternated periodically in space like squares on a chessboard. The boxed resonant elements of both kinds can simply be mixed together. The fabricated isotropic single negative metamaterials are ready for use in many applications where theory has simply assumed an isotropic material, though no-one had been able to produce such a material. These applications can include: ideal lenses, antenna radomes, layers that increase the sensitivity of electrically small antennas, frequency selective surfaces, cases that reduce the effective radar cross-section of a target, and phase compensating layers.

Acknowledgements

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