Experimental Verification of the Behavior of a Double Negative Metamaterial Composed of Planar Resonant Elements

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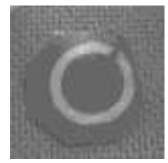
***Abstract*— Measurement of the behavior of double negative volumetric metamaterials is presented in this paper. These metamaterials are composed of planar resonant elements that show negative electric and magnetic polarizabilities. The first metamaterial is a regular 3D periodic structure. The second metamaterial is an analog of an amorphous solid material. The resonant elements are randomly located in space, both in their positions and in their orientation. Planar resonators are inserted into polystyrene spheres to assure their fully random distribution in the space. This has the advantage that the spheres can fill any volume keeping a random distribution of resonant particles. This composite material shows an isotropic response, as it does not prefer any direction of wave propagation. The measurements verified that metamaterials of both types behave as a double negative metamaterial within a narrow frequency band.**

***Index Terms*— Metamaterial, negative permittivity, negative permeability.**

I. Introduction

The work presented in [1, 2] reported on a method for analytical homogenization of volumetric metamaterials composed of planar resonators showing negative electric polarizability or negative magnetic polarizability. The system of these elements located in a regular 3D structure was presented. Finally, a homogenization method was applied to an analysis of 3D structures composed of resonant elements distributed fully randomly in space. This second version of the metamaterial represents the analogy of amorphous material. A double negative (DNG) metamaterial composed of resonant elements showing negative magnetic polarizability - split ring resonators (SRR) [1], and also electric resonators showing negative electric polarizability (NEP) [2, 3], was presented in [4]. The fabricated planar resonant elements are shown in Fig. 1. The element with negative magnetic polarizability is a broad side coupled SRR (BC SRR). The NEP element is a resonator in the shape of a meander on the top surface of a substrate, the bottom surface of which is without metallization [3].

This paper continues the work introduced above, and now presents the measured complex effective permittivity and permeability of the fabricated volumetric metamaterials. These parameters have been determined from the measured scattering parameters [5]. The measurements were performed in a waveguide of rectangular cross-section R32 with the standard dimensions for a metamaterial with a periodic 3D structure. The amorphous metamaterial was assembled as a specimen with dimensions of 72×72×72 mm, i.e. measured in the R32 waveguide with the height raised to 72 mm.



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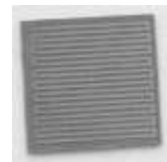

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Fig. 1. The photo of BC-SRR [1] (a), and the planar electric resonator [2,3] (b).

II. 3D Regular System

The first discussion is devoted to the response of the regular 3D periodic system composed of resonant elements from Fig. 1. The experimental realization of this system is shown in Fig. 2. The structure of this metamaterial is better defined than for the amorphous material discussed in the next paragraph. The resonant elements are inserted into three slices of polystyrene with a period of 11 mm on an alternating basis. The BC-SRRs are located with the substrates parallel to the waveguide axis, i.e., perpendicular to magnetic field. The NEPs are located with their substrates perpendicular to the waveguide axis, i.e., parallel to electric field. The structure of this metamaterial corresponds to the structure of a crystalline material. Its response is of course non-isotropic. The behavior of this metamaterial was determined by measuring the scattering parameters in the R32 (WG10) waveguide.

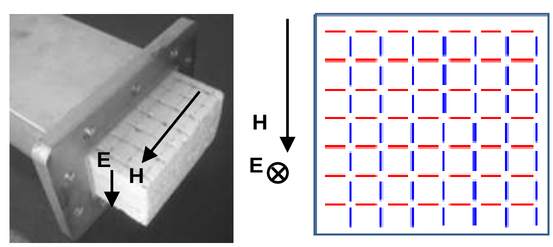


Fig 2. 3D periodical system of planar elements aligned in the same direction, partly inserted into the waveguide. The BC SRRs are shown by the red color, and the NEP resonators by the blue color.

The measured scattering parameters of the assembled DNG metamaterial prism with dimensions of 72×33×72 mm located in the R32 waveguide are plotted in Fig. 3 [4]. The DNG frequency band corresponds to the band in which S_{11} shows a dip. This band can be defined by condition S_{11} < -10 dB, and spans from 3.1 up to 3.13 GHz. However, the band is limited from the low frequency side by the very low value of S_{21}. This is due to the high value of the negative imaginary part of the effective permeability of the system of BC-SRRs in this frequency band [1]. The metamaterial shows a negative refractive index in the 30 MHz frequency band. However, the response is non-isotropic.

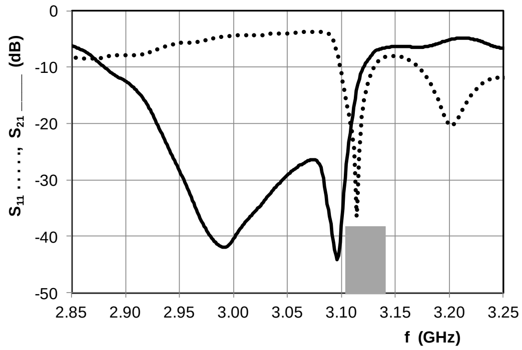
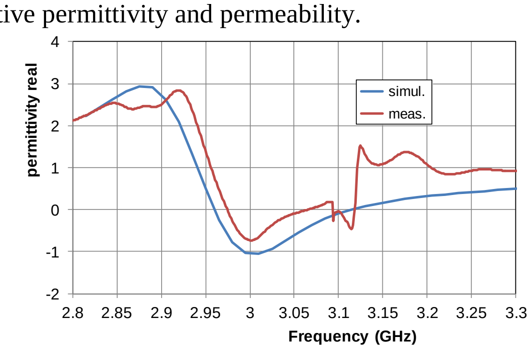


Fig. 3 The measured scattering parameters of the regular 3D periodic DNG system of resonant elements aligned in the same direction.

Figs. 4 and 5 show the dependencies of complex effective permittivity and permeability on frequency. The measured values (red color) are obtained by recalculating from the measured scattering parameters shown in Fig. 3, as proposed in [5]. These values are compared here with data calculated by the homogenization method presented in [1, 2]. The fields excited by the two types of resonant particles in the fabricated system, see Fig. 2, interact together. The effective permittivity of the NEP resonators is therefore affected by the presence of the BC-SRRs, and vice-versa. The simulations (shown by blue lines) represent the permittivity and permeability of a system composed only of NEP resonators and of a system composed only of BC-SRRs. For this reason, there are differences from the measurements performed on the system of each type of element. However, Figs. 4 and 5 show relatively good agreement of the dependences of the effective parameters on the frequency and, above all, the dependences of the resonant frequencies. The measured permittivity and permeability confirm that the fabricated metamaterial designed as a 3D periodical system of planar resonant elements behaves as a material with a simultaneously negative real part of the effective permittivity and permeability.



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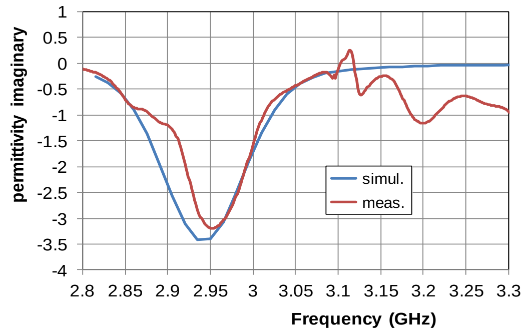

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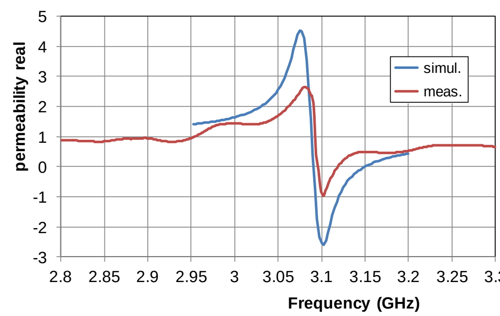
Fig. 4 Dependence of the real part (a), and the imaginary part (b) of the measured and calculated effective permittivity of the metamaterial composed of a regular 3D net of planar resonant particles, see text.



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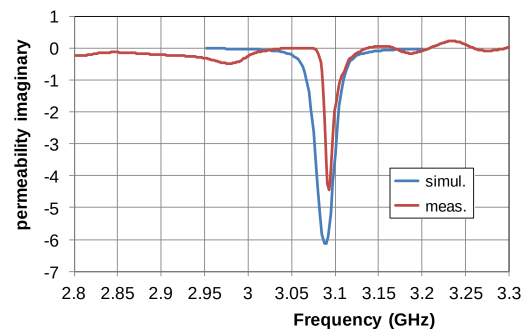


(b)

Fig. 5 Dependence of the real part (a), and the imaginary part (b) of the measured and calculated effective permeability of the metamaterial composed of a regular 3D net of planar resonant particles, see text.

III. Amorphous Metamaterial

The amorphous metamaterial is assembled by putting planar resonators into polystyrene spheres with an outer diameter of 10 mm, see Fig. 6. The spheres are cut into two halves and the resonators are glued inside. The diameter of the spheres determines the system period a. This structure ensures random distribution of the resonant elements both in space and in orientation. This metamaterial can therefore be denoted as an amorphous material. The analyzed models [1, 2] are represented by a system of resonant elements located in a 3D net. Their positions are randomly spread around the nodes of the net in all three directions by ±a/2 with a uniform probability distribution, and are randomly oriented in the interval between ±90 deg with reference to the z axis. The measurement setup is shown in Fig. 6. The spheres fill the volume of a cube 72×72×72 mm in size that is inserted into waveguide R32 with a modified cross-section 72 mm in height. The measured scattering parameters of the two systems of amorphous metamaterials are shown in Fig. 7. Above 3.15 GHz, the system composed of both BC-SRRs and NEPs shows S_{21} much higher than the system of NEPs. In addition, S_{11} decreases sharply here. This indicates DNG behavior in the frequency band above 3.15 GHz up to about 3.2 GHz, i.e., in a band of about 50 MHz. This band is indicated by a grey rectangle in Fig. 8.

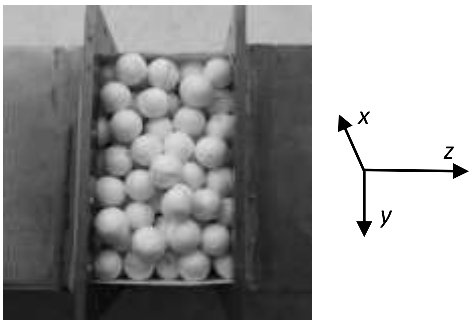


Fig. 6 The amorphous metamaterial in the partly disassembled measurement setup [1] in waveguide R32 with internal dimensions of 72×72 mm. The coordinate system is shown.

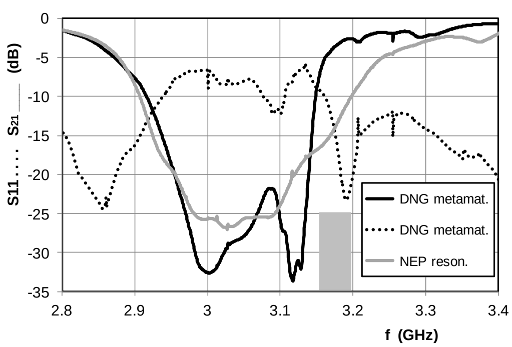
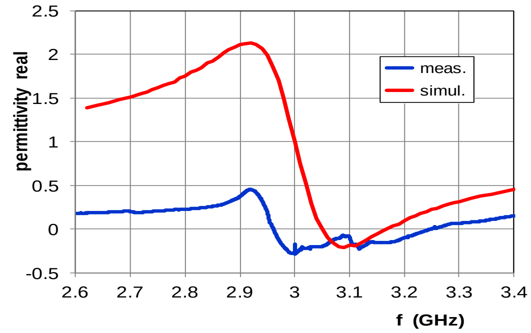


Fig. 7 Measured scattering parameters of the blocks of the amorphous metamaterial located in the R32 waveguide with a cross section of 72x72 mm: the DNG system, and the system composed of NEPs from Fig. 1b. The DNG band is marked by a grey rectangle.

Similarly as in Paragraph II for the 3D regular system of the metamaterial, Figs. 8 and 9 show the complex effective permittivity and permeability of the amorphous system located in the R32 waveguide with cross section 72x72 mm, recalculated from the measured scattering parameters [5], as plotted in Fig. 7. Here, the agreement between the measured effective permittivity and permeability is not so good as in Figs. 4 and 5. However, Figs. 8 and 9 show that the fabricated metamaterial behaves as a double negative material in the narrow frequency band shown in Fig. 7 and specified above.



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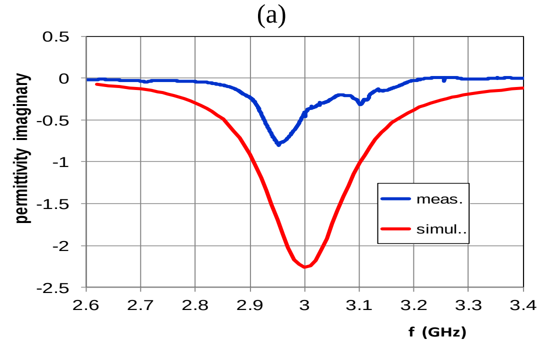

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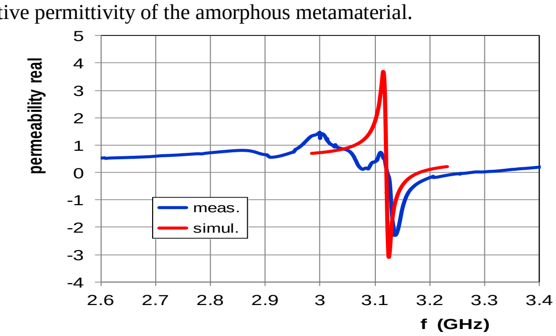
Fig. 8 Dependence of the real part (a), and the imaginary part (b) of the effective permittivity of the amorphous metamaterial.



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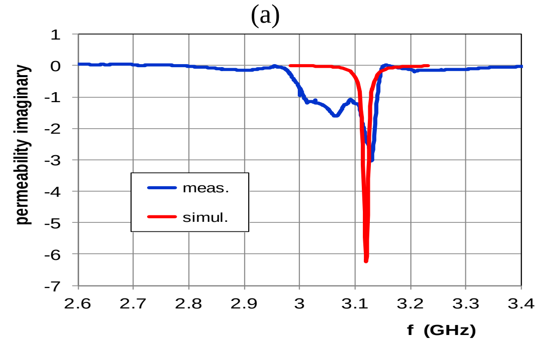

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Fig. 9 Dependence of the real part (a), and the imaginary part (b) of the effective permeability of the amorphous metamaterial.

IV. Conclusion

This paper has presented the results of experiments describing the behavior of two kinds of metamaterial showing double negative behavior. As these metamaterials are composed of resonant elements, their response is rather narrowband. The scattering parameters of the metamaterial specimens were measured in a waveguide with the rectangular cross-section, and the complex effective permittivity and permeability were derived from these scattering parameters. The first kind of metamaterial is designed as a 3D regular structure composed of electric and magnetic resonators. The frequency band of the double negative behavior is about 30 MHz. The response of this metamaterial is non-isotropic. The second metamaterial is an analog of the amorphous material, being composed of resonant elements of both kinds randomly spread both in space and in orientation. The response of this metamaterial is isotropic. The frequency band of double negative behavior is about 50 MHz.

ACKNOWLEDGEMENT

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