A Magnetic Metamaterial Composed of Randomly Oriented SRRs

L. Jelínek, J. Macháč, and J. Zehentner

Czech Technical University in Prague, Technická 2, 166217 Prague 6, Czech Republic

Abstract— The concept, manufacture and testing of a volumetric isotropic magnetic metamaterial composed of randomly distributed broadside coupled split ring resonators is presented in this paper. An estimate of the isotropy based on the measured transmissions is made in terms of the arithmetic mean value and the standard deviation of the sample. We offer conclusions and recommendations for the development of a genuine bulk isotropic medium of various densities and distributions of the particles, based on the 64 measured frequency responses of each sample.

DOI: 10.2529/PIERS060831080303

1. INTRODUCTION

In recent years metamaterials have attracted great attention among scientists, researchers and engineers [1, 2]. The main characteristics of metamaterials, such as left-handed behavior of the waves, negative permeability, negative permittivity and negative index of refraction, can be observed in bulky media and also on periodically loaded transmission lines from microwaves up to optics. The concept of a left-handed transmission line is well known [3]. The main research effort is devoted to the design of practically realizable unit cells in available technology meeting the desired relatively wide-band frequency characteristics. Solving the same task in a bulky medium is much more difficult. This is the challenge that has inspired our work.

Generally, metamaterials are anisotropic media. However, for many applications isotropic materials are needed. Two ways can be used to achieve isotropy. The first is to use a specific form of unit cells, periodically arranged in such a way that the system satisfies selected crystallographic groups of symmetry. The 3D structures introduced in [4] provide an example of this approach. The second way leading to an isotropic medium is based on randomly located cells in the volume of the host. We will follow this approach and will try to verify its usefulness for producing bulky isotropic magnetic metamaterials. The first results are presented here.

2. ARCHITECTURE AND FABRICATION OF A 2D ISOTROPIC METAMATERIAL

3D random location of particles is a great technological problem, and therefore the 2D random system will be studied first. The system will consist of the host material, which has the shape of a parallelepiped cut into three slices that are equal in height, Fig. 1. In each slice an equal number of particles, Broadside Coupled Split Ring Resonators (BC-SRR) [5], is inserted with

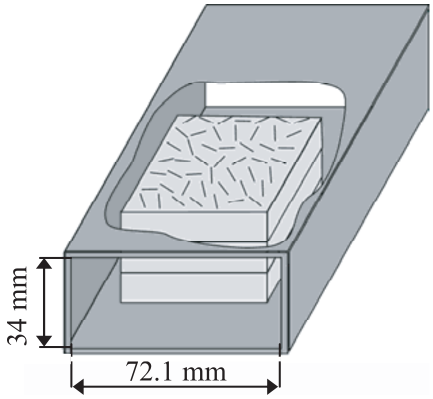


Figure 1: Waveguide loaded with parallelepiped composing of three slices with randomly distributed BC-SRRs.

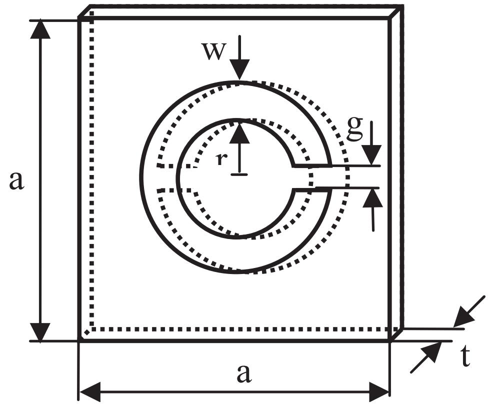
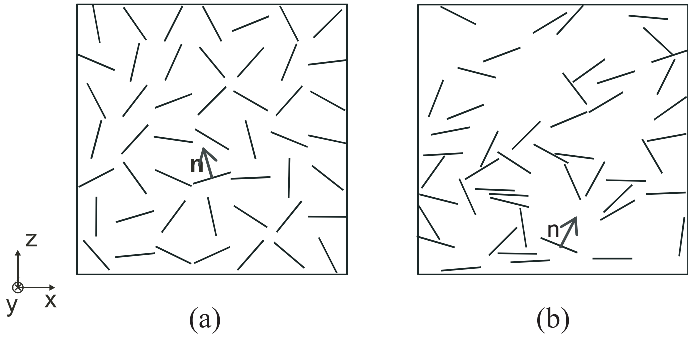


Figure 2: Broadside-coupled split ring resonator.

random orientation. The BC-SRR consists of two split rings placed on the opposite sides of a thin dielectric substrate so that the particle exhibits inversion symmetry, as shown in Fig. 2. Note also that BC-SRR is not a bianisotropic particle [5] and the orientation of its ring-gaps does not play a role when it is excited by a magnetic field. Two different random arrangements, depicted in Fig. 3, representing the top view of a slice, were used and tested. The surface normals of the SRRs, and thus also the magnetic moments, lie only in the x-z plane, forming the desired 2D system. The centers of particular resonators are either positioned periodically in the nodes of a squared net, Fig. 3(a), or their position varies randomly, Fig. 3(b). Randomness is obtained by choosing random angles between the normals of the resonators and the x-axis. The distribution of these angles and also of the particle positions on each slice was 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 particles inside, assuming that the vertical order of the slices is kept. The interchange of the vertical order of the slices, with their three rotations, offers a total of 384 combinations of particle locations. However, we utilized only the first 64 combinations in the experiment.



(a) (b)

Figure 3: (a) Periodic BC-SRR positions in the nodes of the squared net, and (b) their random positions in the slice.

Standard printed circuit technology was used for etching the BC-SRRs on Rogers RT/duroid 5880 substrate of thickness $t = 0.127$ mm with $\varepsilon_r = 2.20$ and 0.017 mm copper cladding. Each resonator resides on a squared leaf with an edge $a = 7$ mm. Froth polystyrene was chosen as the host dielectric. The parallelepiped base edge, equal to the width of the squared slice, is 50 mm, while the height of each slice is 10 mm. The proportions of the BC-SRR are $r = 2.5$ mm, $w = 0.7$ mm and $g = 0.3$ mm.

3. EXPERIMENTS, OBSERVATIONS AND RESULTS

The proportions of the BC-SRRs were designed in such a way that their resonant frequencies occurred around 3 GHz. Consequently, measurements were carried out in the rectangular waveguide R32. The HP 8510B network analyzer measured the scattering coefficients. First we checked the resonant frequency of the single resonator positioned in the middle E plane of the waveguide. A typical transmission is depicted in Fig. 4. It turned out that the resonant frequencies of the individual resonators differed in the 50 MHz interval due to manufacturing imperfections.

In the next step, the isotropy of the above-mentioned parallelepipeds, stacks of three slices, was tested. The stacks were inserted into the rectangular waveguide R32, as depicted in Fig. 1. If the parallelepiped is isotropic, then the measured scattering parameters should stay invariant for any 90° rotations of each slice of the parallelepiped around its central vertical axis. Due to the random arrangement of the particles, this last presumption should hold in a statistical sense and therefore the arithmetic mean value $\bar{x}$

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

and the sample standard deviation σ

$$\sigma = \sqrt{\left(\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2\right)}$$

were calculated from all the 64 measurements. This resulted in the records depicted in Figs. 5–7.

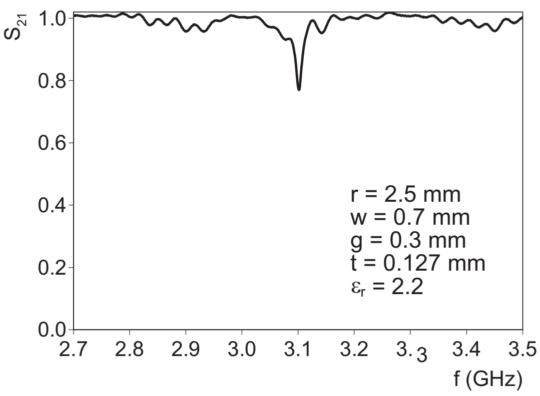


Figure 4: Transmission of one BC-SRR in the R32 waveguide, $f_0 = 3.1015\,\text{GHz}$.

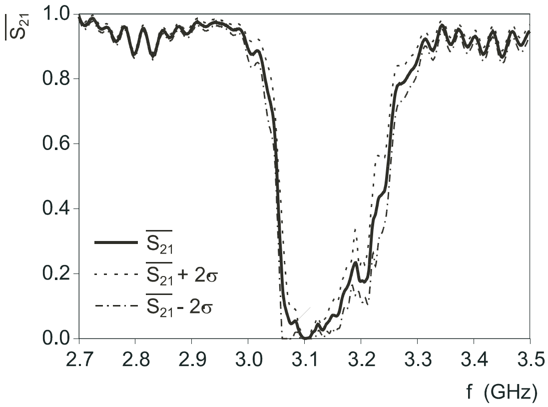


Figure 5: Arithmetic mean value $\bar{s}_{21}$ of the transmission through the sample with 147 BC-SRRs and its disperse $\bar{s}_{21} \pm 2\sigma$ when the resonators are in the nodes of the squared net.

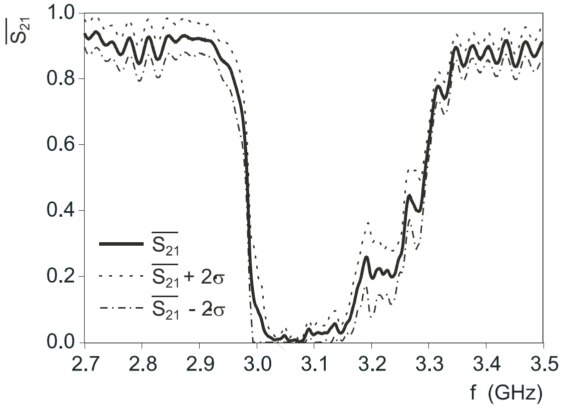


Figure 6: Arithmetic mean value $\bar{s}_{21}$ of the transmission through the sample with 243 BC-SRRs and its disperse $\bar{s}_{21} \pm 2\sigma$ when the resonators are in the nodes of the squared net.

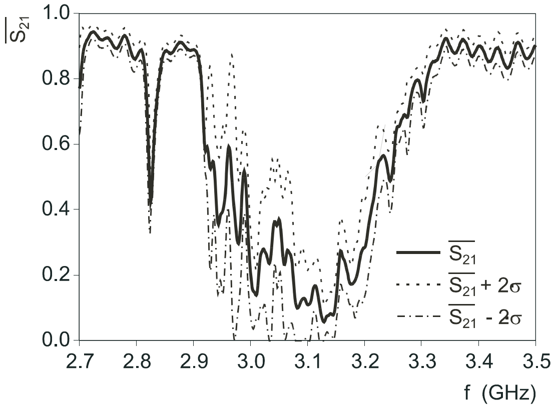


Figure 7: Arithmetic mean value $\bar{s}_{21}$ of the transmission through the sample with 243 BC-SRRs and its disperse $\bar{s}_{21} \pm 2\sigma$ when the resonators are randomly distributed.

All three measured samples can be described by means of three characteristics. The first is the isotropy, which in the measurements presented here is directly proportional to the disperse σ of the transmission coefficient. Furthermore, it was experimentally observed that almost all measured data lies in the interval of $\pm 2\sigma$ around the arithmetic mean value of s_{21}. It is seen from Figs. 5 and 6 that the isotropy depends only slightly on the particle density, as the disperse of the transmission coefficient is nearly the same in both cases. However, the isotropy is very sensitive to the particle distribution, as follows from Fig. 7. This figure shows that the particle distribution from Fig. 3(b) is not very suited for isotropic materials, while the distribution from Fig. 3(a) provides a material with acceptable isotropy. The second and third important characteristics are the bandwidth and the insertion losses at the resonance. It is worth noting that the higher the insertion losses, the higher, in absolute values, are the effective material parameters. It is apparent from Figs. 5 and 6 that widening of the bandwidth can be achieved by using higher density of the particles, and the insertion losses are preserved. Using random positions of the particles, as in Fig. 3(b), leads also to the bandwidth widening shown in Fig. 7. However, in this case the insertion losses are reduced.

Lastly the measured transmissions of the randomly distributed SRRs were compared with transmissions of the sample with regular particle distribution. A parallelepiped was produced with all resonators aligned in such a way that their magnetic moments were oriented along the exciting transversal magnetic field. This parallelepiped consists of three slices, as in the former cases. Regular distribution of the resonators, as depicted in Fig. 8, was used in each slice. Now the resonators in one row occupied positions shifted by the half-pitch with regard to resonators standing in the closest neighboring rows in order to achieve the same density of the particles, i.e., 147 pieces per parallelepiped. The measured transmission coefficient through the waveguide loaded with this highly anisotropic sample is depicted in Fig. 9. Comparing Figs. 5 and 9, we can conclude that the random distribution of particles, which leads to an isotropic response, not only leaves the insertion losses unaffected, but also remarkably widens the bandwidth.

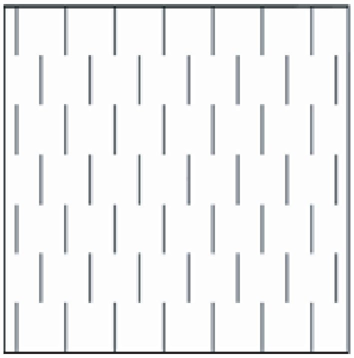


Figure 8: Regular positions of particles in one slice.

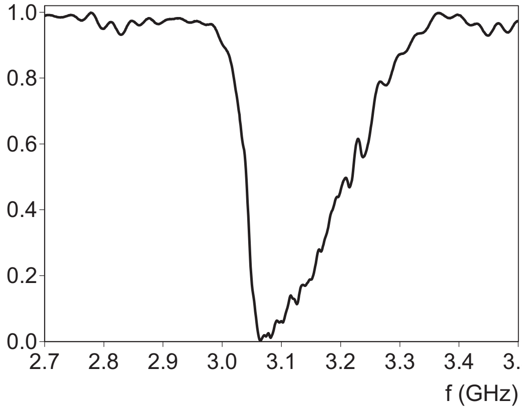


Figure 9: Transmission through 147 BC-SRRs periodically located and axially aligned.

4. CONCLUSIONS

To obtain a genuine 3D isotropic medium the space density of the particles has to be sufficiently great to enable averaging of the responses of all involved effects and couplings participating in the homogenization, and the size of the particles must be kept negligible compared with the wavelength. It turned out in our experiments that the particle distribution is also essential. While random distribution of randomly oriented particles does not lead to an isotropic material, regular distribution of randomly oriented particles shows very good results and with higher particle density it also provides an opportunity to increase the bandwidth of the resonance. The latter particle distribution is thus very promising and should also be used for manufacturing the 3D isotropic material.

ACKNOWLEDGMENT

This work has been supported by the Grant Agency of the Czech Republic under project 102/06/1106 "Metamaterials, nanostructures and their applications".

REFERENCES

1. Engheta, N. and R. W. Ziolkowski Ed., *Metamaterials: Physics and Engineering Explorations*, Willey-IEEE Press, 2006.
2. Eleftheriades, G. V. and K. G. Balmain Ed., *Negative-Refraction Materials: Fundamental Principles and Applications*, Willey-IEEE Press, 2006.
3. Caloz, C. and T. Itoh, *Electromagnetic Metamaterials, Transmission Line Theory and Microwave Applications*, Willey - Interscience, 2005.
4. Baena, J. D., L. Jelinek, R. Marqués, and J. Zehentner, "On the design of isotropic magnetic materials," *Proceedings of MELECON 2006*, 250–254, Malaga, Spain, May 2006.
5. Marqués, R., F. Medina, and R. Rafii-El-Idrisi, "Role of bianisotropy in negative permeability and left-handed metamaterials," *Physical Review B*, Vol. 65, 144440-(1–6), 2002.