UC Irvine

UC Irvine Previously Published Works

Title

Characterization of metamaterials made of stacked layers of dogbone conductor pairs

Permalink

<https://escholarship.org/uc/item/2w4082xx>

ISBN

9781424449682

Authors

Shitvov, AP
Vallecchi, A
Schuchinsky, AG
[et al.](#)

Publication Date

2010-11-22

DOI

10.1109/APS.2010.5561022

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

Characterization of Metamaterials Made of Stacked Layers of Dogbone Conductor Pairs

Alexey P. Shitvov⁽¹⁾, Andrea Vallecchi⁽²⁾,
Alex G. Schuchinsky^{*(1)} and Filippo Capolino^{*(3)}

(1) Queen's University Belfast, UK

(2) University of Siena, Italy

(3) University of California, Irvine, CA, USA

E-mail: a.schuchinsky@qub.ac.uk

Introduction

The metamaterials composed of planar arrays of tightly coupled dogbone-shaped conductors have recently attracted considerable interest owing to their potential of supporting backward wave propagation [1]-[3]. The detailed study of the plane wave interaction with a layer of dogbone pairs has been performed in [3], [4] along with the eigenwave analysis of an infinite stack of array layers. In particular, it has been found that such metamaterial may exhibit negative effective refractive index near the transmission resonances.

In this paper we present the results of the theoretical and experimental studies of the stacked arrays of the dogbone shaped conductor pairs. The obtained results demonstrate for the first time that in the stacks of finite thickness, strong coupling between the closely spaced arrays causes the additional transmittance resonances. The comprehensive interpretation of the observed transmission resonances and underlying physical mechanisms is proposed on the basis of the simulated current distributions in the dogbone conductors.

Metamaterial Structures and Measurement Setup

The metamaterial structures studied in this paper are composed of stacked doubly periodic planar arrays of dogbone-shaped conductor pairs (Fig. 1a). The detailed parametric study in [3], [4] has revealed that such an artificial medium may exhibit negative effective refractive index (NRI) and the resonance transmittance. To examine the properties of these metamaterials experimentally, the specimens of the periodic planar arrays have been designed using the commercial simulator CST Microwave Studio. The simulations have been performed using the constitutive unit cell (Fig. 1b) of a square shape with $A = B = 5.64$ mm. The dogbone shaped conductors have the dimensions (in mm): $A_1 = 0.75$, $A_2 = 5.55$, $B_2 = 0.6$, $H = 0.381$. The array substrates have been made of two laminates with slightly dissimilar parameters: (1) Taconic TLY-5 with permittivity $\epsilon_r = 2.2$ and loss tangent 0.0009, and (2) TLX-9 with permittivity $\epsilon_r = 2.5$ and loss tangent 0.0019. The use of the two laminates with significantly different loss tangents has enabled us to assess the effect of dielectric loss on the metamaterial performance.

Fig. 1. Layout of the stacked doubly periodic arrays of dogbone shaped conductor pairs (a) and geometry of a constitutive unit cell (b).

To make the frequency of the lowest magnetic resonance mode the same for both laminate materials, the length of the dogbone lateral arms has been tailored for each substrate: $B1 = 2.75$ mm for TLY-5, and $B1 = 2.5$ mm for TLX-9. The size C , used as a variable parameter, represents in Fig. 1 either the distance between the stacked layers or the periodicity in the z -direction for an infinite medium. In multilayer arrangements the stacked individual layers are interleaved by the 1 mm thick sheets ($C = 1.42$ mm) of rigid foam RohacelleTM with relative permittivity 1.05 and loss tangent 0.0008. Finally after aligning the unit cells in the stacked arrays, the assembly has been sandwiched between two RohacelleTM slabs of thickness 12 mm each and fitted in a wooden holder as shown in Fig. 2.

The measurement setup comprises a pair of horn antennas spaced apart for about 1.6 m and the fixture with the test specimen in the middle. The holder frame size and the sample distance from antennas have been chosen such that the specimens be located in the far-field region of the horns and the square shaped arrays (67 unit cells along each side in the $x0y$ plane) cover the entire far-zone spot illuminated by the full-angle 3 dB beamwidth of the horn antenna. The boresights of the horns have been aligned in both vertical and horizontal planes and the beam axis has pointed at the centre of the sample holder.

Since the array of dogbone pairs is a strongly anisotropic structure, it exhibits the resonance response in the specified frequency band only if the incident wave contains the x -component of the electric field, see Fig. 1. At the orthogonal polarization of the incident electric field oriented across the dogbone pairs, the array is nearly perfectly transparent. This has been confirmed by the measurements. Because in the measurement setup an incident electric field is vertically polarized, the samples have been mounted in the holder so that the x -axis of the dogbone pairs be always vertical, while the frame rotation axis be either vertical for TE-polarized or horizontal for TM-polarized incident waves.

Experimental Results and Discussion

Transmittance measurements have been carried out for a single layer array of dogbone pairs, and the stacked two and four layer arrays at different wave polarizations and incidence angles. To gain insight in the transmittance properties of the stacked arrays of finite thickness and identify the modes of the observed resonances, the experimental results have been analyzed in comparison with the simulations of the respective structures and, particularly, the current distributions on the dogbone conductor pairs in the layered arrangements.

The features of the stacked arrays of the dogbone shaped conductor pairs are illustrated by the characteristics of a four layer structure. Fig. 2 displays the transmission coefficient of the assembly comprised of the two arrays on TLY-5 substrates and the other two - on TLX-9 laminates, interleaved by 1-mm-thick Rohacell foam sheets (the layers are equally spaced and the distance between their centers is $C = 1.42$ mm). The measurement and simulation results show good qualitative agreement. The peaks at f_1 and f_2 correspond to the perturbed transmission resonances of the single and two layer arrays. The identity of these modes is corroborated by the respective current distributions on the dogbone pairs in Fig. 3. The peak at $f_3 = 9.9$ GHz represents an additional resonance occurring due to the coupling between the interlayer magnetic dipoles. Although the current patterns at f_2 and f_3 look similar in individual interlayer loops, their mutual orientations differ, viz. the current circulation has the same direction in both loops at f_3 but it is opposite in the two loops at f_2 . When the layer separation increases, the transmission resonance at f_3 is suppressed, whereas the resonance at f_2 remains practically unchanged and at f_1 the transmittance magnitude slightly decreases.

The transmission peak at $f_4 = 10.9$ GHz significantly differs. The current distributions in Fig. 3 show that at f_4 the adjacent individual dogbone conductors (*not dogbone pairs*) of different layers compose the interlayer magnetic dipoles strongly coupled with the magnetic dipoles created inside the dogbone pairs.

Fig. 2. Tilted specimen in the holder (TM polarization). Measured and simulated transmittance of four stacked arrays of dogbone pairs on TLY-5 and TLX-9 substrates. Normal incidence, $\theta = 0^\circ$. Layer separation $C = 1.42$ mm.

References

- [1] J. Zhou, T. Koschny, L. Zhang, G. Tuttle, and C. M. Soukoulis, "Experimental demonstration of negative index of refraction," *Appl. Phys. Lett.*, vol. 88, pp. 221103/1–3, 2006.
- [2] J. Hao, Y. Yuan, L. Ran, T. Jiang, J. A. Kong, C. T. Chan, and L. Zhou, "Manipulating electromagnetic wave polarizations through anisotropic metamaterials", *Phys. Rev. Lett.* vol. 99, 063908, 2007.
- [3] G. Donzelli, A. Vallecchi, F. Capolino, and A. Schuchinsky, "Metamaterial made of paired planar conductors: Particle resonances, phenomena and properties," *Metamaterials*, vol. 3, pp. 10–27, 2009.
- [4] A. Vallecchi, F. Capolino, and A. Schuchinsky, "2-D isotropic effective negative refractive index metamaterial in planar technology," *IEEE Microwave Wireless Comp. Lett.*, vol. 19, pp. 269–271, 2009.

Fig. 3. Simulated current distributions in the x_0z cross-section of the unit cell with two stacked dogbone pairs on TLY-5 substrate at the resonance frequencies