Available online at www.sciencedirect.com

SciVerse ScienceDirect

PHOTONICS AND NANOSTRUCTURES
Fundamentals and Applications

Photonics and Nanostructures – Fundamentals and Applications 10 (2012) 329–336

www.elsevier.com/locate/photonics

Retrieval of effective parameters for bianisotropic metamaterials with omega shaped metallic inclusions

Zhaofeng Li [a,*], Koray Aydin [a,b], Ekmel Ozbay [a,b,c]

[a] *Nanotechnology Research Center, Bilkent University, Bilkent, 06800 Ankara, Turkey*
[b] *Department of Physics, Bilkent University, Bilkent, 06800 Ankara, Turkey*
[c] *Department of Electrical and Electronics Engineering, Bilkent University, Bilkent, 06800 Ankara, Turkey*

Received 19 March 2011; received in revised form 17 October 2011; accepted 8 November 2011
Available online 18 November 2011

Abstract

Bianisotropic metamaterials including Ω-shaped metallic elements are investigated experimentally and theoretically. A passband is observed for a composite metamaterial (CMM) based on an Ω-medium below the plasmonic frequency of the corresponding closed CMM. The effective parameters (refractive index, impedances, permittivity, permeability, and magnetoelectric coupling coefficient) are retrieved for the Ω-medium and the CMM based on it. Our retrieval results show that the passband observed for the CMM is a band with positive refractive indices. Our retrieval results confirm the deductions of our previous reports.

Keywords: Metamaterials; Bianisotropy; Omega media; Effective parameters

1. Introduction

Metamaterials have attracted much attention from the scientific community because of their exotic properties, which usually do not exist in natural materials. For instance, metamaterials with a negative refractive index (NRI) [1–4] can be used to construct a superlens [5–9]. More interestingly, metamaterials can even be used to construct an invisible cloak [10,11]. In order to realize such novel properties, metamaterials usually include two types of elements and, therefore, are called composite metamaterials (CMM). For instance, when constructing a metamaterial with NRI, one can use a periodic thin metallic wire medium in order to obtain negative permittivity [12], and use split ring resonators (SRRs) in order to obtain negative permeability [13]. Although SRRs are widely used in metamaterials operating in the microwave region, studies show that there can be problems when SRRs are used at optical frequencies [14]. Bianisotropy usually should be avoided during the design of metamaterials. However, it was proposed recently [15] that it is possible to benefit from the bianisotropic properties of an example metamaterial – Ω medium (omega medium). An omega medium was first introduced by Saadoun and Engheta [16] and was called a pseudochiral medium in 1992. An omega medium is a composite electromagnetic material with Ω-shaped metallic inclusions that are placed in a host dielectric medium. In the omega medium, there is magnetoelectric coupling due to its intrinsic bianisotropic characteristics. Following the ideas described above [15,16], we studied and reported on a series of

* Corresponding author. Tel.: +90 312 2901018;
fax: +90 312 2901018.
E-mail address: zhaofengli@bilkent.edu.tr (Z. Li).

1569-4410/$ – see front matter
doi:10.1016/j.photonics.2011.11.002

metamaterials based on Ω-shaped metallic inclusions experimentally and numerically [17,18]. The results have clearly shown the differences from the traditional metamaterials made of SRRs. A transmission band was observed for a CMM based on an omega medium, which is below the plasmonic frequency of the closed composite metamaterial (CCMM), in which it has been deduced that this transmission band is not a band of negative refraction, although the effective parameters for the bianisotropic metamaterials were not presented in previous reports.

It has been proposed that metamaterials respond to electromagnetic radiation as continuous materials when the wavelength is much larger than the spacing between the composite components and the size of these respective components. Therefore, it is reasonable to assign values of permittivity ε and permeability μ for a metamaterial. Several methods [19–22] have been proposed to retrieve the effective parameters for isotropic metamaterials. Among them, the method based on the scattering parameters (S parameters) of a slab of metamaterial is widely used [23–26]. Compared with isotropic metamaterials, the retrieval of the effective parameters for a bianisotropic metamaterial is more complex due to the existence of the magneto-electric coupling effect. However, it is proposed that by using the S parameters of three orthogonal directions [27], it is possible to retrieve all of the effective parameters for a bianisotropic metamaterial. Very recently, our study revealed that it is also possible to retrieve all of the effective parameters for a bianisotropic metamaterial by using the S parameters of only one direction [28]. In the present paper, we will recount some of the brief conclusions of our retrieval method. Then, we will provide the effective parameters including the magnetoelectric coupling coefficient for the bianisotropic omega medium. Our retrieval results validate what was deduced in our previous reports [17,18].

2. Experimental and numerical results

Fig. 1(a) and (b) shows two unit cells of the omega medium and the CMM with omega structure inclusions under study. Fig. 1(c) shows the details of the omega structure. The parameters in the figure are r = 1.19 mm, W = 0.45 mm, and L = 1.8 mm. The omega structures are made of copper on a FR4 printed circuit board (PCB). The dielectric constant and the conductance of the FR-4 board are 4.4 and 0.0068 S/m, respectively. The thickness of the copper and FR4 are 30 μm and 1.6 mm, respectively. By arranging these omega

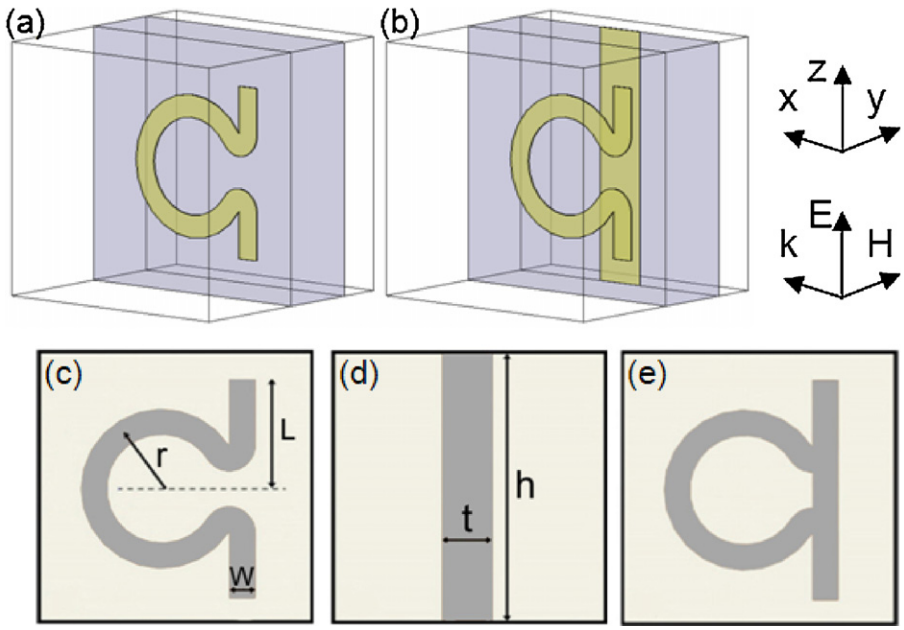

Fig. 1. (a and b) The schematics of unit cells for the omega medium and the CMM with omega structure inclusions. (c) The omega structure. The dimensions of the omega structure are r = 1.19 mm, W = 0.45 mm, and L = 1.8 mm, respectively. (d) The continuous wire structure with its dimensions t = 1.44 mm and h = 5 mm. (e) The closed omega structure, in which its dimensions are equal to the omega structure in (c). The lattice constants for all of the structures are $a_x = a_y = a_z$ = 5 mm.