Available online at www.sciencedirect.com
ScienceDirect
Metamaterials
Metamaterials 2 (2008) 18–25
www.elsevier.com/locate/metmat

Design and measurement of negative permeability metamaterials made from conductor-coated high-index dielectric inclusions

O. Acher*, J.-H. Le Gallou, M. Ledieu

CEA Le Ripault, BP 16, F-37260 Monts, France

Received 12 July 2007; received in revised form 18 October 2007; accepted 19 October 2007
Available online 4 November 2007

Abstract

We investigate metal-dielectric inclusions that provide highly resonant permeability. These inclusions are made of high-index slabs with conductor plating on some faces. Microwave measurements are performed on several types of gratings made from these patterns. Broad band experiments are carried using a coaxial cell. Negative permeability levels lower than −20 have been observed in the GHz range, along with loss levels as low as 0.09 at $\mu' = -1$. We show that among the different theoretical approaches that are adequate to describe these materials, the field summation approach provides a very straightforward way to derive the effective permeability. The simple analytical expression of the permeability is in excellent agreement with the experiments. These inclusions are shown to be attractive both from the technological and the intrinsic performance point of view for metamaterial manufacturing. The effects of inclusion imperfections and finite thickness are discussed.

PACS: 07.55; 84.40; 42.25.Bs; 78.20.C

Keywords: Metamaterial; Negative permeability; High-index dielectric; Effective medium; Field summation

1. Introduction

The design of metamaterials with sophisticated electromagnetic properties using simple starting materials is an important issue. It has been outlined that highly resonant and negative permeabilities could be obtained in the microwave regime through a variety of conductive patterns [1–6], sometimes including magnetic cores [7], but also from high-index dielectric patterns [8–13]. While many inductive pattern topologies have been investigated, the use of high-index dielectric patterns has been restricted to our knowledge to spheres [8,10,12,14], rods with circular or square cross-sections [11] and cubes [8]. This system also has a significant theoretical importance. Early theoretical works predicted resonant permeability behaviour in composites made of high-index spheres [15] or ellipsoids [16], and different theoretical approaches have been used to investigate this system, as described in ref. [10]. In particular, many developments performed to account for the microwave properties of conductive inclusions [17] (corresponding to large imaginary permittivities) have been found to be applicable to high-index inclusions, with large real permittivities. As a consequence this system is very interesting to comfort detailed theoretical approaches. However, only a limited number of experiments have been reported [8,11,18]. One difficulty that has been pointed out in this system is the sharpness of the magnetic resonance [10]. As a consequence inho-

* Corresponding author at: CEA, Department Materiaux, Le Ripault, BP 16, F-37260 Monts, France. Tel.: +33 2 47 34 48 30; fax: +33 2 47 34 51 06.
E-mail address: olivier.acher@cea.fr (O. Acher).

1873-1988/$ – see front matter
doi:10.1016/j.metmat.2007.10.001

mogeneous broadening may be dominant in some observations.

The quest for metamaterials working at optical frequencies has boosted the association of metals and dielectrics [19]. Pairs of nanorods [20], along with more elaborated patterns of metal/dielectric/metal structures denominated fishnet structures, have been designed and operated up to the optical range [21–23]. Such structures have proved superior to other structures in the optical range [24]. In the microwave range, the association of metal and conventional dielectrics has also been demonstrated [25], but only modest negative values were measured on the permeability.

In this work, we show that by combining properly conductive patterns and a dielectric material with a very high dielectric constant, it is possible to design inclusions that exhibit highly resonant permeability. These inclusions are made of high-index slabs with conductor plating on some faces. In a first part, the microwave measurement strategy is presented. Using a finite size sample in a coaxial cell, it is possible to determine the electromagnetic properties of an infinite grating. Then experimental results are presented, and excellent negative permeability features are outlined. In a last part, the theoretical approach that allowed the conception of these metamaterials is presented, and model predictions are shown to be in excellent agreement with the microwave experiments.

2. Experimental details

We want to investigate the properties of lamellar gratings sketched in Fig. 1a. These gratings consist of high-index dielectric lamellas, each lamella being plated with a conductor on two parallel faces. Because of some symmetry planes sketched in Fig. 1b, these gratings can be constructed by symmetrizing the unitary elements sketched in Fig. 1c. A corresponding sample can be manufactured by putting a unitary element of Fig. 1c between parallel perfect metallic plates placed on the symmetry planes. This parallel plate topology can be mapped into a coaxial line topology using a conformal transformation. This transformation changes the polarization into the fundamental mode propagating in the line, with the ***H*** field circumferential and the ***E*** field radial. Such a topological transformation has been used successfully to investigate number of composite materials [5,26–29]. As a consequence, the infinite gratings of Fig. 1a are equivalent to the coaxial samples sketched in Fig. 1d.

Two face-coated samples, named FC1 and FC2, and one edge-coated sample, denominated EC, have been

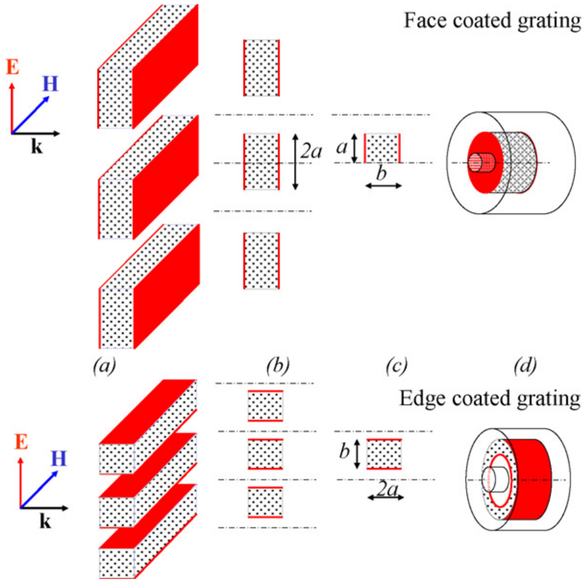

Fig. 1. Sketch of the grating topologies under investigation. The high-index dielectric material is represented in shaded gray; conductor plating is full red. (a) Free space; (b) cross-section; (c) unit cell and symmetry plane; (d) equivalent sample in coaxial line. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

constructed according to Fig. 1d. The dimensions are indicated in Table 1. The high-index material is K-140 from supplier Xtalonics. This material has a dielectric constant $\varepsilon' \approx 140$, and low losses ε''. The conductor plating was made using silver lacquer. The samples were introduced in a 50-Ω coaxial cell with outer diameter 39 mm. The complex reflection and transmission coefficients were measured from 50 MHz up to 3 GHz using a HP 8510 network analyzer. The permeability and permittivity of each sample were retrieved using the conventional Nicholson, Ross and Weir procedure [30]. The relative precision of the method on $|\varepsilon|$ and $|\mu|$ is estimated better than 5% of max ($|\varepsilon|$, $|\mu|$).

Table 1
Geometrical characteristics of the high-index metal-coated gratings under investigation; measured data and comparison with model (Eq. (7), with $\varepsilon = 140$)

Sample	FC1	FC2	EC
a (mm)	9.3	9.3	5.0
b (mm)	3.0	6.0	7.3
f (%)	87	87	58
F_0 experiment	0.63	0.81	1.30
(GHz) model	0.68	0.68	1.27
F_1 experiment	2.16	2.65	>3
(GHz) model	2.04	2.04	3.80
eps′@0.5 experiment	17	12	3.3
GHz model	8	8	2.4