Available online at www.sciencedirect.com
ScienceDirect
Metamaterials
Metamaterials 3 (2009) 140–147
www.elsevier.com/locate/metmat

3D isotropic metamaterial based on a regular array of resonant dielectric spherical inclusions

I.B. Vendik, M.A. Odit*, D.S. Kozlov

St. Petersburg Electrotechnical University, 5 Prof. Popov Str., St. Petersburg 197376, Russia

Received 17 April 2009; received in revised form 28 August 2009; accepted 7 September 2009
Available online 30 September 2009

Abstract

The 3D regular lattice of bi-spherical dielectric resonant inclusions arranged in a cubic lattice as two sets of dielectric spheres having different radii and embedded in a host dielectric material with lower dielectric permittivity was carefully investigated. The magnetic resonance mode in smaller spheres gives rise to the magnetic dipole momentum and the electric resonance mode in bigger spheres is responsible for the electric dipole momentum. The magnetic resonance corresponding to the first Mie resonance in the spherical particles is followed by forming a regular array of effective magnetic dipoles, and the structure of the identical spherical dielectric resonators can be designed as an isotropic μ-negative 3D-metamaterial. At the same time, it was found experimentally and by the simulation that the resonant response of the electric dipole was weakly pronounced and the ε-negative behavior was remarkably suppressed. To enhance the electric dipole contribution, two different ways were considered: (i) using another kind of symmetry of the bi-spherical arrangement of the particles corresponding to the body-centered cubic symmetry instead of the symmetry of NaCl analog considered previously; (ii) using a strong coupling between the identical resonant dielectric spheres arranged in the simple cubic symmetry for creation of the structure exhibiting properties of the isotropic DNG medium.

PACS: 94.20.ws; 78.20.Ci; 41.20.Jb; 94.05.Pt

Keywords: Metamaterial; Resonant inclusion; Mie resonance; Magnetic dipole; Electric dipole; Isotropic; Backward wave

1. Introduction

Medium with simultaneously negative permittivity and permeability or so-called double negative medium (DNG) can be formed by a regular lattice of inclusions considered as artificial “molecules”. In many practical cases, isotropic DNG structure is very attractive. Different ways to create the 3D isotropic DNG medium have been suggested [1–11]. The structure is designed as a regular array of cubic or spherical inclusions. Using a cubic arrangement with split-ring resonators on the faces and a wire medium was suggested and discussed in [1–3]. Another way is to use intrinsic properties of the inclusions, in particular plasmonic nanoparticles to design metamaterial for optical frequency range [4,5]. The isotropic DNG structure for microwave applications can be designed as a regular lattice of resonant dielectric inclusions, providing excitation of electric and magnetic dipoles. These dipoles form the artificial medium exhibiting DNG behavior in a limited frequency range near the resonant frequencies. Dielectric disk, cylindrical, or spherical resonators are suitable for establishing the dipole moments. Metamaterials with desired values

* Corresponding author. Tel.: +7 812 346 0867;
fax: +7 812 346 0867.
E-mail address: maodit@mail.eltech.ru (M.A. Odit).

1873-1988/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.metmat.2009.09.001

of permeability $\pm\mu$ and permittivity $\pm\varepsilon$ are developed by exciting electric and magnetic resonant modes [6–12]. The 3D regular lattice of bi-spherical dielectric resonant inclusions was suggested for the first time in [7,8]. In this structure, the metamaterial medium is composed of two sets of spherical particles made from the same dielectric material embedded in a host dielectric material. The spheres differ by radius. The dielectric constant of the spherical particles is much larger than that of the host material. By combining two sets of the spheres with suitable radii, different modes can be simultaneously exited in the spheres: the magnetic resonance mode giving rise to the magnetic dipole momentum and the electric resonance mode being responsible for the electric dipole momentum. In [8–10], it was suggested that the dielectric resonators do not interact and for the 3D structure the responses of both the spherical particles are superimposed. By full-wave simulation and experimental investigation, it was found that the resonance response of the magnetic dipole is very effective and the μ-negative isotropic metamaterial can be designed as a regular array of dielectric spherical particles with the first Mie resonance. At the same time, the electric dipole corresponding to electric resonance mode is weakly pronounced. As a consequence, the ε-negative behavior is blurred [10].

Detailed theoretical description based on full-wave analysis was performed in [12] for different all-dielectric structures of metamaterial: single-negative (SN) medium based on the spherical particles; bi-spherical DNG medium on an array of the dielectric spherical particles of the same radius made from two materials differing in dielectric permittivity; a set of identical discs and discs made of two different dielectric materials etc. The last structures based on the discs form 2D SN and DNG metamaterials. Interesting 2D structures based on cylindrical resonator arrays situated in a parallel-plate waveguide have been discussed and experimentally verified in [13,14]. In these structures, the DNG properties are provided by magnetic resonance in the cylinders (magnetic dipole, μ-negative behavior) and by ε-negative response of electromagnetic wave in a parallel-plate metallic waveguide with TE_n modes below the cut-off frequency.

Recently the experimental investigation of isotropic metamaterials based on resonant dielectric inclusions has been reported [15–17]. The resonant μ-negative response was registered in the 3D structure based on a regular array of dielectric cubes in [15] and the 2D array of cubes in [16]. The 3D DNG material was realized as a set of dielectric spherical particles regularly distributed in a metallic wire frame exhibiting cubic symmetry. The wire frame provides an environment with evanescent waves followed by effective negative permittivity, which in combination with the resonant dielectric particles giving rise to magnetic dipole and negative permeability leads to a propagating wave with negative phase velocity, i.e. forms the 3D isotropic DNG medium.

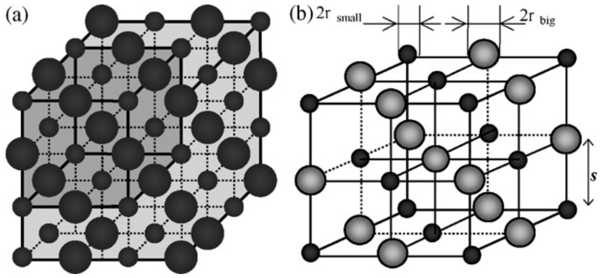

Fig. 1. (a) Bi-spherical NaCl-like structure with two types of resonators. (b) Single cell of the NaCl-like structure.

All these achievements support the fruitful idea of a realization of the isotropic metamaterial using dielectric resonant inclusions. In order to improve the performance of the all-dielectric DNG medium with cubic symmetry based on spherical dielectric particles, we suggest the new structures obtained by: (i) changing the symmetry of the single cell of the bi-spherical structure to enhance the contribution of the electric resonance in the effective dielectric permittivity; (ii) to use strongly coupled resonant dielectric spherical particles arranged in a simple cubic symmetry, when the magnetic dipole is originated inside the spheres, whereas the electric dipole arises from the electrical coupling between the spheres.

In this paper, we consider both the approaches: the 3D DNG bi-spherical structure based on the single cell exhibiting the body-centered cubic symmetry and the medium formed by strongly coupled spherical resonant inclusions.

2. 3D isotropic bi-spherical metamaterial of cubic symmetry with high packing density

Let us consider two sets of the spherical particles arranged in the NaCl-like structure (Fig. 1a). This structure has face-centered cubic lattice and is a member of the cubic system of symmetry pertaining to the class $m3m$ [8,18]. In the case of cubic symmetry, the second rank tensors of all physical parameters of the media are diagonal and have the components of the same values [18]. Thus the permittivity and permeability tensors are