Available online at www.sciencedirect.com
ScienceDirect

Metamaterials 3 (2009) 10–27

Metamaterials

www.elsevier.com/locate/metmat

Invited paper

Metamaterial made of paired planar conductors: Particle resonances, phenomena and properties

G. Donzelli [a,d], A. Vallecchi [a], F. Capolino [b,*], A. Schuchinsky [c]

[a] Department of Information Engineering, University of Siena, Via Roma 56, 53100 Siena, Italy
[b] Department of Electrical Engineering and Computer Science, University of California, Irvine, CA 92697, USA
[c] Queen's University Belfast, Belfast BT3 9DT, United Kingdom
[d] Now with Altran Italia, 20154 Milano, Italy

Received 4 April 2008; received in revised form 11 November 2008; accepted 16 December 2008
Available online 24 January 2009

Abstract

The properties and characteristics of a recently proposed anisotropic metamaterial based upon layered arrays of tightly coupled pairs of "dogbone" shaped stripe conductors have been explored in detail. It has been found that a metamaterial composed of such stacked layers exhibits artificial magnetism and may support backward wave propagation. The equivalent network models of the constitutive conductor pairs arranged in the periodic array have been devised and applied to the identification of the specific types of resonances, and to the analysis of their contribution into the effective dielectric and magnetic properties of the artificial medium. The proposed "dogbone" configuration of conductor pairs has the advantage of being entirely realizable and assemblable in planar technology. It also appears more prospective than simple cut-wire or metal-plate pairs because the additional geometrical parameters provide an efficient control of separation between the electric and magnetic resonances that, in turn, makes it possible to obtain a fairly broadband left-handed behaviour of the structure at low frequencies.

Keywords: Artificial magnetism; Coupled conductors; Dogbones; Metamaterials; Microwaves; Negative refractive index; Planar technology; Transmission lines

---

1. Introduction

Artificial magnetism is considered as one of the major attributes of metamaterials along with negative refractive index (NRI). Periodic arrays of magnetic dipoles emulated by resonant loops are often realized with the aid of split ring resonators (SRRs) [1–3]. Combined with wires, SRRs are used as the constituent particles of artificial media in which effective NRI can be observed for plane waves of fixed polarization incident at certain angles [4,5]. In numerous publications, such media are described as materials with negative permeability and permittivity.

At optical frequencies, materials made of pairs of nanorods have been suggested in Ref. [6] to create current loops resonating in the transmission line mode, i.e., each pair of rods constitutes a waveguide resonator comprised of two conductors. It has been shown that a pair of coupled conducting wires may possess two types of resonances, named electric and magnetic resonances, and could represent the basic building block of a NRI medium. Although the SRRs and coupled rods have demonstrated feasibility of producing the NRI response of the medium, search of novel physical structures for

---

* Corresponding author.
E-mail address: capolino@dii.unisi.it (F. Capolino).

1873-1988/$ – see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.metmat.2008.12.001

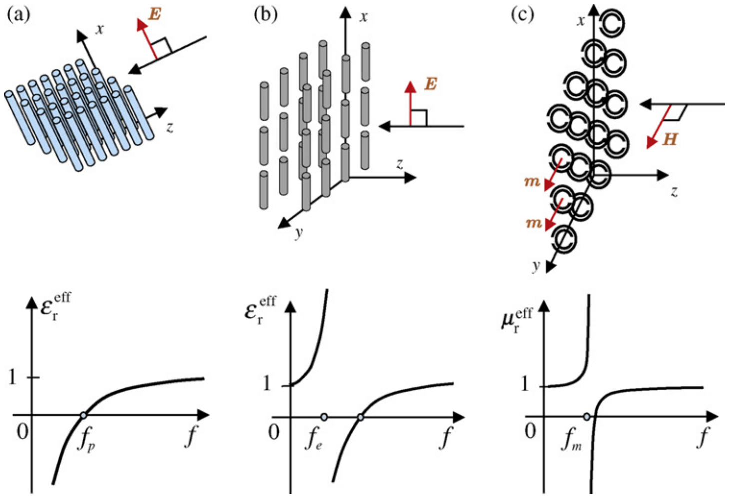

Fig. 1. Wire medium (a) and cut-wire medium (b). The frequency dependent effective permittivity at the shown polarization of the incident electric field is characterised by a plasma-like resonance frequency f_p and by an electric resonance frequency f_e associated with a standard stop band of FSS. (c) One layer of SRRs, polarization of incident magnetic field and induced magnetic moments m at the magnetic resonance f_m. The layer of SRR is in the x–y plane, the SRRs are aligned parallel to the x–z plane.

the constituent particles still remains an acute problem. Alternative geometries based on the same principles have been proposed for microwave frequencies in Refs. [7–10], and the planar arrangement of the "dogbone" shaped tightly coupled conductor stripes [11–14] is the subject of this paper.

In this work we perform a detailed study of the resonances in the dogbone structure, their types and dependences on the geometrical parameters. We also propose an accurate transmission line model of a single dogbone particle, which enables us to predict the magnetic resonance frequencies and provides simple approximate formulas useful for design purposes. A single layer of dogbone pairs is analyzed first. Then multilayered structures are investigated, and we show the existence of a frequency band where artificial magnetism and backward wave propagation exist in the periodic arrangements with lattice constants significantly smaller than the wavelength. Using the simple algorithm based on the observation of the transmitted wave phase (see, e.g. [15,16]), the metamaterial backward wave propagation characteristics are retrieved from the scattering parameters of a wave normally incident on a few stacked layers of arrayed dogbone pairs. The metamaterial properties are retrieved also by observing the Bloch propagation constant between layers that clearly identifies the backward wave propagation bands. We address the readers to [17] for a comprehensive discussion of metamaterial homogenization. The results of these analyses provide the theoretical demonstration that the dogbone pair structure can exhibit a fairly broadband NRI behavior at low frequencies.

The paper is organized as follows. In Section 2 we introduce the main concepts and recall the effective medium description of metamaterials made of wires, cut-wires and SRRs. In Section 3 we carry out an extensive parametric analysis and investigate the transmission properties of a single layer of dogbone pairs on a dielectric substrate and in free-space. In Section 4, a transmission line model is introduced and applied to prediction of the magnetic resonance frequency. In Section 5 we show that metamaterials composed of several layers of dogbone pairs may exhibit backward wave propagation. Major findings are summarized in Section 6.

2. Background. Electric and magnetic resonances in wire and SRR materials

The wire medium, the cut-wire medium, and the periodic array of SRRs shown in Fig. 1 represent the canonical types of metamaterials, which are usually characterized by effective permittivity and permeability expressed in terms of the associated plasma frequency, and electric and magnetic resonances. Since the 50's and 60's the wire medium shown in Fig. 1(a) has been described for an incident electric field parallel to the wires as an artificial dielectric [18–20] with an isotropic effective plasma-like relative permittivity $\varepsilon_r^{eff} = 1 - f_P^2/f^2$, where f is the signal frequency, f_p