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Metamaterial in Planar Technology Exhibiting Negative Refractive Index for Arbitrary Incident Plane Wave Polarization

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Introduction

Magnetic and negative index metamaterials (NIM) have attracted considerable attention because of their unusual microwave and optical properties [1] and potential applications, such as, for example, "perfect lenses" [2]. The latter require a negative refractive index, which can be realized by a negative electric permittivity and a negative magnetic permeability at the same frequency. Most NIM implementations to date have utilized the topology proposed by Pendry [2]-[4] consisting of split-ring resonators (SRRs) providing the negative μ and continuous wires providing the negative ϵ .

As alternatives to conventional SRR-based NIMs, pairs of finite-length wires, have been recently shown to be able to replace the SRRs and to possibly lead to a negative refractive index directly, without the need for additional metallic wires [5]-[7]. In particular, it has been shown that pairs of coupled conducting wires exhibit both a magnetic resonance (antisymmetric or transmission line mode) and an electric resonance (symmetric mode) that can be properly located in frequency by adjusting the length of the pair. As a result, different NIMs based on a periodic arrangement of wire-pair structures have been proposed for operation at microwave and optical frequencies [8]-[11]. It is noteworthy that, unlike SRR and continuous wire media, cut-wire pair materials lend themselves to greatly simplified fully planar technology fabrication and assembly.

Many of the previously designed NIMs are anisotropic, i.e., their properties are directionally dependent. Concerning cut-wire pairs, for example, the aforementioned magnetic and electric resonances are only observed for an incident electric polarization along the long axis of the wires, and magnetic polarization orthogonal to the plane containing the two wires. These resonances are sensitive to the wave polarization and may not occur at some polarizations (e.g., when the E field is orthogonal to the wires). This polarization dependence of the cut-wire pairs is undesired, for example in potential applications such as "perfect lenses". A fully printable NIM responsive to any type of linear incident polarization was presented in [12]. An alternative planar NIM configuration featuring identical electromagnetic properties for the two orthogonal incident linear polarizations is investigated in this contribution, in contrast to [10],[11], where the material was designed for a single polarization.

Proposed Geometry

The proposed structure's unit cell is illustrated in Fig. 1. The structure is formed by a dielectric slab of thickness $H = 0.5$ mm and dielectric constant $\epsilon_r = 2.2$ printed identically on both sides with a $10\text{ }\mu\text{m}$ metal layer. The metallization pattern has a square unit cell with side length $A = B = 7.5$ mm.

Fig. 1. Dual-dogbone particle (forming a Jerusalem cross) made by four tightly coupled conductors exhibiting a transmission line-type resonance for both orthogonal incident linear polarizations. The structure parameters used in the simulations $A = B = 7.5$ mm, $A1 = B2 = 0.5$ mm, $A2 = 7.4$ mm.

To make the structure responsive to arbitrary linear polarization of the incident field, two orthogonal pairs of dogbone shaped stripes [10] are combined as illustrated in Fig. 1 to form a pair of tightly coupled Jerusalem crosses. The phenomenology is quite analogous to that of the single dogbone particle pair: whatever the orientation of the incident field is, the cross pair will exhibit not only a magnetic resonance resulting in a negative μ but also an electric resonance with a negative ϵ , simultaneously. The magnetic resonance originates from the antiparallel currents in the pair of the stacked stripes with the opposite sign charges accumulated at the corresponding ends; the electric resonance is due to the excitation of parallel currents in the pair of the stacked stripes with the same sign charges accumulated at the corresponding ends of both stripes. The symmetry of the unit cell is expected to provide a polarization independent response at normal incidence.

Simulation Results

The properties of the dual dogbone particle pair of Fig. 1 have been characterized by using CST Microwave Studio. Simulations have been performed to determine the reflection and transmission coefficients from a single layer of tightly coupled Jerusalem crosses, modeled as a single unit cell with a periodic boundary

condition in the directions perpendicular to the direction of the incidence. The calculated magnitude of transmission (S_{21}) and reflection (S_{11}) spectra are shown in Fig. 2. The resonances for NIM behavior seem to occur near 7.6 GHz.

Fig. 2. Simulated reflection (black solid curve) and transmission (blue dashed curve) coefficients for a layer of periodic arrangement of pairs of tightly coupled Jerusalem crosses, shown in Fig. 1.

To better demonstrate the appearance of the expected NIM transmission band, we have calculated the eigenmode characteristics assuming the structure to be periodic also along the direction perpendicular to the planar stripe plane with period $C = A = B$. In Fig. 3 we report the calculated one-dimensional dispersion diagram for the wave propagating along the direction perpendicular to the Jerusalem crosses. A backward-wave mode is observed between 7.61 and 7.66 GHz, which is a quite narrow frequency band. Improvement of bandwidth performance can be possibly obtained by an optimization of the unit cell geometry. It is important to note that in the NIM band the ratio of wavelength to lattice constant is of the order of $\lambda/A = 6$.

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Fig. 3. Dispersion curve for a wave with the propagation constant β in the infinite periodic stack (period C) of layers made of pairs of tightly coupled Jerusalem crosses shown in Fig. 1.