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Tunable left-handed metamaterial based on electrorheological fluids

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Abstract

A tunable left-handed metamaterial consisting of a periodic array of the left-handed dendritic structure units infiltrated with electrorheological fluids is demonstrated. Experimental results show that the passband can move from the original 8.50–10.60 GHz to 7.16–8.39 GHz after electrorheological fluids are infused. When a dc (direct current) electric field of 666 V/mm is applied, the passband moves toward lower frequency of within 7.08–8.30 GHz. This method provides one convenient way to design adaptive metamaterials.

Keywords: Left-handed metamaterials; Dendritic model; Electrorheological fluids; Omnidirection

1. Introduction

Electric permittivity ε and magnetic permeability μ are two fundamental electromagnetic parameters describing the electromagnetic response of continuous medium. Most of the naturally existing substances have positive permittivity and permeability. Veselago firstly studied theoretically the electromagnetic properties of substances with simultaneously negative permittivity and permeability which were referred to as left-handed metamaterials (LHMs) [1]. However, there is no such material in nature. Therefore, the research of LHMs is almost in stagnancy. Decades later, Pendry et al. proposed that the array of metallic wires [2] and split ring resonators [3] (SRRs) can produce a negative permittivity and a negative permeability, respectively. In particular, after negative refraction was experimentally verified by Smith et al. [4], studies on LHMs have attracted much attention on their peculiar electromagnetic properties and have become an attractive topic in the area of physics and electromagnetism.

Electrorheological fluids (ERF), a kind of smart materials, are suspensions of polarizable dielectric particles dispersed in insulating liquid, which can abruptly change from liquid to solid upon the application of an external electric field (E field) due to structural change when the particles align themselves along the field direction to form chains. ERF have the characteristic of being anisotropic dielectric, i.e. the dielectric constant increases along the field direction while it decreases in the transverse direction [5–7]. Moreover, the dependence of the resonance frequency of the SRRs on the substrate permittivity has been studied in some papers. With the increasing permittivity of the substrate, the resonant frequency of the SRRs moves toward lower frequency [8]. Therefore, this property of ERF may be utilized to dynamically control the position of passband of the LHMs by applying an external E field.

The traditional SRRs are a two-dimensional (2D) anisotropic medium, which is disadvantageous to design the isotropic LHMs. In addition, the majority of research methods on the LHMs and the negative permeability metamaterials are static and passive, which enormously restrict their practical applications. Concerning these deficiencies, the feasibility of dynamically tunable electromagnetic behaviors in negative permeability metamaterials and

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LHMs has been studied by several methods, such as E field [9,10], optical excitation [11], defect effect [12], loading varactor [13], adjusting the permittivity of the substrate or varying the substrate thickness [14]. However, so far, no study is reported on analyzing the omnidirectional resonance of this dendritic model, which simultaneously has $-\varepsilon$ and $-\mu$, and using ERF to realize the tunable passband of this unitary dendritic. In this letter, we will propose a kind of dendritic model which is easier to cancel electromagnetic coupling than the traditional SRRs. The simulated results show that this left-handed model has the 2D isotropic property. Furthermore, we demonstrate the effects of electrorheological fluids on the passband of the periodic dendritic array.

2. The left-handed dendritic model

As is well known, most of the LHMs are realized through combining the SRRs and wires. Furthermore, some unitary structures, such as the S-shaped resonators or Ω-shaped resonators, have been proposed. We have proposed a kind of quasi-periodic dendritic model (Fig. 1(a)), and our theoretical and experimental studies proved that the dendritic model has negative permeability in the microwave and infrared domain [15–17]. When appropriately adjusting the parameters of the dendritic structure, we can obtain the LHMs based on the unitary dendritic structure, which can simultaneously realize $-\varepsilon$ and $-\mu$ in the same frequency range. The simulations, negative refractive index and planar focus experiments verified that the dendritic structure has left-handed properties [18].

3. The 2D isotropic property of the dendritic structure

3.1. Simulation section

The traditional SRRs have an asymmetric gap, which can easily produce the electromagnetic couple [19,20], namely E field and magnetic field (H field) jointly couple a magnetic polarization. It is a restriction to design the 2D or 3D isotropic LHMs by using the SRRs and wires. However, the highly symmetric quasi-periodic dendritic model has the 2D isotropic property to a certain extent, and it provides a feasible way to design the multidimensional isotropic metamaterials.

To prove the 2D isotropic property of the dendritic structure, electromagnetic resonances were simulated by using commercial software CST Microwave Studio involving the cases of parallel incident and normal incident. The thickness of the metal is $t = 0.03$ mm and that of the substrate is 1 mm ($\varepsilon = 4.65$). The other dimensions of the dendritic structure are $a = 2$ mm, $b = 0.9$ mm, $c = 0.9$ mm, and $\theta = 45°$. In the simulation, the number of unit cell employed was chosen as 1 in order to limit the computational cost of simulations, and the boundary conditions were defined by setting periodic boundary conditions on the transverse boundaries and open conditions on two ports.

3.1.1. Normal incident mode

The relative orientation of the electromagnetic excitation is shown in Fig. 1(b). The distribution of surface current shows that the positive and negative charges accumulate at the two ends of the dendritic structure along

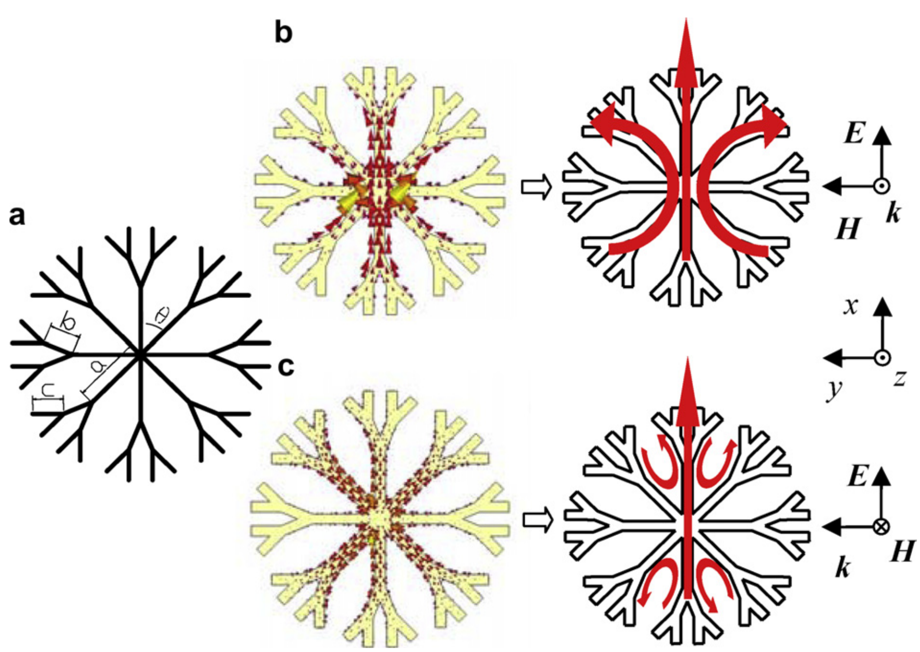

Fig. 1. Schematic representation of one unit cell of the left-handed dendritic structure. (a) One unit cell of the dendritic structure; (b) distribution of the surface current under normal incident; (c) distribution of the surface current under parallel incident. The arrows indicate the instantaneous current direction.