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Broadband planar left-handed metamaterials using split-ring resonator pairs

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Abstract

In this paper, we showed that split-ring resonator (SRR) pairs can be used as broadband planar left-handed metamaterials (LHMs). Simulations were carried out for one layer of infinite LHM slab using SRR pairs. The results showed that by carefully adjusting dimensions of the SRR pairs, magnetic and electric resonances can be coexistent at some frequency ranges and in the frequency range where there are both negative magnetic and electric responses, there is a broad LH band. Equivalent circuits for the magnetic and electric resonance were offered to give a qualitative and quantitative explanation of the LH behaviors of LHMs using SRR pairs.

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Keywords: Planar left-handed metamaterials; Broadband; SRR pairs

1. Introduction

In 1968, Veselago [1] investigated the characteristics of electromagnetic (EM) waves that propagate in media with simultaneously negative ε and μ. But because there are no such materials in natural world, his work was neglected for almost 30 years. In 1999, Pendry et al. [2] showed that negative ε can be realized by using conducting wires and negative μ by split-ring resonators (SRRs). Smith et al. [3] constructed a real structure composed of conducting wires and SRRs, and demonstrated its negative ε and μ at microwave frequencies. From then on, materials with simultaneously negative ε and μ have been a hot issue in many research fields and such materials were terms as left-handed metamaterials (LHMs).

Many novel methods of realizing LHMs have been proposed [4–9]. The above methods of realizing LHMs enrich greatly the content of LHMs. Nevertheless, there is an annoying problem for the LHMs realized by the above methods. Incident EM waves must be paralleled to the substrate plane, which make it quite troublesome to fabricate and use those LHMs. Therefore, there's an urgent need to design and fabricate LHMs that allow the incident EM waves to be perpendicular to the substrate plane. In 2003, the work of Podlovsk et al. [10] showed that using pairs of finite length wires would not only allow replacing the SRRs as magnetic resonators but could also give simultaneously a negative ε in the same frequency range. This opened a new way to the design

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of the so-called planar LHMs and some planar LHMs have been proposed and tested [11–16]. Such planar LHMs are much easier to fabricate and use. Moreover, the size of the LHM unit cells in the propagation direction can be very small compared with the wavelength. Thus, the planar LHMs have many advantages over the SRR/wire LHMs.

However, to date, LH bandwidths of the existing planar LHMs (short wire pairs and fishnet structures) are quite narrow, which limits the wide applications of these planar LHMs. In this paper, we showed that SRR pairs can be used as planar LHMs with broad LH bandwidth. Equivalent circuits were employed to offer a qualitative and quantitative explanation for the LH behaviors of the SRR pairs.

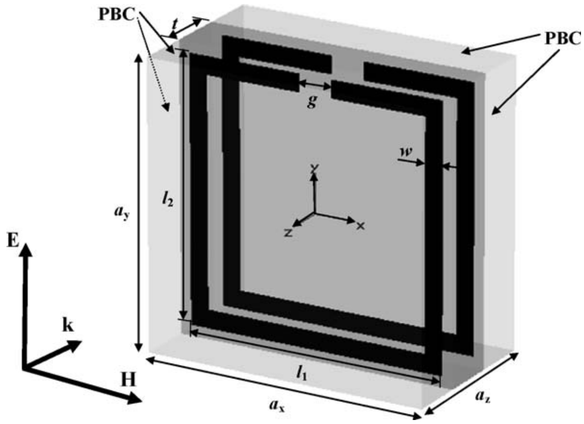

Fig. 2. The SRR pair LHM unit cell.

2. SRR pairs as the unit cell of broadband LHMs

In Fig. 1(a), unit cell of LHMs using short wire pairs is shown schematically. By continuous evolution, the short wire pairs can evolve to be SRR pairs (in Fig. 1(c) and (d)) separated by a dielectric of thickness t. Fig. 1(b) gives the interim U-shaped wire pairs. The short wire pairs have been demonstrated to have LH behaviors in some frequency ranges [12]. The mutual capacitance and inductance between the front and back short wires as well as their own self-inductance form an equivalent L–C loop, responding to the magnetic field. In response to the electric field, short wires on the same side of two adjacent unit cells behave like cut-wires, which can provide a negative permittivity. Since there are mutual inductances and capacitances between the front and back wires in Fig. 1(b)–(d), so LH behaviors are expected for these three structures.

In order to verify our speculation, numerical simulations were carried out for one layer of the SRR pair LHM slab by using the frequency domain solver of CST Microwave Studio (Computer Simulation Technology). The metal we used is copper whose conductivity $\sigma = 5.8 \times 10^7$ and thickness $t_1 = 0.010$ mm. Teflon (PTFE) with a dielectric constant $\varepsilon_r = 2.08$, thickness $t = 1.0$ mm and loss tangent $\tan\delta = 0.0004$ is selected as the substrate. The side length of the square substrate board is $a_x = a_y = 5$ mm. Geometrical dimensions of the SRR pair are: $w = 0.3$ mm, $g = 0.6$ mm, $l_1 = l_2 = 4.6$ mm. The unit cell is put into a lattice $a_x \times a_y \times a_z = 5\text{mm} \times 5\text{mm} \times 2$ mm. The polarization of the incident EM waves is shown in Fig. 2. The EM waves are incident onto the LHM along the $-z$ direction, with the electric field along y direction and magnetic field along x direction. In the (x, y) plane, the four lateral boundaries are periodic boundary conditions (PBC), so the simulated structure is actually an LHM slab that is infinite in the (x, y) plane.

Fig. 3 show the simulation results of field distributions at 12 GHz. Fig. 3(a) and (b) show the side-view and front view of electric filed distributions in (y, z) and (x, y) planes, respectively. As can be seen clearly from Fig. 3(a) and (b), the electric field between the two up-and-down adjacent SRRs is very strong, which indicates a strong electric resonance. Thus, a negative effective permittivity is expected in the negative resonance frequency range. Fig. 3(c) shows the surface current on the front and back SRR of the same unit cell. As shown in Fig. 3(c), the surface current on the front SRR is anti-paralleled to that

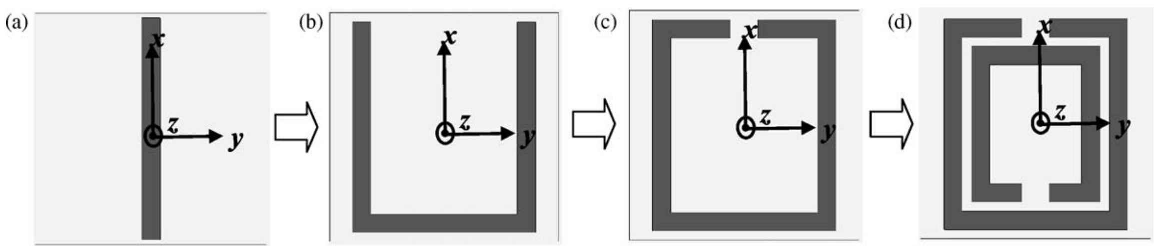

Fig. 1. Based on the working principle of LHMs using short wire pairs (a), the short wire pairs can evolve to be SRR pairs separated by a dielectric. For convenience, one side of the pairs is given. (b) U-shaped wire pairs; (c) SRR pairs; (d) double SRR pairs.