Optik 125 (2014) 1841–1845

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Study on the resonance properties of combinations of different split ring resonator cells

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ARTICLE INFO

Article history:
Received 2 May 2013
Accepted 28 September 2013

Keywords:
Split ring resonators
Combinations of SRRs
Bandwidth expansion
Isolated negative permeability bands

ABSTRACT

We combine different split ring resonator (SRR) unit cells along three axes respectively and study the electromagnetic behaviors of combinations numerically, with the purpose of broadening the frequency band of negative permeability. When combining SRRs in *z*-direction, the wave propagation direction, it is found that the bandwidth of negative permeability is broadened by 0.22 GHz. The same bandwidth expansion effects, however, are not observed along the other two axes. In addition, it is feasible to obtain two isolated frequency bands with negative permeability by combining SRRs along three axes.

1. Introduction

In 1968, V.G. Veselago proposed a concept of left-handed medium (LHM) with simultaneously negative dielectric permittivity (ε) and magnetic permeability (μ) [1]. This new material has many fascinating electromagnetic properties such as negative index of refraction etc. [1]. In modern literatures, LHM is always referred to as metamaterial. The phenomenon of negative refraction was firstly observed experimentally by Shelby et al. [2], which was viewed as a proof of the existence of LHM. In the experiment, they used a new composite presented by Smith et al. [3]. The composite is constructed with a periodic array of metal wires and split ring resonators (SRRs), which are used to produce negative permittivity and permeability respectively, based on the studies of Pendry et al. [4,5]. So far, researchers have proposed various LHM structures, such as S-shaped, Ω-shaped and fishnet structures [6–8], etc.

For the known LHM structures, the bandwidth of negative permeability is usually smaller than that of negative permittivity [6,9]. Thereby, the bandwidth of negative index of refraction is limited mainly by that of negative permeability. In the following discussions, we take SRRs as example and investigate the resonance properties of combinations of different SRRs, aimed at achieving a broadened bandwidth of negative permeability.

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0030-4026/$ – see front matter © 2013 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2013.09.081

2. Numerical studies on the combinations of SRRs

The LHM constructed with periodic arrays of conducting elements behaves as an effective medium when the wavelength of electromagnetic wave is much longer than both the element dimension and lattice spacing [3,10]. In this paper, we consider it preferable to use effective permittivity and permeability to describe the electromagnetic properties of metamaterials when the ratio of the free space wavelength to the lattice constant is greater than 3.5 [11].

In the following discussions, it is assumed that *z*-direction is the wave propagation direction and the electric field is polarized along *y*-direction. The simulation software used below is HFSS, "a commercial finite-element-based electromagnetic mode solver" [12]. Different SRR unit cells are combined in *x*-, *y*-, and *z*-directions respectively and accordingly the sections below are divided into three parts.

2.1. Combining different SRR unit cells along x-direction

As shown in Fig. 1, a circle-shaped SRR unit cell is combined with a square-shaped one along *x*-direction. Extend the combination periodically in *x*–*y* plane and a new periodic array of SRRs is obtained. Fig. 2 shows the schematic front view of the structured SRRs array. The white and black rectangles in Fig. 2 represent circle-shaped and square-shaped SRR unit cells respectively. And the parts enclosed with solid or dashed frames represent the unit cells (Fig. 1) of the array. The lattice constants: a_x = 5.0 mm, a_y = 2.5 mm and a_z = 2.5 mm. It is worth to note that for all the models in the

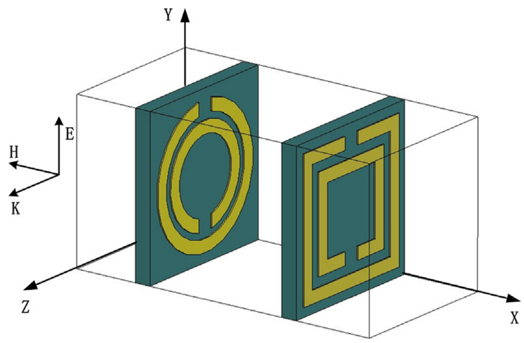

Fig. 1. Model of the unit cell when combining SRRs along *x*-direction.

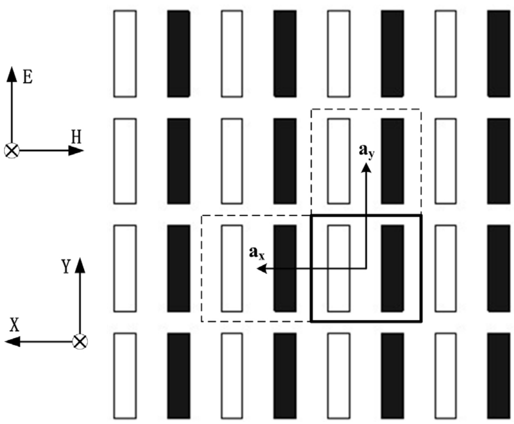

Fig. 2. Schematic front view of the array when combining SRRs along *x*-direction.

simulations, 0.02 mm thick copper SRRs are positioned on substrates of FR4 of which the thickness is 0.2 mm.

In the wave propagation direction, the lattice constant a_z is 2.5 mm. The resonance frequencies of SRRs are all below 14 GHz. The parameter λ/a_z is far greater than 3.5 where λ is the free space wavelength. So it is effective to use permittivity and permeability to describe the electromagnetic behaviors of combined SRRs. A plane wave incident vertically on SRRs with the electric field polarized along *y*-direction is considered, as shown in Fig. 2. For magnetic permeability tensor $\bar{\mu} = (\mu_x, \mu_y, \mu_z)$, negative values of μ_x can be obtained near the high frequency side of the resonance band [3].

According to the former studies by Pendry et al. [4], the formula of μ for circle-shaped SRRs is:

$$\mu_{\text{eff}} = 1 - \frac{\pi r^2}{a^2} \frac{1}{1 + (2l\sigma/\omega\mu_0 r)j - (3lc_0^2/\omega^2\pi r^3 \ln(2c/d))}. \qquad (1)$$

The parameters in Eq. (1) are illustrated in Fig. 3 [4]. According to Eq. (1), the resonance frequencies of circle-shaped SRRs can be

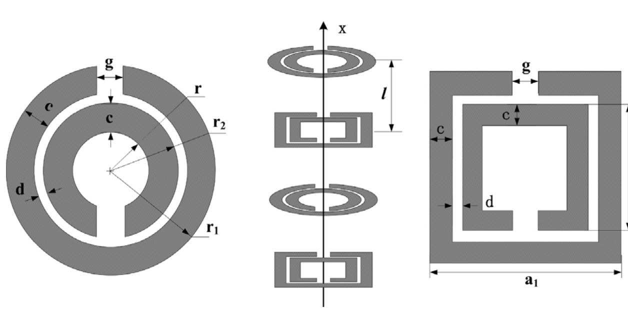

Fig. 3. Schematic drawing of circle-shaped and square-shaped SRRs.

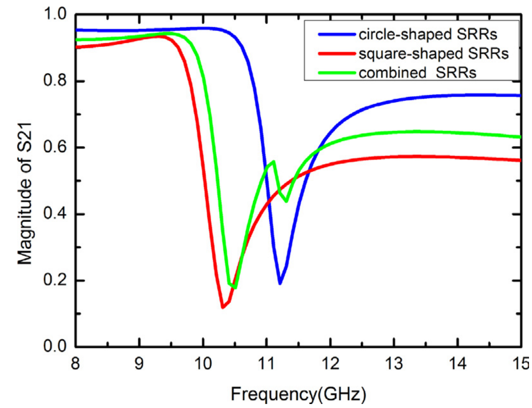

Fig. 4. Simulated S21 curves of circle-shaped, square-shaped and combined SRRs.

shifted by adjusting the geometrical parameters [4,13]. And this method also applies to square-shaped SRRs.

By comparing the simulation results, the parameters in Fig. 3 are chosen as follows: for circle-shaped SRRs, $r_1 = 1.1$ mm, $c = 0.2$ mm, $d = 0.068$ mm and $g = 0.3$ mm; for square-shaped SRRs, $a_1 = 1.1$ mm, $c = 0.2$ mm, $d = 0.15$ mm and $g = 0.3$ mm. We can get scattering coefficients from simulations. Fig. 4 shows the transmission (S21) spectra of circle-shaped, square-shaped and combined SRRs. Performing S-parameter retrieval methods [9,12,14,15], the curves of permeability versus frequency are shown in Fig. 5. In this case, the bandwidth of negative permeability of combined SRRs is smaller than that of square-shaped SRRs, as demonstrated in Fig. 5. Then we change the distance *l* (Fig. 3) between two kinds of SRR unit cells and carry out numerical studies as above.

Finally, through repeated simulations, we find that it is unlikely to achieve the goal of broadening the band of negative permeability by combining two kinds of SRRs in the pattern shown in Figs. 1 and 2.

2.2. Combining different SRR unit cells along y-direction

In this part, we combine a circle-shaped SRR unit cell with a square-shaped one in *y*-direction, as shown in Fig. 6. Fig. 7 shows the schematic front view of the array of combined SRRs. The lattice constants: $a_x = 2.5$ mm, $a_y = 5.0$ mm and $a_z = 2.5$ mm. In Fig. 7 the white and black rectangles represent circle-shaped and square-shaped SRR unit cells respectively. And the parts enclosed with solid or dashed frames represent the unit cells shown in Fig. 6.

Then we investigate the electromagnetic properties of combined SRRs numerically. For combined SRRs, different from the simulation results shown in Fig. 4, it is impossible to get a

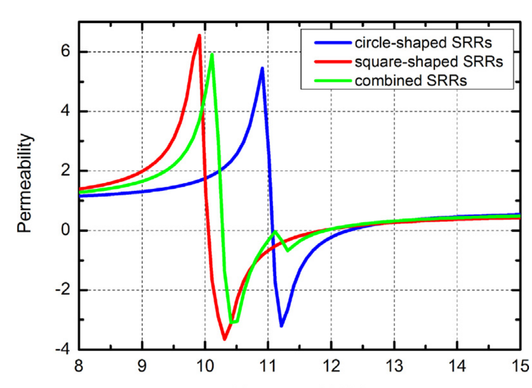

Fig. 5. Permeability curves of circle-shaped, square-shaped and combined SRRs.