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A TUNABLE LEFT-HANDED METAMATERIAL BASED ON MODIFIED BROADSIDE-COUPLED SPLIT-RING RESONATORS

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Abstract—Based on the broadside-coupled split-ring resonator (BC-SRR), a tunable left-handed metamaterial (LHM) was proposed in this paper. The two rings of BC-SRR are etched on two separate substrates so that the coupling between the two rings can be adjusted by slightly slipping one of the two substrates relative to the other one. Thus, the magnetic resonance frequency of the modified BC-SRR can be tuned. By combining the modified BC-SRR (MBC-SRR) with continuous conducting wires, a tunable LHM can be realized. The tunable LHM can realize both rough and minor tunings by minor slips along and perpendicular to the gap direction of BC-SRR, respectively. The proposed tunable LHM has many potential applications in microwave devices.

1. INTRODUCTION

Left-handed metamaterials (LHM) with simultaneously negative permeability and permittivity have been attracting great attentions since the initiatory work of Pendry and Smith [1, 2]. Due to their unique electromagnetic properties, LHMs have great potential application values at microwave. A great variety of metamaterials

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have been envisioned and fabricated. Similar to the working principle of SRR/Wire metamaterial [2], dielectric-metallic LHM unit cells, like S-shaped [3], Ω-shaped [4], coplanar magnetic and electric resonator unit cells [5], have been proposed. Nevertheless, incident waves must be paralleled to the substrate plane, which make the above LHMs quite troublesome to be fabricated and used. With an aim to overcome this problem, planar metamateirals, which allow the incident waves to be perpendicular to the substrate plane, were proposed and fabricated [6–9]. Recently, many all-dielectric metamaterial unit cells, such as binary spherical [10], cubic [11] and disk-like unit cells [12], were proposed.

The above researches are mostly about the realization of LHMs with low loss and broad band. While, in some applications, tunable LHMs, whose left-handed bands can be tuned to upper or lower ranges, are required, so many authors have proposed different methods of realizing tunable LHMs. For dielectric-metallic LHMs, higher dielectric constant of the substrate or the background contributes to the red-shift of resonance frequencies, so some authors proposed tunable LHMs by changing substrate properties [13–15]. Tunable LHMs based on nematic liquid crystals were investigated by placing a periodic array of split ring resonators in nematic liquid crystal background [16–19]. By changing the inductances or the capacitances in the equivalent circuits, resonance frequency of LHMs can be tuned, too. On the basis of this idea, active LHMs collaborated with microwave varactors were proposed and studied [20–22] by changing the capacitances in the equivalent circuits. Capacitor-loaded split ring resonators were proposed as tunable metamaterial components [23]. By using yttrium iron garnet, it was shown that tunable LHMs can also be realized [24, 25]. Some tunable LHMs based on high-dielectric materials were also proposed and investigated. Tunable LHMs can be realized by a dielectric block with a thin metallic rod [26] and by dielectric ceramic cube arrays [27]. Moreover, some tunable metamaterials realized by mechanical ways were also proposed [28].

Since mechanical realization of tunable LHMs is comparatively easy to achieve, it is important to develop new kinds of mechanically tunable LHMs with good performances. In this paper, we proposed a mechanically tunable LHMs based on Broadside-Coupled Split-Ring Resonators (BC-SRR) proposed by R. Marqués et al. [29]. The two rings of BC-SRR are etched on two separate substrates. By slipping slightly one of the two substrates relative to the other one, the coupling between the two rings can be adjusted. By combining the modified BC-SRR (MBC-SRR) with continuous conducting wires, tunable LHMs can be realized. The MBC-SRR/Wire LHM can realize both rough and minor tuning by minor slips along and perpendicular to the gap direction of BC-SRR, respectively. The tunable LHMs in this paper can be used in many microwave devices such as antennas and filters.

2. THEORY AND DESIGN

Figure 1(a) shows the structure of the MBC-SRR. Compared with BC-SRR, there are two relative slips S_x and S_y between the two broadside-coupled rings. Fig. 1(b) shows the corresponding equivalent circuit, where L, R are the equivalent inductance and resistance, respectively; C_0 is mutual capacitances between the two rings; C_s is the capacitance of the split.

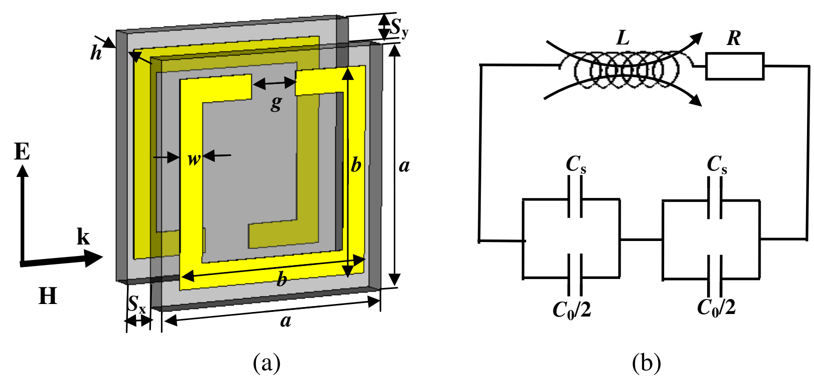

Figure 1. Modified broadside-coupled split-ring resonator (a) and its equivalent circuit (b). For numerical simulations, copper (the conductivity $\sigma = 5.8 \times 10^7$ S/m) SRR is fabricated on Quartz glass (the thickness $h = 0.2$ mm, dielectric constant $\varepsilon_r = 3.78$, loss angle tangent $\tan\delta = 0.0001$). The geometrical parameters of the SRR are: $b = 4.2$ mm, $g = 1$ mm, $w = 0.5$ mm, $a = 5$ mm. The thickness of the copper strip is $t = 0.017$ mm. S_x and S_y are the relative slips between the two Quartz substrates along and perpendicular to the gap direction.

According to the loop antenna theory, the self-inductance per unit length of the two rings is approximately:

$$L = \frac{\mu_0 b}{\sqrt{\pi}} \left[\log\left(\frac{32b}{w\sqrt{\pi}} \right) - 2 \right] \tag{1}$$

The mutual inductance between the two rings is minor compared with the self-inductance, so mutual inductance is neglected here. The magnetic resonant frequency of BC-SRRs is

$$\omega = \frac{1}{\sqrt{LC}} \tag{2}$$

From Eqs. (1) and (2), it can be found that the self-inductances is invariant when there are relative slips between the two rings. Thus, it is the capacitance that affects the magnetic resonant frequency. Because of this, it is crucial to obtain the mutual capacitance between the two rings as well as the capacitances of the two splits. The capacitance C_s and the mutual capacitance C_0 can be approximated by the parallel-plate capacitance. When there is no relative slip between the two rings, we have

$$C_s \approx \varepsilon \frac{wt}{g} \tag{3}$$

$$C_0/2 = \varepsilon \frac{w(2b + 2b - g)}{2h} \tag{4}$$

From (3) and (4), we can find that C_s is negligible compared with C_0 because t is always very small. Thus, we neglect the split capacitance in this paper. From (2), the magnetic resonance frequency is

$$\omega_0 = \frac{1}{\sqrt{LC_0/4}} = \frac{1}{\sqrt{L\varepsilon \frac{w(b + b - g/2)}{2h}}} \tag{5}$$

When there is relative slip between the two rings, there are two cases we need to consider. The first case is that the relative slip is along the gap direction, that is, $S_x > 0$ and $S_y = 0$. In this case, the corresponding area of the left and right bars of the two rings is reduced greatly, which contributes to the reduction of mutual capacitance. Moreover, there is a comparatively minor reduction for the corresponding area of the upper and lower bars. The mutual capacitance can be approximated as

$$C_0'/2 = \varepsilon \frac{w(b - 2S_x - g/2)}{h} + \varepsilon \frac{wb}{\sqrt{h^2 + S_x^2}} \tag{6}$$

The magnetic resonance frequency becomes

$$\omega_x = \frac{1}{\sqrt{LC_0/4}} = \frac{1}{\sqrt{L\left(\varepsilon \frac{w(b - 2S_x - g/2)}{h} + \varepsilon \frac{wb}{\sqrt{h^2 + S_x^2}}\right)}} \tag{7}$$

Let $k_1 = S_x/h$, then from (5) and (7), we can obtain

$$\omega_x = \omega_0 \sqrt{\frac{2b - g/2}{b - g/2 - 2S_x + \frac{b}{\sqrt{1+k_1^2}}}} \tag{8}$$

The second case is that the relative slip is perpendicular to the gap direction, that is, $S_y > 0$ and $S_x = 0$. In this case, the mutual capacitance is approximately

$$C_0'''/2 = \varepsilon \frac{w(b - 2S_y)}{h} \tag{9}$$

Similarly, in this case, the magnetic resonance frequency is

$$\omega_y = \omega_0 \sqrt{\frac{2b - g/2}{b - 2S_y + \frac{b - g/2}{\sqrt{1+k_2^2}}}} \tag{10}$$

where $k_2 = S_y/h$. From (8) and (10), it can be found that the magnetic resonance frequency is larger than in the case without slips. This is because when there is a slip, whether the slip is along or perpendicular to the gap direction, the coupling between the two rings is reduced. Thus, the mutual capacitance is reduced, which results in a blue-shift of the magnetic resonance frequency.

Moreover, for the same slip $S_x = S_y$, we have

$$\frac{\omega_x^2}{\omega_y^2} = \frac{b - g/2 - 2S_x + \frac{b}{\sqrt{1+k_1^2}}}{b - 2S_x + \frac{b - g/2}{\sqrt{1+k_1^2}}} > 1 \tag{11}$$

That is to say, for the same slip $S_x = S_y$ along and perpendicular to the gap direction, the blue-shift of magnetic resonance frequency caused by S_x is larger than that caused by S_y. Thus, we can realize rough and minor tunings by S_x and S_y, respectively.

3. SIMULATION RESULTS AND ANALYSIS

3.1. The MBC-SRR-based LHM Unit Cell

By combining the MBC-SRR with continuous conducting wires, a tunable LHM is expected. The MBC-SRR-based LHM unit cell

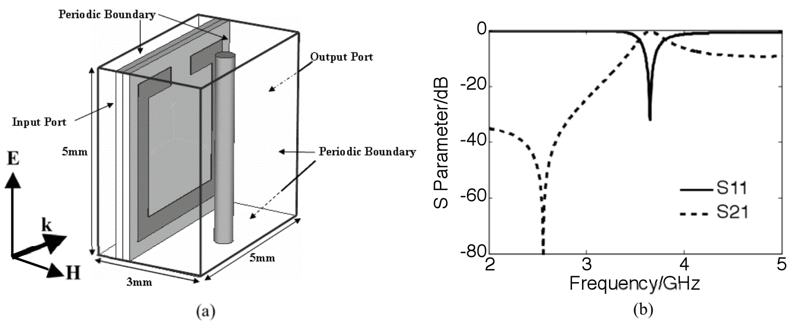

Figure 2. The MBC-SRR-based LHM unit cell without relative slips (a) and its transmission spectra (b).

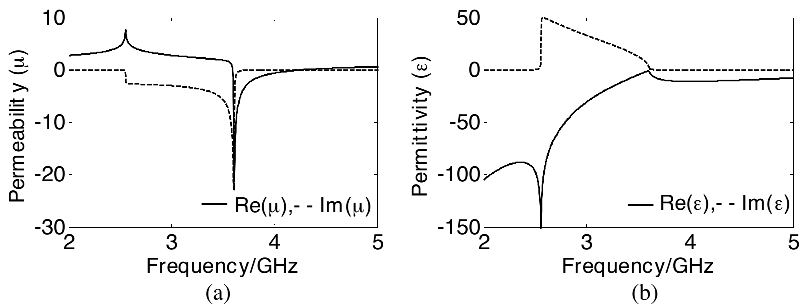

Figure 3. Retrieved effective permeability (a) and effective permittivity for the MBC-SRR-based LHM without slips.

is shown in Fig. 2(a). The continuous conducting wire is made of copper and its radius is 0.25 mm. Numerical simulations were carried out by using frequency domain solver of the CST Microwave Studio (Computer Simulation Technology). For the sake of numerical simulations, the polarization of incident plane waves is shown in Fig. 2(a) and the four lateral boundaries are set to be Periodic Boundary Conditions (PBC). The simulated S parameters for the case without slips are shown in Fig. 2(b). As shown in Fig. 2(b), there is a transmission peak around 3.6 GHz, which indicates a LH band.

The effective permeability and permittivity can be retrieved from S parameters obtained by simulations or experiments [31, 32]. Figs. 3(a) and (b) shows the retrieved permeability and permittivity for one layer of the MBC-SRR-based LHM slab. As shown in Figs. 3(a) and (b), the real part of effective permeability is negative in $3.6 \sim 4.2$ GHz while that of the effective permittivity is negative over the whole considered range. The imaginary parts of effective permeability and permittivity are very large around 3.6 GHz, which indicates high magnetic and electric loss around 3.6 GHz. In 3.65 ∼ 4.2 GHz, the imaginary parts of effective permeability and permittivity are nearly zero, so both magnetic and electric losses in this range are very small.

3.2. Rough Tuning

When there is a relative slip between the two rings, the coupling between the two rings decreases. Thus, the capacitance in the equivalent circuit decreases, which results in the blue-shift of the magnetic resonance frequency. Since the effective permittivity in the whole considered range is negative, so the LH band can be regarded dependent on the negative permeability range. Thus, by just comparing the negative permeability range, LH bands under different relative slips can also be compared.

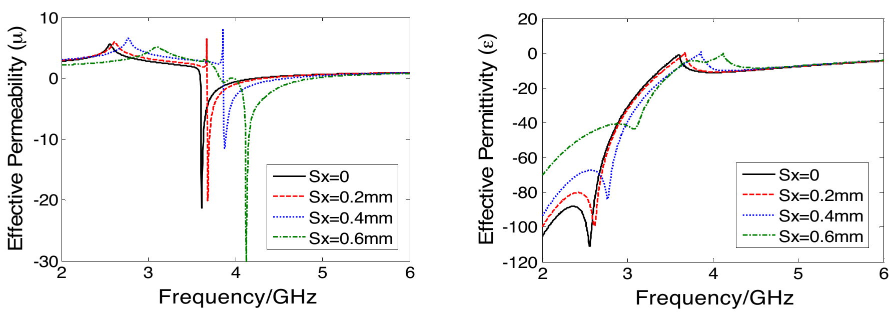

Figure 4. Real parts of retrieved effective permeability (a) and permittivity (b) under different relative slips $S_x = 0$, 0.2 mm, 0.4 mm and 0.6 mm.

Figures 4(a) and (b) show real parts of the effective permeability and permittivity under different relative slips S_x, respectively. As shown in Fig. 4 (a), as the relative slip S_x increases, the magnetic resonance frequency increases. Thus, negative effective permeability range shift upwards. Since the effective permittivity is negative in the whole considered range, LH band also shift upwards. In the three cases $S_x = 0.2$ mm, 0.4 mm and 0.6 mm, the corresponding LH bands are 3.67 ∼ 4.3 GHz, 3.86∼4.6 GHz and 4.0 ∼ 4.9 GHz, respectively. With the increase of the relative slip S_x, not only the LH shift upwards, but also the LH bandwidth increases. For by a quite minor relative slip S_x, a quite considerable blue-shift of the LH band can be realized, the relative slip S_x can be used to realize rough tuning.

3.3. Minor Tuning

Figures 5(a) and (b) show real parts of the effective permeability and permittivity under different relative slips S_y, respectively. As shown in Fig. 5(a), as the relative slip S_y increases, the magnetic resonance frequency increases slightly. Thus, negative effective permeability range has a minor blue-shift, so there is a minor blue-shift for the LH band. In the two cases $S_y = 0.4\,\mathrm{mm}$, $0.6\,\mathrm{mm}$, the corresponding LH bands are $3.62 \sim 4.24$ GHz and $3.72 \sim 4.4$ GHz, respectively. With the increase of the relative slip S_y, the blue-shift of LH band is quite minor when $0 < S_y < 0.4\,\mathrm{mm}$. Thus, the relative slip S_y can be used to realize minor tuning.

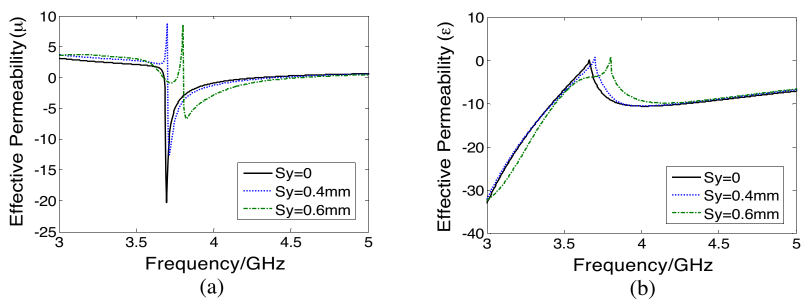

Figure 5. Real parts of retrieved effective permeability (a) and permittivity (b) under different relative slips $S_y = 0$, $0.4\,\mathrm{mm}$ and $0.6\,\mathrm{mm}$.

4. CONCLUSIONS

Based on the equivalent circuit theory of LHMs, MBC-SRR was proposed as a kind of tunable magnetic metamaterial. By combining the MBC-SRR with continuous conducting wires, a tunable LHM can be realized. Rough and minor tuning can be achieved by a relative slip along and perpendicular the gap direction of the SRR, respectively. Since the tuning is by a mechanical means, the MBC-SRR-based tunable LHM is quite easy to be fabricated. The proposed LHM has many potential applications in microwave components such as antennas and filters.

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