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ANALYSIS OF BALANCED COMPOSITE RIGHT/LEFT HANDED STRUCTURE BASED ON DIFFERENT DIMENSIONS OF COMPLEMENTARY SPLIT RING RESONATORS

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Abstract—In this paper, rectangular shape complementary split ring resonators (CSRRs) with different dimensions are introduced to realize balanced composite right/left handed (CRLH) structure. As the dimensions of CSRRs is altered, the required series capacitance should also be modified and the propagation characteristics will be changed, which gives the facility of designing microwave/RF components using the balanced CRLH structure. The propagation characteristics of proposed structures are demonstrated by simulated and measured results, which are in good agreement.

1. INTRODUCTION

In recent years a new type of metamaterials called left-handed materials (LHM) has attracted many attentions. These materials with effective negative permittivity and permeability simultaneously are first realized [1] by arranging arrays of thin metallic continuous wires and split ring resonators (SRRs) [2]. LHM supports propagation of backward waves which phase velocity is opposite to the direction of energy flow and many distinctive characteristics can be found [3–8]. From duality, negative permittivity medium can be generated by complementary split ring resonators (CSRRs) [9]. Marquest et al. firstly introduced these two resonators into planar structures and a LH pass-band can be found while CSRRs combined with a series gap are fabricated in microstrip technology and SRRs combined with a shunt strip are fabricated in coplanar waveguide technology [10–12].

There are another completely independent approach based on the theory of transmission lines to make LHM. A host transmission line with series capacitances and shunt inductances can produce left-handed propagation at lower frequency region and right-handed propagation at higher frequency region, which can be defined as composite right/left handed transmission line. As the elements are adjusted to remove the bandgap between LH band and RH band, the balanced CRLH TL with wider pass-band bandwidth is defined [13]. Following this idea, balanced CRLH structure based on CSRRs can be produced by increasing the series capacitance [14, 15]. In these proposed papers, only circular or square shape CSRRs are utilized. However, CSRRs can also be made various rectangular shapes to produce balanced CRLH structure. In this paper, three different dimensions of rectangular shape CSRRs combine with required series capacitor are proposed to produce balanced CRLH structure. To compare these different structures, the dimensions of CSRRs and series capacitors are all optimized to achieve the same transition frequency. These proposed structures are simulated, fabricated and measured.

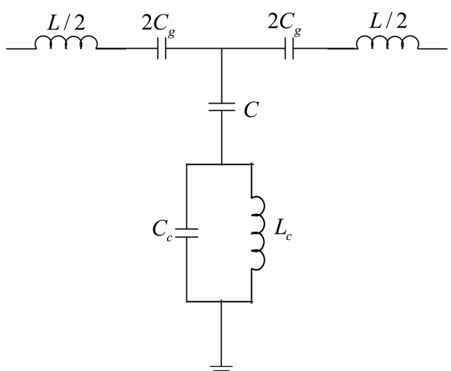

Figure 1. Equivalent circuit model.

2. ANALYSIS OF CRLH STRUCTURE BASED ON CSRRS

Following the analysis in [15], the CSRRs combined with the series gap can be depicted as an equivalent circuit model, as shown in Fig. 1. L is the per-section inductance of the microstrip line and C accounts for the line capacitance and the fringing capacitance of the gap, C_g is the series capacitance, L_c and C_c model the CSRRs and $1/\sqrt{L_c C_c}$ is equal to the resonant angular frequency ω_0 of CSRRs. under the assumption that the electrical size is small compared with the wavelength and considering the part as the basic cell of periodical structure, the phase shift factor and characteristic impedance can be obtained:

$$\cos\phi = 1 + \frac{C(1-\omega^2 LC_g)(1-\omega^2 L_c C_c)}{2C_g\left[1-\omega^2 L_c(C_c+C)\right]} \tag{1}$$

$$Z_B = \sqrt{\frac{(1-\omega^2 LC_g)^2}{-4\omega^2 C_g^2} + \frac{1-\omega^2 LC_g}{\omega^2 CC_g} + \frac{L_c(1-\omega^2 LC)}{C_g(1-\omega^2 L_c C_c)}} \tag{2}$$

From Equations (1) and (2), we can find that LH propagation occurs in the region delimited by the following frequencies:

$$f_L = \frac{1}{2\pi}\sqrt{\frac{\left[\frac{4L_c(C_c+C)C_g}{C} + (LC_g + L_c C_c)\right]}{2LC_g L_c C_c} - \frac{\sqrt{\left[\frac{4L_c(C_c+C)C_g}{C} + (LC_g + L_c C_c)\right]^2 - 4LC_g L_c C_c\left(1+\frac{4C_g}{C}\right)}}{2LC_g L_c C_c}} \tag{3}$$

$$f_H = \frac{1}{2\pi\sqrt{L_c C_c}} \tag{4}$$

Simultaneously, we also can find that RH propagation occurs above the cutoff frequency:

$$f_c = \frac{1}{2\pi\sqrt{LC_g}} \tag{5}$$

Increasing C_g can lower f_c. While C_g is increased to a certain value f_c is equal to f_H and balanced CRLH structure with wider pass-band bandwidth can be produced, which has been validated by simulated and measured results in [14, 15].

However, we can find that increasing L can also lower f_c and balanced CRLH structure should also be produced. Moreover, the effects of increasing L on the propagation characteristics should be different from those of increasing C_g. Considering the balanced case, Equation (3) can be simplified to

$$f_L = \frac{1}{2\pi}\sqrt{\frac{\frac{2L_c(C_c+C)C_g}{C} + L_c C_c - 2\sqrt{\frac{L_c^2(C_c+C)^2 C_g^2}{C^2} + L_c^2 C_c C_g}}{L_c^2 C_c^2}} \tag{6}$$

From the Equation (6), we can find that as the transition frequency has been determined increasing C_g can drive f_L toward higher frequency value which means left handed band is narrowed. On the contrary, increasing L can drive f_L toward lower frequency value and left-handed band is widened. In addition, we can find that increasing C can also drive f_L toward lower frequency and widen the left-handed band.

3. RESULTS AND DISCUSSIONS

To validate the above conclusion, three different CSRRs with different dimensions combined with different numbers of interdigital capacitors are proposed to produce balanced CRLH structure as shown in Fig. 2. All structures are realized on a 0.5 mm thick substrate having ε_r =

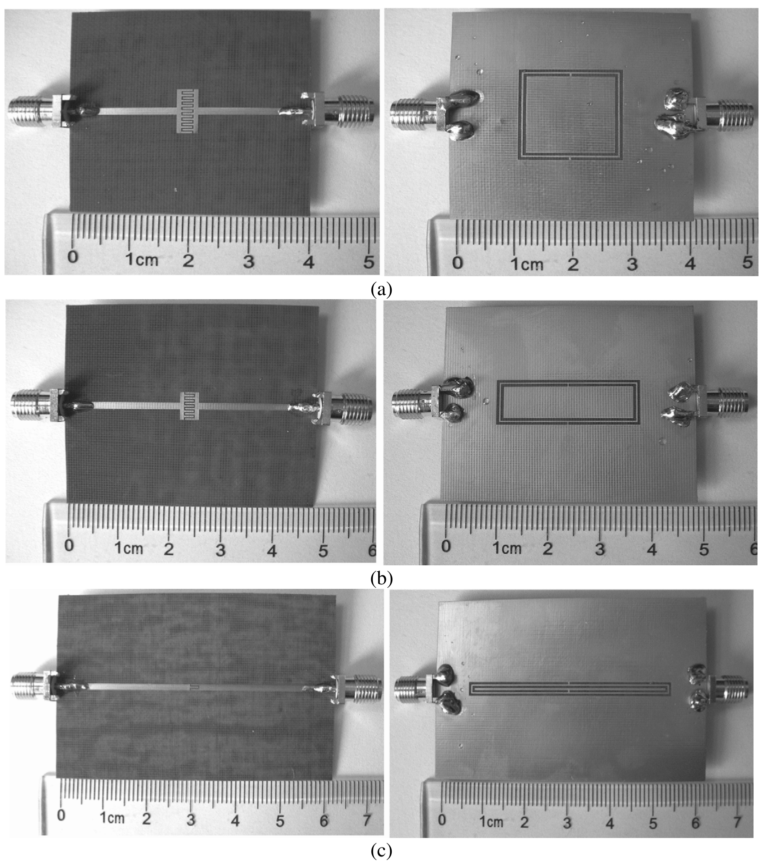

Figure 2. Photograph of three different CRLH structures (a) type 1, (b) type 2, (c) type 3.

2.65. Width of the line is 1.33 mm designed for 50 Ω characteristic impedance. For type 1 shown in Fig. 2(a), CSRRs are made into square shape. The side length of outer ring of CSRRs is 17 mm and gap between outer ring and inner ring is 0.3 mm. To produce the suitable series capacitance, the interdigital capacitor with 21 fingers separated 0.2 mm is used. The width of finger is 0.31 mm and length is 1.8 mm. The whole length of structure is 40 mm. This structure is simulated by Ansoft HFSS and measured by Agilent vector network analyzer 8722ES. The simulated and measured results are shown in Figs. 3(a) and (b) respectively. The simulated transition frequency between LH band and RH band is 1 GHz and measured is 1.04 GHz. The simulated 3 dB cutoff frequency at the below-band is 0.74 GHz while the measured is 0.7 GHz. Because of the increased series capacitance, the transition band at the below-band edge is sharp which can be observed from simulated and measured results.

For comparison, type 2 structure shown in Fig. 2(b) is proposed. The length of outer ring of CSRRs is 27 mm and width is 9 mm. The gap between outer ring and inner ring is also 0.3 mm. Because the length of CSRRs along strip line is increased, the effective length of strip line is also increased, which can increase the per-section inductance L obviously. As the inductance is increased, the series capacitance can be reduced to produce the balanced CRLH structure and therefore the interdigital capacitor with 11 fingers separated 0.2 mm is used. The whole length of structure is 48 mm. The simulated and measured results are shown in Figs. 4(a) and (b) respectively. The simulated transition frequency between LH band and RH band is 1.01 GHz and measured is 1.03 GHz. Because the inductance L is increased and capacitance C_g is decreased, the transmission peak is shifted toward lower frequency and the simulated 3 dB cutoff frequency at the below-band is 0.68 GHz while the measured is 0.65 GHz, which means that the LH band is widened. Furthermore, the transition band at the below-band edge become flatter compared with type 1.

For type 3 structure shown in Fig. 2(c), the dimensions of structure are designed as follows: The length of outer ring of CSRRs is 46 mm and the width is 3 mm; The gap between outer ring and inner ring is also 0.3 mm; the interdigital capacitor has 3 fingers separated 0.2 mm; The whole length of structure is 62 mm. For this structure, L is further increased, C_g is further decreased. However, because the area of interdigital capacitor is reduced obviously the decrement of C can not be ignored. The simulated and measured results are shown in Figs. 5(a) and (b) respectively. The simulated transition frequency between LH band and RH band is 1.01 GHz and measured is 1.03 GHz. The simulated 3 dB cutoff frequency at the below-band is 0.7 GHz while

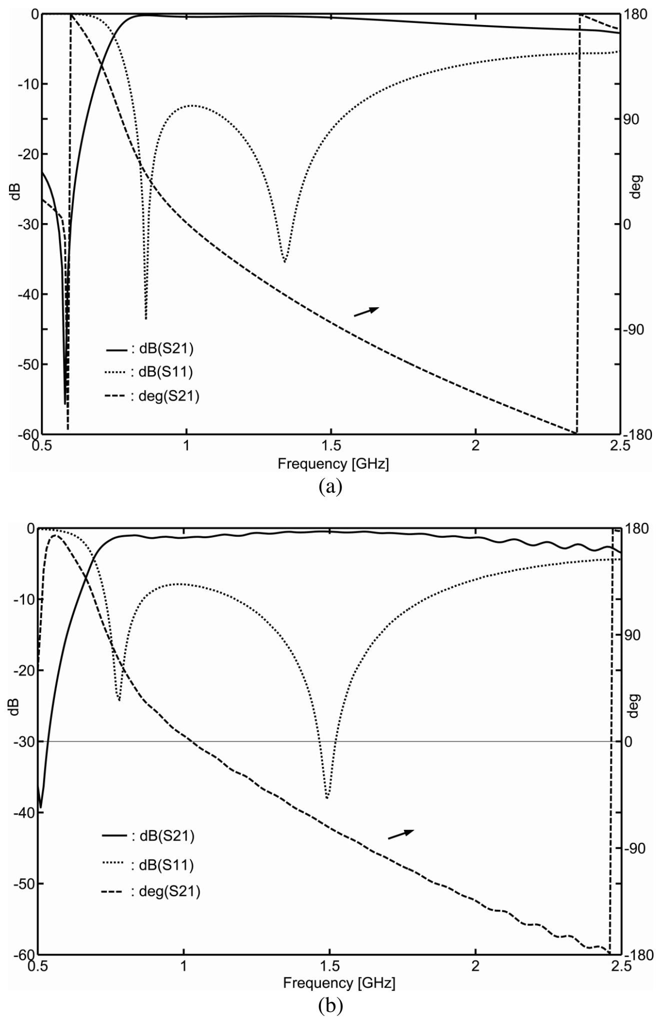

Figure 3. (a) Simulated results of type 1, (b) measured results of type 1.

the measured is 0.68 GHz. The LH band is not widened compared with type 2, which is mainly due to the obvious decrement of C. In addition, the RH band is narrowed compared with type 1 and type 2 structures. Because the occupied width of type 3 structure is almost equal to the width of strip line, it can be easily added to the complicated microwave/RF components to produce required balanced CRLH propagation.

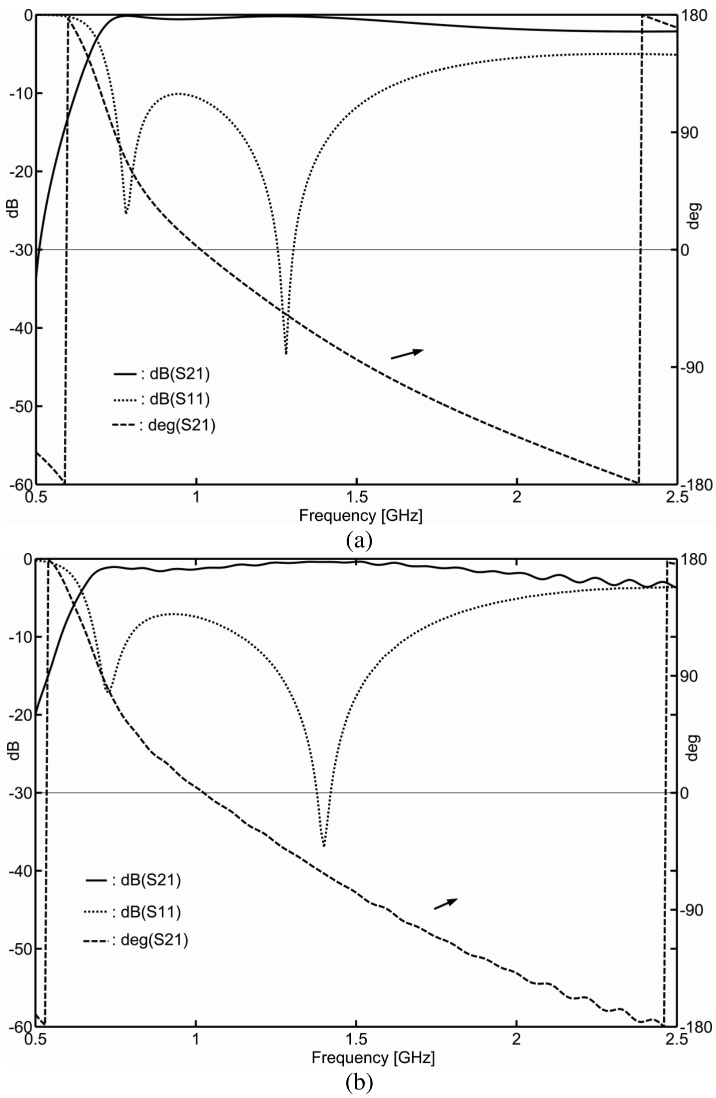

Figure 4. (a) Simulated results of type 2, (b) measured results of type 2.

To further understand the wave propagation in these balanced composite right/left handed structures and explain how to distinguish the LH band and RH band, the dispersion characteristics are studied.

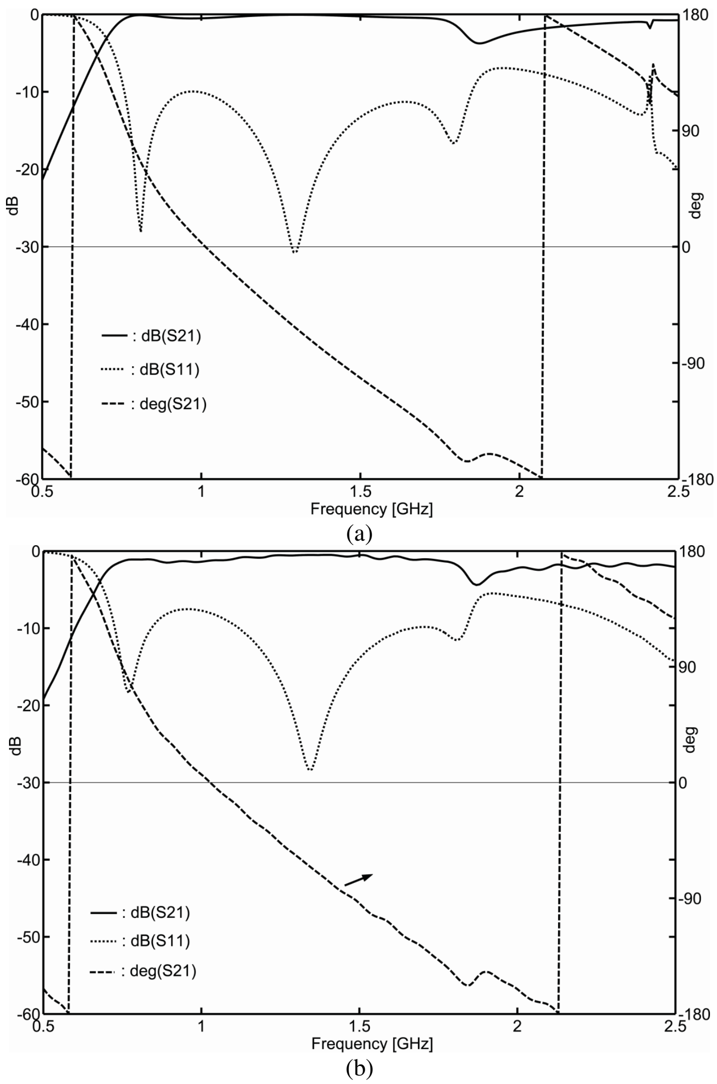

Figure 5. (a) Simulated results of type 3, (b) measured results of type 3.

As the structure is considered as the basic periodical cell, the wave propagation constant can be obtained from the scattering parameters [16]:

$$\gamma = \frac{1}{d}\cosh^{-1}\left\{\frac{[(1+S_{11})(1-S_{22})+S_{12}S_{21}]+\dfrac{Z_{01}}{Z_{02}}[(1-S_{11})(1+S_{22})+S_{12}S_{21}]}{4S_{21}}\right\} \quad (7)$$

Where Z_{01} and Z_{02} are the impedances of port 1 and port 2. d is the length of per unit cell. The real part of γ is the attenuation constant and the imaginary part is the propagation constant. Following this method, the propagation constants of these different CRLH structures are computed from their simulated S parameters, which are shown in Fig. 6. In region 1, the phase velocity is negative but the group velocity is positive, which means that the LH band is produced. In region 2, the phase velocity is positive and the group velocity is also positive, which means the RH band. At the transition frequency, the propagation constant is equal to zero.

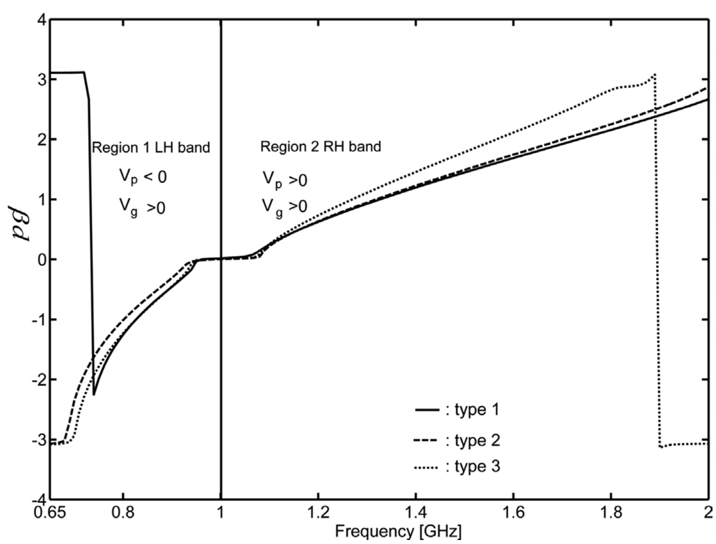

Figure 6. Dispersion diagram of the proposed CRLH structures.

4. CONCLUSION

In this paper, three different balanced CRLH structures base on different dimensions of CSRRs and different numbers of interdigital capacitors are investigated and compared. Influence of dimensions of CSRRs and series capacitance to the performance is analyzed. Simulated and measured results are in good agreement. The changeability of dimensions of balanced CRLH structure enlarges the field of its application to the design of microwave/RF components.

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