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ANALYSIS AND APPLICATION OF NOVEL STRUCTURES BASED ON SPLIT RING RESONATORS AND COUPLED LINES

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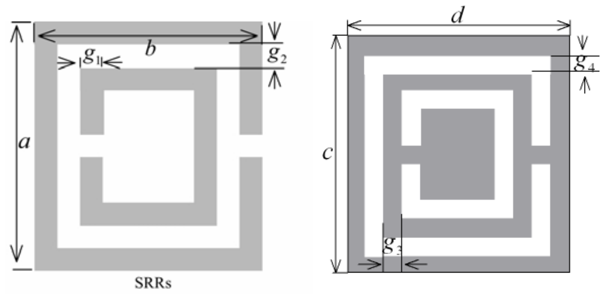
Abstract—In this paper, novel structures using split ring resonators (SRRs) and coupled lines are proposed and analyzed. SRRs are etched on three different planes and their propagation characteristics are compared. Two compact narrow band band-pass filters based on these structures are designed and their performances 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 material (LHM) has attracted many attentions. The material 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]. Compared with other types of resonators, SRRs and CSRRs shown in Fig. 1 have numbers of advantages such as miniature size and high quantity factor, therefore these two types of resonators have been used to design several different types of filters [10–12]. In this paper, novel structures based on split ring resonators combined with coupled lines are introduced. SRRs are etched on three different planes and different propagation characteristics can be observed. Subsequently, two compact narrow band band-pass filters based on our proposed structures are designed. Measured and simulated results are in good agreement.



(a) (b)

Figure 1. (a) The topology of SRRs, (b) the topology of CSRRs.

2. SRRS COMBINED WITH COUPLED LINES

As proposed in [13], a narrow band band-pass filter can be realized by using an open-loop resonator combined with coupled lines. As SRRs are used to substitute the open-loop resonator, narrow band band-pass phenomena can be anticipated. The structures with different locations between SRRs and coupled line are designed and fabricated for comparison, as shown in Figs. 2(a)–(c). These structures have two stages and each stage consist of two SRRs and coupled line which produces gap capacitance. The equivalent circuit model for each stage is shown in Fig. 2(d). The circuit parameters can be extracted from the measured or simulated S-parameters. Following the circuit model, the Bloch impedance and phase shift for periodical structure can be calculated as

$$Z_B = \tag{1}$$

$$\sqrt{-\frac{(1-\omega^2 LC_g)^2}{4\omega^2 C_g^2}+\frac{(1-\omega^2 LC_g)L_cC+2L_cC_g}{CC_g(1-\omega^2 L_cC_c)}-\frac{\omega^2 L_c^2}{(1-\omega^2 L_cC_c)^2}-\frac{1-\omega^2 LC_g}{\omega^2 CC_g}} \tag{2}$$

$$\cos\beta d = 1+\frac{(1-\omega^2 LC_g)C}{2C_g}-\frac{\omega^2 L_cC}{1-\omega^2 L_cC_c} \tag{3}$$

where L and C are the per-section inductance and capacitance of the microstrip line, C_g is the gap capacitance, L_c and C_c are the coupled inductance and capacitance through the magnetic coupling. $1/\sqrt{L_cC_c}$ is equal to the resonant frequency ω_0 of SRRs. From the above equations we can find that the propagation constant β can be taken as real value among a narrow band below the resonant frequency of SRRs, which means a narrow pass-band occurs. By adjusting the circuit parameters dependent on the dimensions of SRRs and relevant

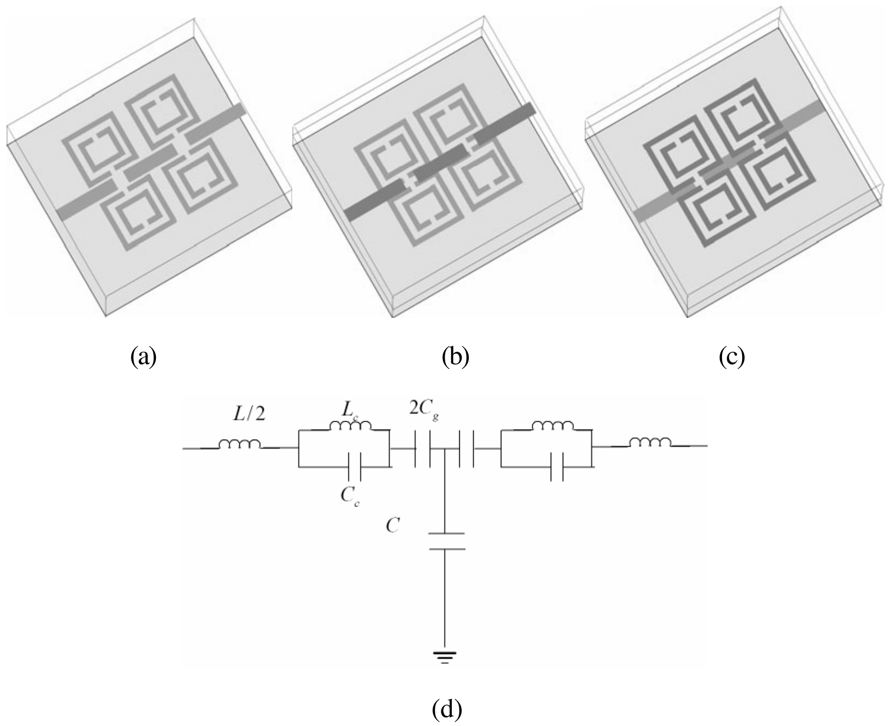


Figure 2. Layout of SRRs with coupled line and equivalent circuit model (a) type 1: SRRs coplanar with coupled line, (b) type 2: SRRs below coupled line, (c) type 3: SRRs above coupled line, (d) equivalent circuit model.

location between SRRs and coupled lines the filtering properties will be changed.

For comparison, in all of structures the dimensions of SRRs are designed as follows: $a = 9.8\,\text{mm}$, $b = 4.6\,\text{mm}$, $g_1 = 0.55\,\text{mm}$, $g_2 = 0.3\,\text{mm}$. The gap width of coupled line is chosen as 2.5 mm. These structures are fabricated on the substrate with $\varepsilon_r = 2.65$. Thickness of substrate is 1.5 mm and width of microstrip line is designed for $50\,\Omega$ characteristic impedance. The S-parameters are all simulated in IE3D and measured by means of Agilent vector network analyzer 8722ES. For type 1 SRRs and coupled lines are coplanar. The distance between SRRs and the microstrip line is 0.2 mm. Simulated and measured results are shown in Fig. 3(a). A very narrow pass-band centered at 3.64 GHz and very large inserting loss can be found form these results, which are mainly due to the inefficient magnetic coupling. For type

2, SRRs are etched below coupled lines. The thickness of substrate between SRRs and coupled line is 0.5 mm. The distance between two SRRs in the same stage is 1.2 mm. Simulated and measured results of S-parameters are shown in Fig. 3(b). The measured 3 dB bandwidth and simulated one are 2.2% centered at 3.18 GHz and 2.82% at 3.19 GHz respectively. For type 3, SRRs are etched above coupled lines. The thickness of substrate between SRRs and coupled lines is also 0.5 mm and the distance between two SRRs in the same stage is also 1.2 mm. Simulated and measured results of S-parameters are shown in Fig. 3(c). The measured insertion loss is 1.53dB at the center frequency of 3.38 GHz while the simulated is 0.4 dB at 3.47 GHz. The measured 3 dB bandwidth and simulated one are 5.33% and 5.76% respectively. From Fig. 3, we can find that magnetic coupling can be improved significantly by locating SRRs below or above coupled

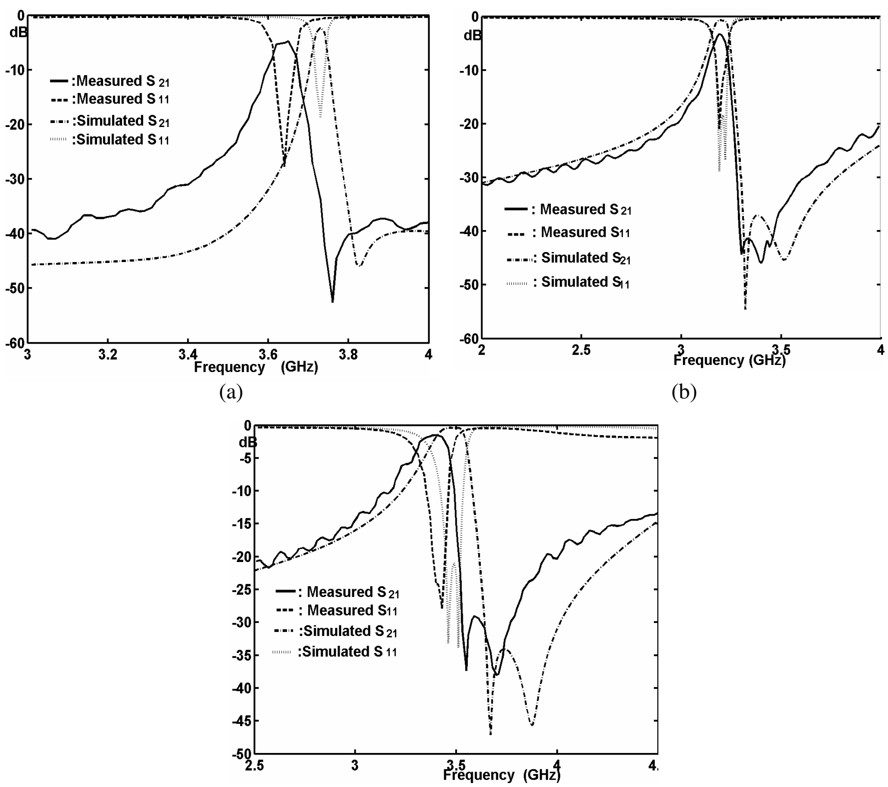


Figure 3. Simulated and measured results (a) type 1, (b) type 2, (c) type 3.

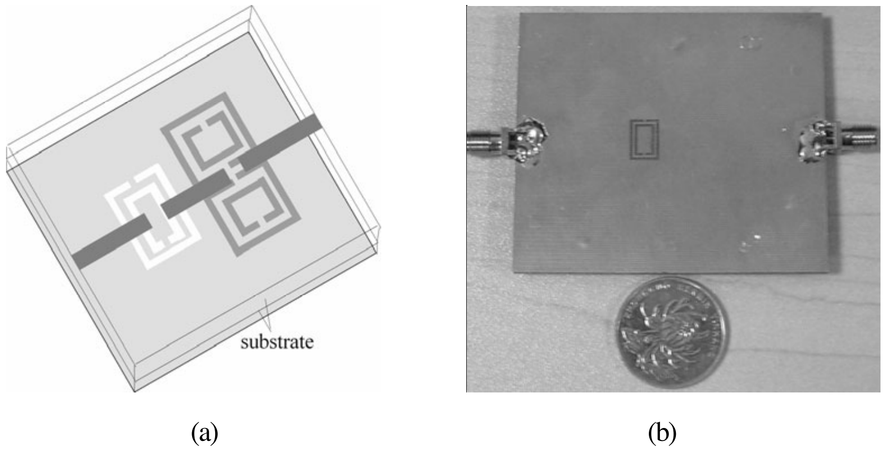


Figure 4. (a) The layout of filter 1, (b) the bottom photograph of filter 1.

lines and locating SRRs above coupled lines can produce the stronger magnetic coupling. Furthermore, the magnetic coupling can also be influenced by the distance between SRRs and coupled lines. As SRRs are located closer to coupled lines the stronger magnetic coupling is produced. The offset of operation frequency between these filters observed from Fig. 3 results from different locations of SRRs in the substrate which can produce different resonant frequency.

3. NARROW BAND BAND-PASS FILTERS DESIGN

Similar with the discussion in [10, 11], as the magnetic coupling is improved, the frequency selectivity at the below-band edge becomes poor, which will influence the performances of filter. Here two methods are proposed to improve the frequency selectivity at the below-band edge.

A. Filter 1

The method 1 is to cascade a stage composed of CSRRs and coupled line which can offer good frequency selectivity at the below-band edge [11]. The layout and bottom photograph of the filter 1 is shown in Fig. 4. Two SRRs are etched below the coupled line. The dimensions of CSRRs shown in Fig. 1(b) are as follows: $c = 9.3\,\mathrm{mm}$, $d = 6.5\,\mathrm{mm}$, $g_3 = g_4 = 0.55\,\mathrm{mm}$. The structure composed of CSRRs combined with coupled line can also be modeled by equicalent T-type circuit shown in Fig. 5.

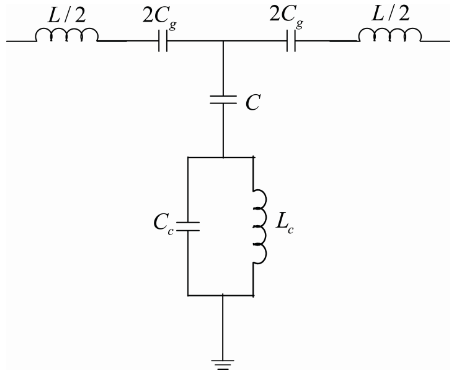


Figure 5. Equivalent circuit model for the structure composed of CSRRs combined with coupled line.

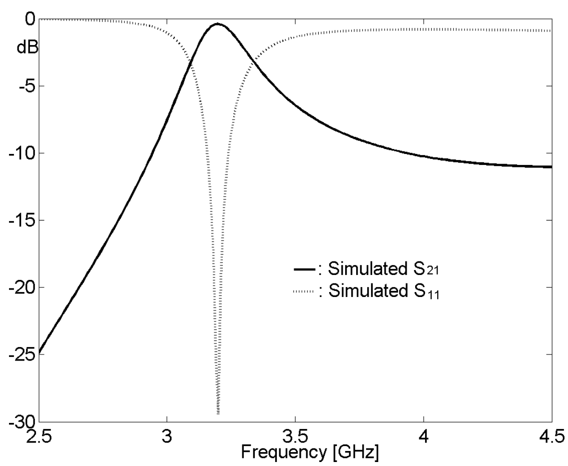


Figure 6. Simulated results for the structure composed of CSRRs combined with coupled line.

The Bloch impedance and phase shift can be calculated as

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

$$\cos\phi = 1 + \frac{C(1-\omega^2 LC_g)(1-\omega^2 L_c C_c)}{2C_g[1-\omega^2 L_c(C_c+C)]} \tag{5}$$

A left-handed pass-band can be found by calculating the above equations. The simulated S-parameters for this structure are shown

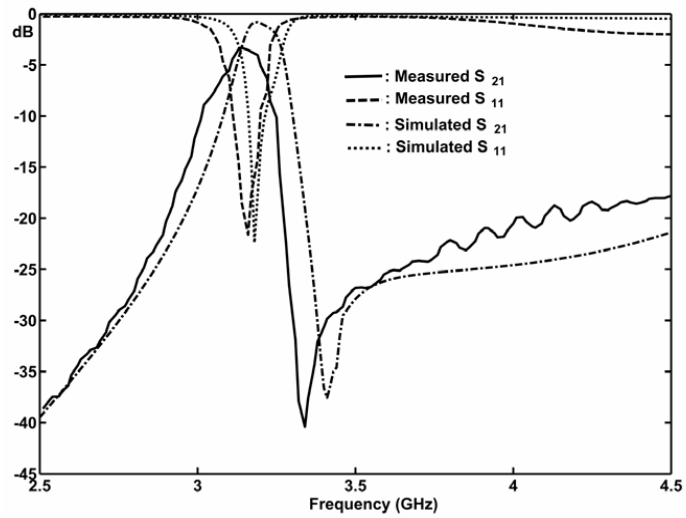


Figure 7. Simulated and measured results of filter 1.

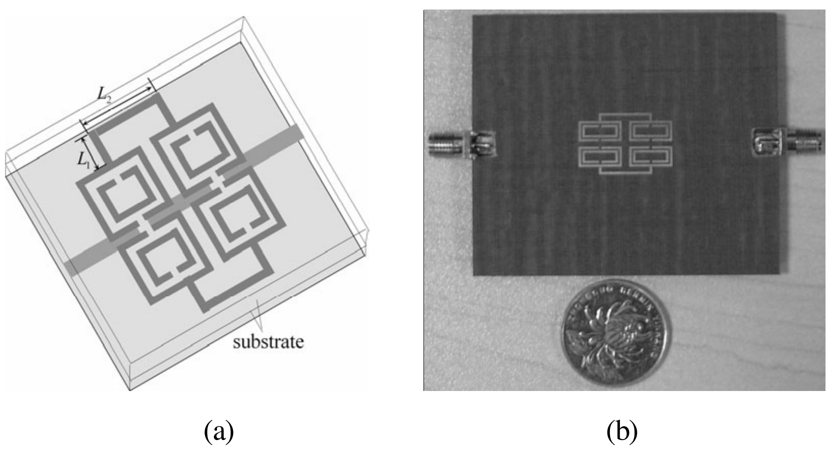


Figure 8. (a) The layout of filter 2, (b) the top photograph of filter 2.

in Fig. 6. A sharp transition band at the below-band edge can be observed. By cascading these two stages, good frequency selectivity at two edges can be produced. Simulated and measured results are shown in Fig. 7. Sharp transition band with rejection levels better than 40 db can be observed, which proves the effectiveness of this method.

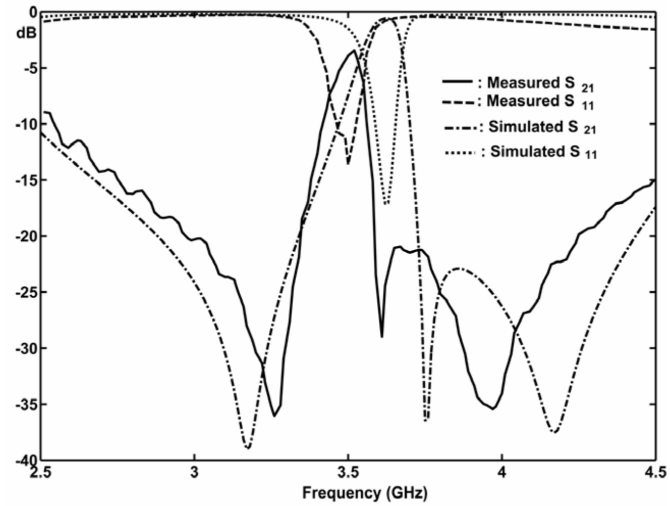


Figure 9. Simulated and measured results of filter 2.

B. method 2

Method 2 is to add another transmission path to produce a transmission zero at the below-band edge by using the microstrip crossing lines [13]. The layout and top photograph of the filter 2 is shown in Fig. 8. Four SRRs are etched above the coupled line. The dimensions of the crossing line are as follows: $L_1 = 1.8\,\text{mm}$, $L_2 = 12.55\,\text{mm}$ and the width of line is the same as one of SRRs. Simulated and measured results are shown in Fig. 9. Sharp transition band with rejection levels better than 35 dB can be obtained, which also proves the effectiveness of this method. Differences between measured results and simulated ones are mainly due to the conductor loss and fabrication tolerances.

4. CONCLUSION

Novel structures using split ring resonators and coupled lines are proposed and analyzed. As the SRRs are etched on different planes, different propagation characteristics can be found because of different magnetic couplings. Based on these novel structures, two compact narrow band band-pass filters are designed, fabricated and measured. For the laboratory prototype filters, acceptable measured results have been achieved. Through further optimizations, these filters can be applied in the mobile and personal communication systems.

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