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BANDPASS FILTER USING MINIATURIZED SCRLH MZOR

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Abstract—A highly miniaturized simplified composite right/left handed (SCRLH) mushroom zeroth-order resonator (MZOR) is proposed for bandpass filter (BPF) design. By introducing the U-slot etched around the metallic via, more flexible selection of the shunt inductance value can be achieved compared with the original one. As the length of U-slot increased, zeroth-order resonant frequency of the MZOR decreased, even 88% size reduction can be achieved. Finally, a bandpass filter based on the proposed MZOR is designed, fabricated and measured. The simulated and measured results are presented and good agreement is obtained.

1. INTRODUCTION

In 2004, a general composite right/left-handed (CRLH) TL structure was proposed by Sanada et al. [1], led to a suite of microwave devices based on CRLH ZORs [2, 3]. Shortly after, a simplified CRLH TL with no equilibrium condition is introduced by Lin et al. [4]. Compared with CRLH ZORs, both the size and the structure complexity of SCRLH ZORs with relaxed broadband matching condition are reduced by taking away the series capacitor [5, 6]. The SCRLH Mushroom ZOR has been proposed in [7], which has more simplified structure than the conventional one. However, the shunt inductance value determined by the metallic via is determined by the thickness of the substrate, this tunable limitation narrows its applications in microwave systems.

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Herein, there are two methods to increase the shunt inductance: introducing the grounded stub or etching slot in the patch or ground [8–10].

In this work, a miniaturized SCRLH MZOR with U-slot is proposed for the BPF design. By introducing U-slot, the effective electrical length between the patch and the ground is not only determined by the length of the metallic via but also determined by size of the stub connecting the metallic via and the ground. Therefore, more flexible selection of inductance value can be obtained compared with the conventional one. As the length of the U-slot increased, the shunt inductance value increased, and the zeroth-order mode resonant frequency decreased. The SCRLH MZOR miniaturization is achieved. Moreover, without expanding the MZOR size, the zeroth-order resonant frequency can be controlled within a wide range by tuning U-slot. Finally, a bandpass filter based on the miniaturized MZOR is realized by utilizing the coupling coefficient method [11, 12]. The fractional bandwidth of the bandpass is 3% (4.77 GHz–4.93 GHz), the insertion loss of about 1.5 dB and the return loss of about 13.2 dB. Meanwhile, the wide upper-stopband is from 5 GHz to 13.2 GHz with the insertion loss higher than 20 dB.

2. THEORETICAL ANALYSIS

2.1. Miniaturized SCRLH MZOR

The conventional SCRLH MZOR presented in [7] and the proposed SCRLH MZOR are shown in Figures 1(a) and 1(b), respectively. The U-slot is etched around the metallic via connecting the patch and the ground. The effective electrical length between the patch and the ground is only determined by metallic via in the conventional structure, however, it depends on the metallic via and the stub connecting the metallic via and ground in the proposed structure. The conventional

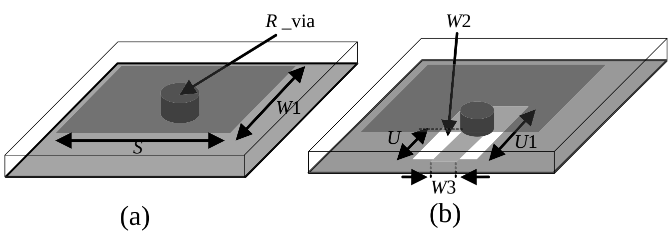

Figure 1. Geometries dimension. (a) Conventional SCRLH MZOR. (b) Proposed SCRLH MZOR.

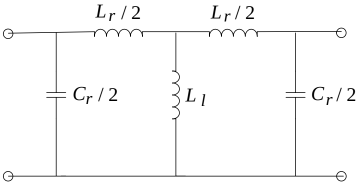

Figure 2. Equivalent circuit of SCRLH MZOR.

and proposed MZORs can be analyzed using the same equivalent circuit shown in Figure 2. The series inductor (L_r) and the shunt capacitor (C_r) are the parasitical inductance and capacitance of the resonator, the shunt inductor (L_l) is realized by the effective electrical length between the patch and the ground.

The transmission line theory is applied to analyze the lumped circuit, and the zeroth-order and the first positive mode resonant frequency can be solved as [6, 13]

$$f_0 = \frac{1}{2\pi\sqrt{C_r L_l}} \tag{1}$$

$$f_{+1} = \frac{1}{2\pi}\sqrt{\frac{1}{C_r L_l} + \frac{4}{C_r L_r}} \tag{2}$$

f_0 is zeroth-order resonant frequency of the MZOR, f_{+1} is first positive mode resonant frequency of the MZOR. From (1) (2), it's obvious that as C_r and L_l are increased, the resonant frequencies decreased. Under the stationary resonator size and substrate thickness, the value of C_r is limited. While, in the new MZOR, L_l is not only determined by the length of the metallic via but also determined by the stub connecting the metallic via to the ground. It is easy to adjust L_l by tuning the length of U-slot. Therefore, L_l is a suitable parameter to adjust the resonant frequency to the desired resonant frequency.

As L_l increases, the zeroth-order resonant frequency moves towards to the lower region, so that the MZOR can be of compact size. In order to get a larger shunt inductance, the U-slot is introduced on the ground. By introducing U-slot, the effective electrical length between the patch and the ground increases and the shunt inductance becomes much greater than it is without U-slot. An example of the proposed MZOR is given. Compared with conventional MZOR presented in [7], the patch size and the substrate of the proposed resonator are unchanged and the dimensions of U-slot are given below: the width of U-slot $W2 = 0.2$ mm, the inner and outer length of the slot $U = 5.14$ mm, $U1 = 5.5$ mm, the inner width of U-slot $W3 = 0.1$ mm. Therefore, the zeroth-order resonance frequency of the resonator is

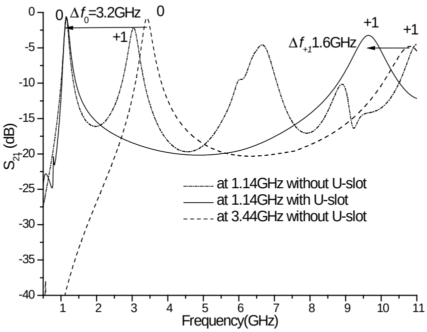

Figure 3. Zeroth-order and the first positive mode resonant frequency of the MZOR with and without slot.

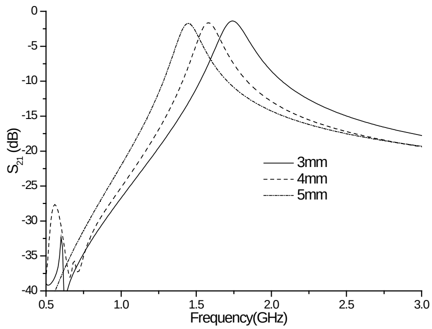

Figure 4. Simulated zeroth-order resonant frequency with different length of $U1$ which is relevant to L_l.

1.14 GHz, and the first positive mode resonant frequency is 9.8 GHz.

Figure 3 shows the size reduction effect of the U-slot. It is obvious that zeroth-order resonant frequency decreases from 3.44 GHz to 1.14 GHz by etching slot on the ground plane of the conventional MZOR. The size of the conventional MZOR with the zeroth-order resonant frequency at 1.14 GHz is 33 mm $\times$ 30 mm and a 88% size reduction is achieved. In addition, the band from zeroth-order resonant frequency to the first positive mode resonant frequency is wider. These characters are attractive in designing a compact filter with wide upper-stopband.

As shown in Figure 1(b), the slot is etched around the metallic via connecting the patch and the ground plane. Thus, as the length of U-slot increased, the electrical length between the patch and the ground plane increased. Figure 4 shows that when $U1$ (related to L_l) increases and other parameters are fixed, the zeroth-order resonant frequency decreased. It is easy to adjust the resonant frequency by tuning the length of the U-slot without expanding the patch size.

2.2. Design of BPF

In this part, the proposed MZOR is used for bandpass filter design. The resonator with the zeroth-order resonant frequency at 4.85 GHz is chosen, and the resultant dimensions of the resonator are given below: the length of the patch $S = 7$ mm, the width of the patch $W1 = 6$ mm, the width of the slot $W2 = 0.4$ mm, the inner and outer length of the slot $U = 1.2$ mm, $U1 = 2.8$ mm, the inner width of U-slot $W3 = 1.2$ mm, the diameter of metallic via $R\_\text{via} = 1.5$ mm.

The filter is designed by utilizing the coupling coefficient method presented by Hong and Lancaster [11, 12]. The BPF network is shown in Figure 5(a), which is inferred from the low-pass filter prototype by well-known frequency and element transformations. The fractional bandwidth is set to $w = 3\%$ and the specified pass-band ripple is 0.1 dB with the central frequency $f_0 = 4.85\,\text{GHz}$. Given these specifications, the element values of the low-pass filter prototype are selected as $g_0 = 1.0$, $g_1 = 0.8431$, $g_2 = 0.6220$, $g_3 = 1.3554$. Then, the interstage coupling coefficients k and external Q_e values can be determined from

$$k = \frac{w}{\sqrt{g_1 g_2}} \tag{3}$$

$$Q_e = Q_{ei} = Q_{eo} = \frac{g_0 g_1}{w} = \frac{g_2 g_3}{w} \tag{4}$$

Therefore, $k = 0.04$ and $Q_e = 28$.

In order to satisfy the interstage coupling coefficient k, the structure is designed, as shown in Figure 5(b), and the coupling coefficient k is related by

$$k = \frac{f_a^2 - f_b^2}{f_a^2 + f_b^2} \tag{5}$$

where, f_a and f_b are peak frequencies in the transmission response obtained by using excitation through a gap to the outer end of the coupled MZORs. The tunable parameter g_1 is adjusted to k.

The structure which is exploited to realize the required Q_e is shown in Figure 5(c). Find the frequencies f_+ and f_- at which the phase shifts

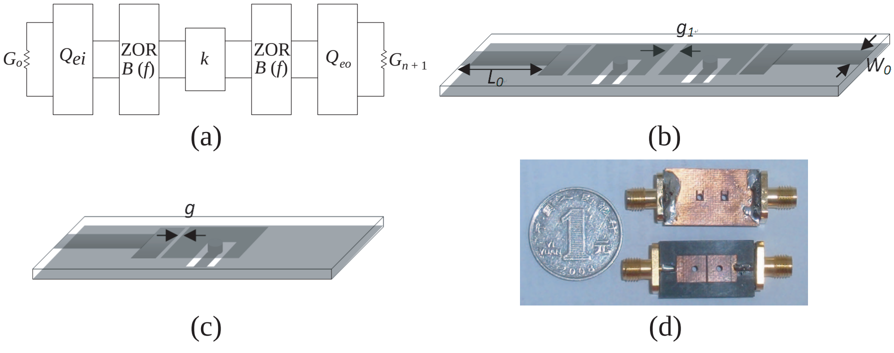

Figure 5. BPF based on the proposed MZOR. (a) Schematic structure. (b) Coupling structure designed to satisfy k. (c) Coupling structure exploited to realize Q_e. (d) Photograph of the fabricated BPF.

$+90°$ and $-90°$ with respect to the phase at f_0 respectively, and then the external quality factor Q_e is calculated by

$$Q_e = \frac{f_0}{|f_+ - f_-|} \tag{6}$$

The tunable parameter g_0 is adjusted to Q_e. Finally, the optimized parameters are $g_0 = 0.09\,\text{mm}$, $g_1 = 0.49\,\text{mm}$. The feed line is designed to match the impedance of the input and output ($50\,\Omega$).The dimensions of the feed line are given below: the length of feed line $L_0 = 4.75\,\text{mm}$ and the width of feed line $W_0 = 1.5\,\text{mm}$ (shown in Figure 5(b)). According to the above optimized structural parameters, a prototype filter is designed and fabricated. Photographs of the developed compact filter are displayed in Figure 5(d).

3. MEASURED RESULTS

The substrate used herein is RT/Duroid 5880 with a thickness of 0.508 mm, relative permittivity of 2.2 and loss tangent of 0.0009. The size of the conventional mushroom zeroth-order resonator with the zeroth-order resonant frequency at 4.85 GHz is 12.5 mm ×10.4 mm, and a 67% size reduction is achieved. As shown in Figure 6, the results of S-parameters magnitude with full wave simulations and measurements are depicted. The BPF is designed with fractional bandwidth of 3% (4.77 GHz–4.93 GHz), the insertion loss of about 1.5 dB, and the return loss of about 13.2 dB. Meanwhile an excellence characteristic of wide

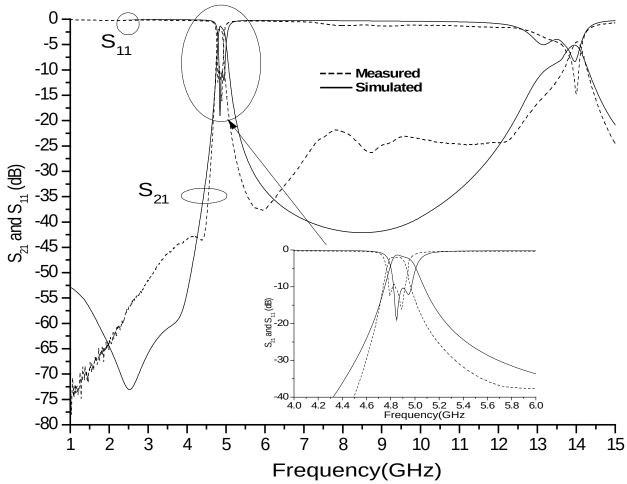

Figure 6. The simulated and measured results of the BPF.

upper-stopband which is from 5 GHz to 13 GHz with the insertion loss higher than 20 dB is achieved. A good agreement between simulated and measured results is obtained.

4. CONCLUSION

In this work, a novel SCRLH MZOR is proposed. By introducing *U*-slot, the SCRLH MZOR miniaturization is realized. The equivalent circuit of SCRLH MZOR is analyzed. The SCRLH MZOR has a very simplified structure and the resonant frequency can be decreased without extending the resonator size. Finally, a band-pass filter based on miniaturized SCRLH MZOR is designed fabricated and measured. The BPF with wide upper-stopband may have further applications in microwave systems.

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