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COMPACT RECONFIGURABLE HMSIW BANDPASS FILTER LOADED BY CSRR

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Abstract—A reconfigurable half-mode substrate integrated waveguide (HMSIW) bandpass filter (BPF) loaded by complementary split-ring resonator (CSRR) is investigated. The proposed HMSIW-CSRR structure allows the implementation of a forward-wave passband propagating below the characteristic cutoff frequency of the waveguide. By changing the effective capacitance to ground of the CSRR, frequency tuning of the resonator is observed without other external circuit. The proposed filter exhibits improved selectivity due to the employment of the pseudo-S defected structure to generate transmission zero at the low stopband. To verify the presented design method, the predicted compact reconfigurable filter, tuned between 3.6 GHz and 4.5 GHz with insertion loss less than 3.6 dB and return loss better than 17 dB, is fabricated based on the standard printed circuit board process. The measured results are in good agreement with the simulation.

1. INTRODUCTION

Recently substrate integrated waveguide (SIW), which is realized by metallic vias on low loss substrate through printed circuit board (PCB) or low temperature co-fired ceramic (LTCC) fabrication process, has provided a useful technology for designing high Q-factor, compact size and low cost filters [1–7]. HMSIW has similar propagation characteristics to that of SIW and realizes highly compactness that is several times smaller in area compared to the SIW counterparts [8, 9]. Moreover, the HMSIW BPF has a wider stopband between the passband and the first spurious passband due to the HMSIW intrinsically can not support the $\mathrm{TE}_{2n,0}$ modes as well as TM mode [10]. The HMSIW technology has provided a very attractive platform to the design of low-cost and highly integrated waveguide components.

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Since the first experimental demonstration of metamaterial particles exhibits negative permittivity such as the CSRR, different implementations combining waveguide with such a structure have been widely investigated for bandpass filters. Firstly, the CSRRs have extraordinary property of generating forward wave transmission below the waveguide cutoff frequency [11–16]. Moreover, the intrinsic resonance frequency of the CSRR can be electronically tuned by adding variable capacitors to the inner conductors for CSRR's behaviour as a resonant LC tank [10]. In addition, HMSIW is very convenient to etch the CSRR on the waveguide surface in a mode that has little resemblance with the original TE_{10} mode [11], resulting in a significant size reduction effect.

Most efforts have been focused on operating SIW to implement bandpass filters and dual mode filters [17–27]. However, few works concerned about reconfigurable HMSIW filters due to the difficulty in adding PIN diodes or other components. The corresponding experimental realization is still rare and ordinary in performance. In [28], the insertion loss of the designed tunable filter is up to 5.4 dB. In [10], the HMSIW tunable filter has no transmission zero on the lower band to improve the selectivity performance of the passband.

In this study, a reconfigurable HMSIW bandpass filter loaded by complementary split-ring resonator with zero ohmic resistance is presented. The predicted frequencies, which focus on 3.6 GHz and 4.5 GHz respectively, are obtained by the change of inner inductances and capacitances of the CSRR, which is implemented by using zero ohmic resistance as a connection switch in practical application. For improving the selectivity performance of the filter, the pseudo-S defected structure is applied to generate lower transmission zero and heighten the coupling degree at the input and output port of the filter. Without extra circuit, the low insertion-loss performance in the passband and compact size can be realized. To certify the proposed method, a reconfigurable HMSIW filter is optimally designed, fabricated and measured. Simulations and measurements are carried out to prove the validity of this reconfigurable filter.

2. DESIGN AND ANALYSIS OF PROPOSED FILTER

2.1. HMSIW-CSRR Resonator

Configuration of the proposed HMSIW-CSRR resonator is presented in Fig. 1 [12]. The linear array of metallic vias in HMSIW unit cell is used to form the electric side-wall of the waveguide. The open side of the HMSIW behaves as a magnetic wall, which in combination with the vias row allows the wave propagation. The complementary

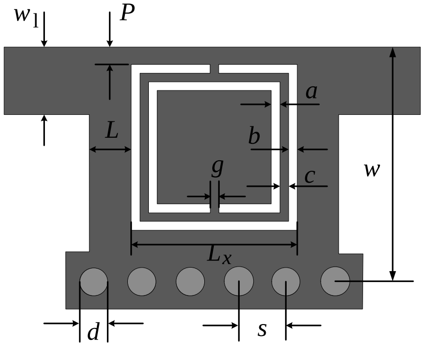


Figure 1. Layout schematic of HMSIW-CSRR unit cell, from [12].

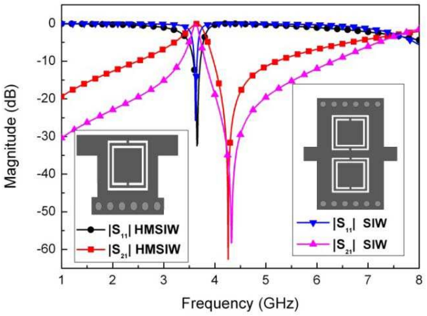


Figure 2. Simulated transmission responses corresponding to HMSIW and SIW unit cells.

split-ring resonator (CSRR) is etched on the metallic surface of the waveguide. The waveguide cutoff frequency of Fig. 1 is selected to be 6.3 GHz, which is achieved with an optimized width w of 7.35 mm implementations. A 50 ohm microstrip line with a width w_1 of 2.5 mm is connected directly to the waveguide with no transition.

The substrate with a thickness of 0.8 mm and a relative permittivity of 2.65 is used in all of our design. The metallic vias has a diameter of 0.4 mm and a center to center spacing of 1.4 mm. Using Ansoft's High Frequency Structure Simulator (HFSS) software package, the transmission responses, shown in Fig. 2, for the proposed HMSIW resonator and the corresponding SIW resonator are simulated and investigated. HMSIW has the similar propagation characteristics to that of SIW and achieves the realization of highly compactness that is several times smaller in area compared to their SIW counterparts [12].

2.2. Design of Proposed Reconfigurable Structure

As seen in Fig. 3, the proposed HMSIW structure can be considered as an ordinary two-wire transmission line which is formed by the metal surface and the ground [6]. And the metallic vias-walls form the infinite number of short-circuited stubs. The equivalent circuit of pseudo-S defected structure is LC return tank, which is in series with transmission line.

Although this circuit model presented in Fig. 4 is simplified, it is basically correct and is fully capable of explaining the transmission characteristics of this structure because the CSRR can be interpreted

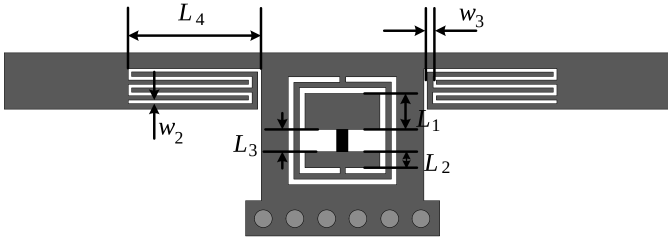
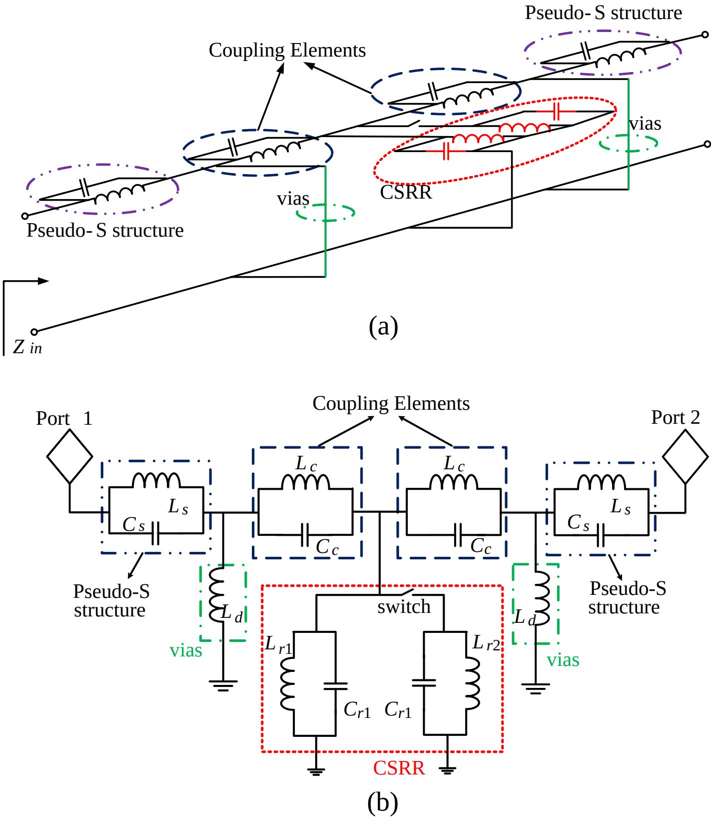


Figure 3. Layout of the proposed reconfigurable filter with zero ohmic resistance as switch.



(a)

(b)

Figure 4. Electrical equivalent circuit for (a) stereo model and (b) simplified model of the reconfigurable filter. Prameters are $L_s = 2.731\,\text{nH}$, $L_d = 0.5642\,\text{nH}$, $L_c = 1.284\,\text{nH}$, $L_{r1} = 2.311\,\text{nH}$, $L_{r2} = 2.333\,\text{nH}$, $C_s = 1.083\,\text{pF}$, $C_c = 0.642\,\text{pF}$, $C_{r1} = 1.110\,\text{pF}$, $C_{r2} = 1.950\,\text{pF}$.

as a resonant LC tank. The equivalent circuit model gives a center frequency of the CSRR at

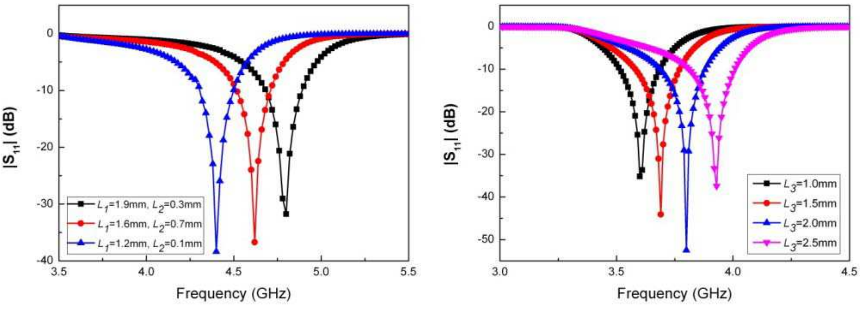
$$f_{o1} = \frac{1}{\sqrt{L_{r1}C_{r1}}} \tag{1a}$$

$$f_{o2} = \frac{1}{\sqrt{\left(\frac{L_{r1}+L_{r2}}{L_{r1}L_{r2}}\right)(C_{r1}+C_{r2})}} \tag{1b}$$

The center frequencies as a function of the capacitances and inductances of inner CSRR are plotted in Formula (1), where f_{o1} and f_{o2} are the center frequencies for "on" or "off" state of the switch. The adoption of zero ohmic resistance performing switching task to change the capacitance of CSRR accomplishes the tunability between f_{o1} and f_{o2}. When the switch is "on" state, the values of L_{r1} and C_{r1} in Equation (1a) are impacted by the ratio of L_1 and L_2; With "off" state, the variation of L_3 leads to different values of L_{r1}, C_{r1}, L_{r1}, C_{r2} in Equation (1b).

As shown in Fig. 5, the larger the ratio of L_1 to L_2 is while the switch off, the higher the center frequency f_{o1} will be. When the switch is on, the capacitance of the inner CSRR becomes smaller as L_3 increases, resulting in a lower center frequency f_{o2}.

The selectivity in Fig. 2 will be further improved when another transmission zero can be achieved. However, generating transmission zeros for tunable HMSIW filter has been still a challenging work. In this design, an introduction of pseudo-S defected structure strengthening the source-load coupling generates additional transmission zero located at the low stopband. The source-load coupling becomes stronger with increasing L_4, and the transmission zero located at low stopband moves towards the passband. However,



(a) (b)

Figure 5. Simulated S_{11}-parameters for different values of (a) the ratio of L_1 and L_2 while the switch off and (b) L_3 while the switch on.

the variation of L_4 has little effect on the transmission zero at the high stopband, as presented in Fig. 6.

In this design method, we should at first get the initial sizes of CSRR and HMSIW. Then, we can get the key parameters L_1, L_2 and L_3 from Fig. 5 to select the center frequencies. When $L_1 = 1.6\,\mathrm{mm}$, $L_2 = 0.7\,\mathrm{mm}$, $L_3 = 1\,\mathrm{mm}$, the center frequencies of the filter are set to be 3.6 GHz and 4.5 GHz, respectively. The parameter L_4 is mainly used to locate the transmission zeros. Finally, better performance of the proposed filter can be obtained by optimizing each parameter.

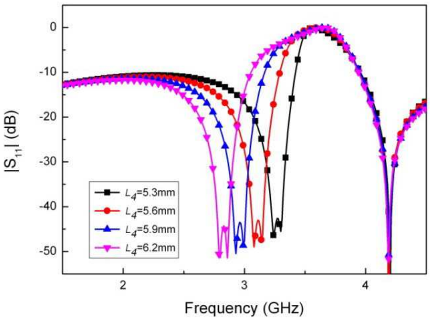


Figure 6. Simulated S_{11}-parameters for different values of L_4.

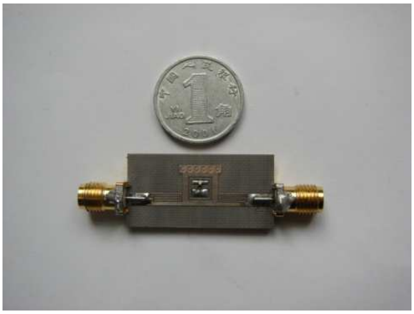


Figure 7. Photograph of the fabricated filter.

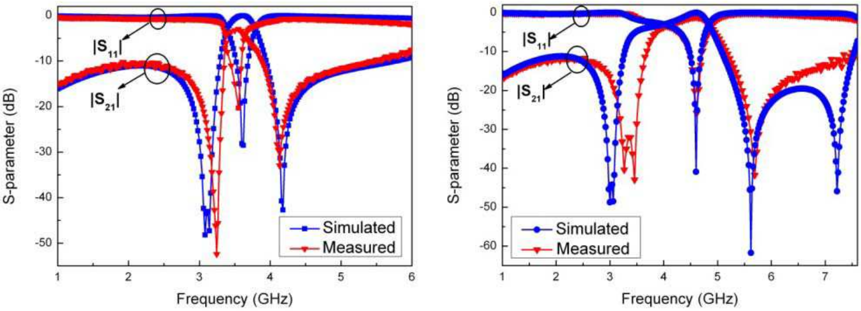
3. IMPLEMENTATION AND RESULT

The fabricated reconfigurable filter is shown in Fig. 7, which was processed using a single-layered printed circuit board, with a relative permittivity of 2.65, a loss tangent of 0.0035, and a thickness of 0.8 mm. The appropriate equivalent capacitances, C_{r1} and C_{r2} corresponding to Equation (1), are obtained by optimzing L_1, L_2 and L_3. All the dimensions of the filter are summarized in Table 1. The reconfigurable filter was measured with a vector network analyzer (Agilent N5230A), and its simulated and measured S-parameters are plotted in Fig. 8.

As a result of appropriate inner capacitance of the CSRR in Equation (1), its simulated center frequencies are 3.6 GHz and 4.5 GHz when the switch is cited "on" and "off" states, respectively. The transmission zero at low stopband is located at about 3.12 GHz, which is mainly contributed by the pseudo-S defected structure. The total length of the pseudo-S defected structure is 27.8 mm, which approximately corresponds to the quarter guided wavelength at the frequency of the newly introduced transmission zero. The measured

Table 1. Geometrical sizes of the filter (unit: mm).

Parameters	value	Parameters	value	Parameters	value
$a = b = c = g$	0.25	L	1.2	L_x	4.8
w	7.35	L_1	1.6	p	4.05
w_1	2.5	L_2	0.7	d	0.8
w_2	0.15	L_3	1	s	1.4
w_3	0.25	L_4	5.9		



(a) (b)

Figure 8. Results of the reconfigurable filter with switch (a) "on" and (b) "off".

in-band insertion and return losses are about 3.6 dB and below −17 dB, respectively. Slight differences between the measurement and simulation results are observed which would be attributed to tolerances in the component values and the fabrication process. The total area of the devices is only 30 mm ∗ 15 mm.

4. CONCLUSION

In this paper, a reconfigurable HMSIW bandpass filter with low insertion loss and compactness is proposed and constructed by using complementary split-ring resonator. A zero ohmic resistance on the inner CSRR is used to perform a switch, which on/off states complete tunability between two predicted frequencies. The two attractive frequencies are determined by inner capacitances of the CSRR in Equation (1). Moreover, the selectivity of this proposed filter is improved slightly by using pseudo-S defected structure. In addition, very compact size is achieved since no transition is needed. A sample reconfigurable HMSIW bandpass filter has been optimally designed, fabricated and measured. The measured result is slightly different from the simulated result, which may be caused by the reflections from the connectors and the finite substrate.

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