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Compact HMSIW Broadband Filter with Symmetrical CSRRs and Metallized Holes

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Abstract—A simple broadband and wide stopband half-mode substrate integrated waveguide (HMSIW) filter is proposed. Symmetrical complementary split ring resonators (CSRRs) and metallized holes are loaded on the surface of the HMSIW resonator. Metallized holes placed in the center of the CSRRs are used to create two passbands. CSRRs can reduce the return loss of the first passband, and a transmission zero is introduced to suppress the performance of the second passband, thus generating broadband covering the entire X-band. The simulated results show that the center frequency and fractional bandwidth of the filter are 9.26 GHz and 60.7%. There is a transmission zero at 13.18 GHz, and the insertion loss in the range of 12.30 to 21.46 GHz is better than −10 dB, which means that the out-of-band suppression performance is good. The measured results are in good agreement with the simulated ones. This new combination not only obtains broadband frequency, but also makes the filter more compact. The filter has some practical and application significance.

1. INTRODUCTION

Filters have always been an indispensable part in microwave and millimeter wave systems, and their performance affects the communication quality of the whole system. Typically, broadband filters can be obtained by cascading low-pass filters and band-pass filters, designed using spiral transmission lines [1] or folded multimode resonators [2]. However, these structures have some defects, such as poor out of band suppression, large insertion loss of the passband and large size. As a new method of transmission, the SIW looks like two parallel fences that have a specific spacing in which EM waves are well confined. The position and size of the holes in the SIW resonator can affect performance. The dimension of the HMSIW is half of the SIW. The performance of the waveguide is basically kept unchanged, and the filter size can be reduced effectively.

A broadband filter can be obtained by loading a variety of structures on the HMSIW. High selectivity, good resistance band and small volume can be achieved by combining HMSIW with electromagnetic bandgap or electric source-load electric cross-coupling configuration in [3], but the bandwidth is too narrow. In [4], a filter is obtained by integrating a ridge into HMSIW. A novel ridged HMSIW filter with a lower cutoff frequency and a more compact size is proposed in [5]. The bandwidth and frequency of the transmission zero can be tuned by changing parameters of the embedded metal strip and inductive window. The CSRR is applied to realize a compact UWB bandpass filter based on HMSIW in [6]. Sharpened rejection skirts and widened upper stopband are achieved due to the proposed CSRR. The defected ground structure (DGS) [7], as a resonator on the metal ground, can produce two transmission zeros, aiming to improve the frequency selectivity and extend the upper stopband. Combining the HMSIW with periodic DGS, the broadband bandpass filters with compact size can be realized in [8] and [9]. A wideband SW-HMSIW BPF was fabricated on a double-layer

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printed circuit board (PCB) by etching a U-shape slot on the cavity, which can achieve a wide passband response and make the dimension of the filter much more compact. However, the double-layer technology is too demanding [10].

In this paper, symmetrical CSRRs and metallized holes are added to an original HMSIW, and this simple operation can get a broadband filter from 6.45 to 12.07 GHz without increasing the size. The model has the feasibility of applying to various microwave and millimeter wave devices.

2. ANALYSIS AND DESIGN OF FILTER

2.1. Analysis of Symmetric Metallized Holes

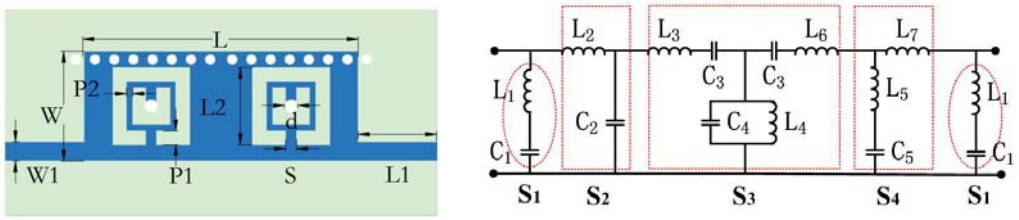
We loaded symmetrical metallized holes in the HMSIM resonator and then observe the effect of the hole diameter d on S_{11} parameters. As shown in Fig. 2(a), when d value decreases, the whole working frequency moves to the low frequency; the first working bandwidth increases; there is little change in the bandwidth of the second working band. In Fig. 2(b), when d value increases, S_{21} parameters move lower in the low frequency; there is little change in the high frequency; the out-band suppression increases. Size and shape affect the polarizability and susceptibility, thus affecting frequency and bandwidth.

For comprehensive consideration, $d = 1$ mm in this paper. When $d = 1$ mm, the filter resonates at 9.82 GHz and 17.74 GHz, and generates a transmission zero at 21.5 GHz to enhance out-band inhibition. It can be seen that the return losses of 9.46 to 10.18 GHz and 17.44 to 18.03 GHz are less than -10 dB, and the insertion loss at 21.5 GHz is -33.4 dB. The X-band refers to the radio wave band with frequency of 8–12 GHz. Therefore, the first working band should be widened, and the second working band should be suppressed.

2.2. Analysis of CSRRs and Design Procedure

Studies show that apoptosis waves exist in the following parts of waveguide operating frequency. These apoptosis waves are supposed to decay rapidly from the source of excitation and cannot be transmitted to the other end of the waveguide. Etching CSRRs on the surface of HMSIW resonator can amplify the apoptosis wave near the resonant frequency.

SRR shows negative permeability near the resonant frequency and becomes an important component of left-handed materials. CSRR is a complementary structure of SRR and strictly follows the duality principle, so CSRR shows negative permittivity near the resonant frequency. When the electric field of the incident electromagnetic wave is perpendicular to the plane of CSRR, it can be regarded as an LC resonator. Current flows on the metal surface, producing inductance effect, and a gap between the metal and the medium creates capacitance effect. CSRR will generate an electric resonance at the first resonance point and obtain equivalent mononegative dielectric constant media. When CSRR is used on the surface of the waveguide structure, due to its negative permittivity constant effect, phase mutation occurs. So insertion loss drops sharply, and signal propagation is inhibited, which can generate band resistance effect, then good out-band inhibition can be obtained. Traditional CSRR has only one resonant frequency, and narrow band limits its application. In order to obtain stronger harmonic suppression, multiple conventional CSRRs have to be introduced, which will lead to



(a) (b)

Figure 1. Surface structure and equivalent circuit of the proposed broadband HMSIW filter. (a) Surface structure, (b) equivalent circuit.

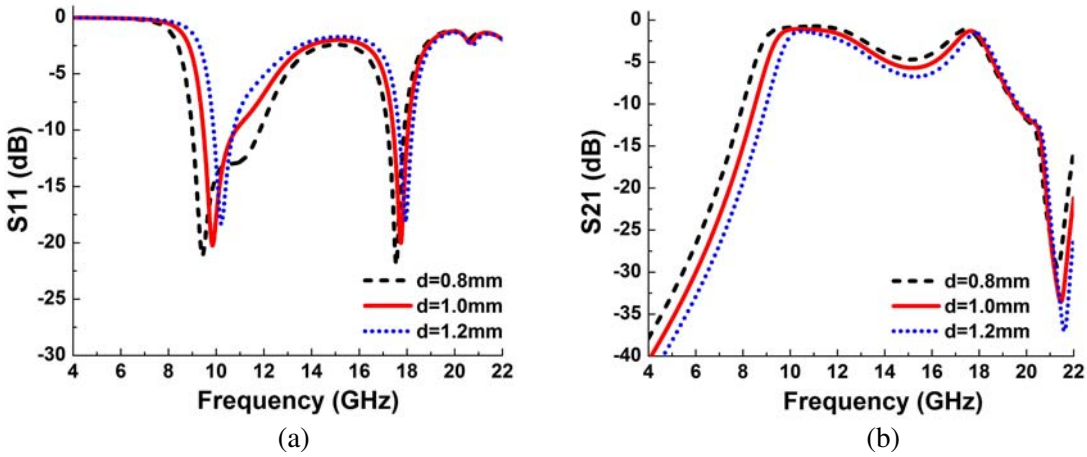


Figure 2. Simulated S-parameters of HMSIW for different d values. (a) S_{11} parameters, (b) S_{21} parameters.

the increase of filter size. So we etch CSRRs on the HMSIW surface and place symmetrical metallized holes in the center of them. The combination of CSRRs and metallized holes not only increases the bandwidth but also has wider and steeper resistance band, which can be used to suppress high harmonic and obtain better skirt edge response.

According to the above analysis, we place a metallized hole in the center of each CSRR, as shown in Fig. 1(a). The outer ring opening faces the magnetic wall, which is mainly reflected by magnetic field coupling, so the resonant frequency moves to the low frequency. As the distance between the opening of the outer ring and the magnetic wall increases, the frequency will move to the low frequency. The spacing P_2 between inner and outer rings is decreased. Increased mutual inductance between them leads to increased coupling, and the frequency will also be lower. This filter structure is modeled and simulated in HFSS software, and the equivalent circuit of the designed filter structure is shown in Fig. 1(b). The circuit is divided into S_1, S_2, S_3 and S_4. S_1 is the equivalent circuit of the transmission line for matching purposes. S_2 aims to generate a transmission zero at 13 GHz. S_3 is the equivalent circuit of CSRRs and metallized holes, and the purpose is to generate broadband. S_4 produces stopband. The capacitor and inductor values are as follows: $L_1 = 0.607$, $L_2 = 0.91$, $L_3 = 2.869$, $L_4 = 0.391$, $L_5 = 1.365$, $L_6 = 2.53$, $L_7 = 0.57$ (unit: nH). $C_1 = 0.136$, $C_2 = 0.455$, $C_3 = 0.14$, $C_4 = 0.90$, $C_5 = 0.101$ (unit: pF). We will use ADS to simulate the equivalent circuit, and the circuit results and HFSS simulated results are shown in Fig. 3.

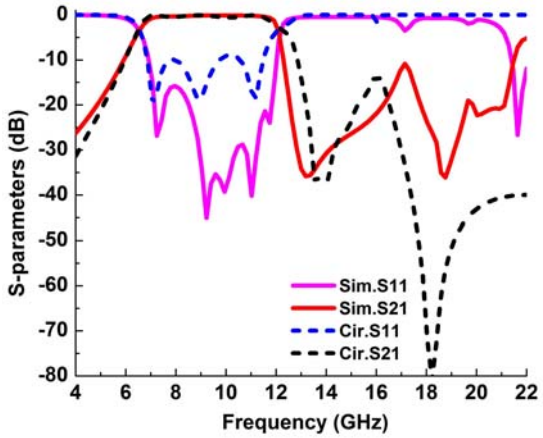


Figure 3. Comparison of circuit results by ADS and simulated results by HFSS.

The HFSS simulated results are compared with Fig. 2, and CSRRs amplify the apoptosis wave in the resonant cavity, extending the first passband. At the same time, a transmission zero at 13 GHz is introduced, which effectively inhibits the second passband. We can see that the insertion loss at 17 GHz is less than −10 dB. The circuit results are similar to simulated results, slightly different in high frequency, because circuit elements are idealized standard numeric elements without considering parasitic circuits. However for the patch elements that are restricted by electromagnetic wave propagation, the higher the frequency is, the more the existence of parasitic inductance capacitors cannot be ignored. So there are differences in performance.

According to the above analysis, we make the filter. The fabricated filter is shown in Fig. 4. It is fabricated on an RO5880 substrate ($\varepsilon_r = 2.2$, $\tan\delta = 0.0009$). The geometrical parameters are: $W = 8$, $W_1 = 1.4$, $W_2 = 2$, $L = 20$, $L_1 = 5.7$, $L_2 = 5.6$, $P_1 = 1$, $P_2 = 0.5$, $d = 1.0$ and $S = 0.8$ (unit: mm). The fabricated filter was measured by an Agilent 8722ES network analyzer.

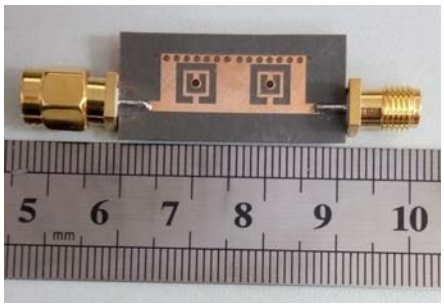


Figure 4. Photograph of the fabricated filter.

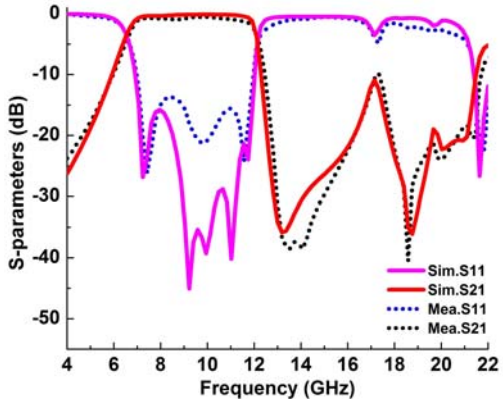


Figure 5. Measured and simulated results of the filter.

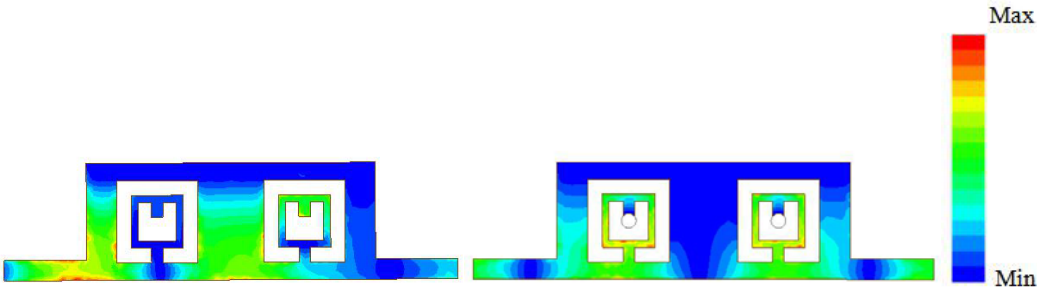


Figure 6. The surface electric field of CSRRs with (a) no holes, (b) symmetrical holes.

3. EXPERIMENT RESULTS AND DISCUSSION

As we can see, the measured results are basically consistent with the simulated ones in Fig. 5. From 6.45 to 12.07 GHz, the return loss is all below −13 dB, the center frequency 9.26 GHz, and the 3 dB fractional bandwidth 60.7%. The measured insertion loss of the passband is 1.2 dB, and the insertion loss at 13.18 GHz is less than −40 dB, which provides a good transmission zero. Although insertion loss at 17.14 GHz is −10.88 dB, this parameter in the range of 12.30–21.46 GHz is lower than −10 dB, which indicates that it has a certain out of band suppression capability. These data show that the proposed filter has broadband and wide stopband performance. There are some errors, which may be caused by

the welding defect of the SMA and microstrip feed line, especially when the frequency is greater than 5.0 GHz, and other factors such as imperfect calibration standard and fabrication error.

For holes not on the waveguide edge or angle, the power cord will pass through the hole and spread out near the hole. Metallized holes are used here to help reduce energy leaks, which not only help to enhance the coupling between CSRRs, but also improve the matching of the filter. As shown in Fig. 6, the electric field around CSRRs is enhanced with the addition of metallized holes.

Here, some comparisons are summarized in Table 1. The filter in [1] has 3.51–7.87 GHz bandwidth, but the stopband is too narrow. The filter in [2] has 3.78–6.98 GHz bandwidth, but the size is much larger than the proposed filter, and there is the same defect in [7]. The filter size in [10] is smaller, but it has a narrow band of resistance, and the production is more complicated. In summary, the proposed filter has the best performance.

Table 1. Comparison of the proposed filter with some references.

Ref.	Freq (GHz)	FBW (%)	Size ($\lambda_g \times \lambda_g$)	Type	Stopband (GHz)
[1]	5.7	72.6	0.30×0.16	Spiral transmission line	8.7–14.1
[2]	5.3	60.0	0.67×0.39	Folded multiple-mode	7.2–13.7
[7]	8.98	47.4	1.17×0.69	SIW-DGS	11.8–13.3
[10]	8.32	58.1	1.01×0.32	HMSIW with U-slotted	11.2–14.0
This work	9.26	60.7	0.96×0.46	HMSIW-CSRRs and metallized holes	12.3–21.5

4. CONCLUSION

An approach to get a broadband HMSIW filter covering the entire X-band by loading metallized holes and CSRRs is proposed. The holes are loaded in the center of CSRRs, and the bandwidth is widened. After simulation and optimization, a filter working from 6.45 to 12.07 GHz is obtained. The band suppression is up to -40 dB and the suppression bandwidth up to 10 GHz. The insertion loss is -10.88 dB at 17.14 GHz. If the insertion loss is reduced here, the stopband performance will be enhanced, but other performances will be sacrificed. This method of loading the metallized holes does not increase the size of the original HMSIW filter. Such a compact broadband HMSIW filter with a wide impedance band has good performance, and it is feasible in engineering.

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