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Design of Compact Bandpass Filters Using Sixteenth Mode and Thirty-Second Mode SIW Cavities

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Abstract—This paper presents two novel bandpass filters using sixteenth mode substrate integrated waveguide (SMSIW) and thirty-second mode SIW (TMSIW) cavities, respectively. The overall size of SMSIW and TMSIW cavities can be reduced by a factor of 15/16 and 31/32 in comparison to the filters designed in the conventional SIW resonator, while keeping almost the same resonant frequency. Based on SMSIW cavity, a first-order filter with the center frequency of 2.45 GHz and a transmission zero (TZ) located at the upper-stopband is proposed. The second-order TMSIW cavity filter exhibits one TZ at the lower-stopband and two TZs at the upper-stopband, and it has a better performance of the passband than the former with the same size and center frequency. It also has a wider upper-stopband with suppression of an unwanted harmonic at 7.6 GHz. Two intersecting rectangular slots are etched between the two cavities with a smaller angle between them of 30 degrees. The whole size of the filter is 24.2 mm × 29.1 mm × 0.508 mm. The filters are fabricated in SIW technology, and the frequency response shows good agreement between simulated and measured results.

1. INTRODUCTION

With the rapid development of wireless communication systems, the demand for filters with compact size, good stopband, low cost and high-performance has been increasing over the last few decades. SIW cavity resonators with low loss, compact size, high Q-factor and easy integration have become a hot research in the current wireless communication system [1–3]. However, for low frequency microwave components, the size of SIW filter is still too large. In order to reduce the size of the circuit, miniaturization techniques need to be investigated, while maintaining good performance characteristics of SIW. Several structures have been proposed by cutting SIW resonators on their fictitious magnetic walls to achieve half mode SIW (HMSIW), quarter mode SIW (QMSIW), eighth mode SIW (EMSIW), or even sixteenth mode SIW (SMSIW) with the improvement of size reduction. Among them, the size of SMSIW decreases dramatically about 93.75%. In [4], a new type of HMSIW periodically loaded with different lumped elements and structures was proposed [5] which presented a systematic investigation of SIW filters from a thorough analysis of the quarter-mode SIW cavity. In [6], a dual-band bandpass filter using EMSIW resonators was proposed. A novel sixteenth-mode substrate integrated waveguide (SMSIW) bandpass filter loaded with complementary split-ring resonator (CSRR) was introduced in [7].

In this paper, two compact bandpass filters with the same size and center frequency using SMSIW cavity and TMSIW cavity are proposed. The former is a first-order filter, while the latter is a second-order filter, where two metallized via-holes are implemented on both filters. Two intersecting rectangular slots are etched on the TMSIW cavity. The dominant resonant mode of the proposed resonator is TM_{010} mode. Both bandpass filters are analyzed and designed using full-wave EM simulator software (Ansys HFSS). The filter prototypes are fabricated on a Rogers RT/Duroid 5880 substrate using the standard PCB process, and good agreements are achieved between simulated and measured results.

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2. FILTER DESIGN

2.1. SMSIW and TMSIW Cavities

The electric field distributions in the conventional SIW, HMSIW, QMSIW, EMSIW, SMSIW and TMSIW cavities at the dominant TM_{010} mode are shown in Fig. 1. As shown in Fig. 1(a), symmetrical planes A-A1, B-B1, C-C1, D-D1 of the circular SIW cavity can be regarded as perfect magnetic walls. The HMSIW can be realized by cutting the SIW cavity along A-A1, as shown in Fig. 1(b), whose size is half of the size of the SIW. The QMSIW is further obtained by bisecting the HMSIW cavity along B-O (Fig. 1 (c)). The EMSIW is generated by cutting along fictitious magnetic wall C-O of the QMSIW cavity, as shown in Fig. 1(d). Then ESMSIW and SMSIW are realized by cutting the previous SIW along E-O and F-O. Finally, TMSIW is produced by cutting the cavity along O-G as shown in Fig. 1(f). It is pointed out that the overall size of these cavities can be reduced compared to the conventional SIW resonator, while keeping almost the same resonant frequency. Among them, SMSIW cavity and TMSIW cavity can be reduced by a factor of 15/16 and 31/32.

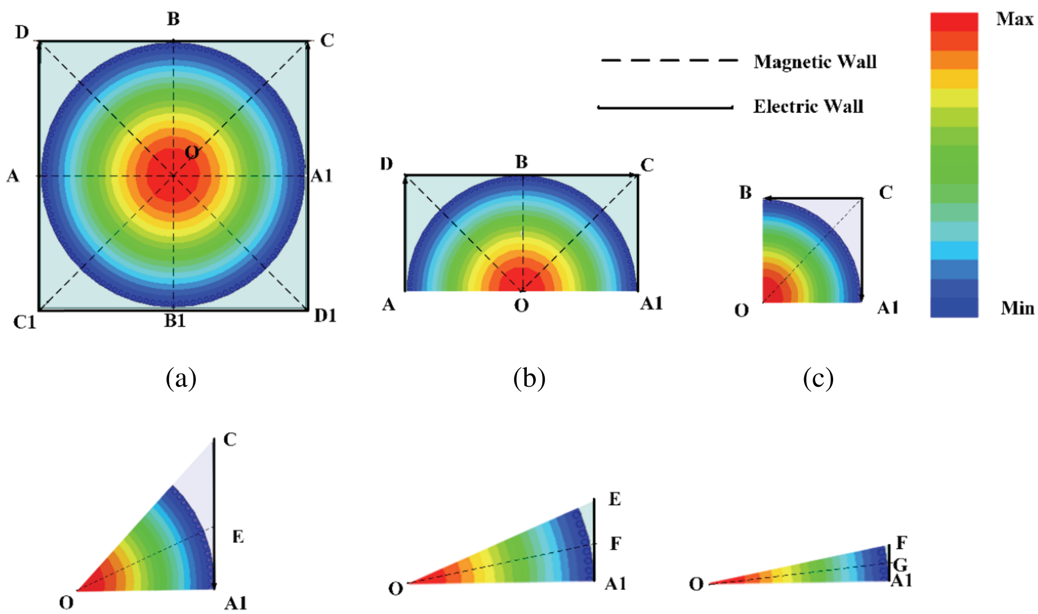


Figure 1. Electric field distributions of (a) full-mode SIW, (b) HMSIW, (c) QMSIW, (d) EMSIW, (e) SMSIW, (f) TMSIW.

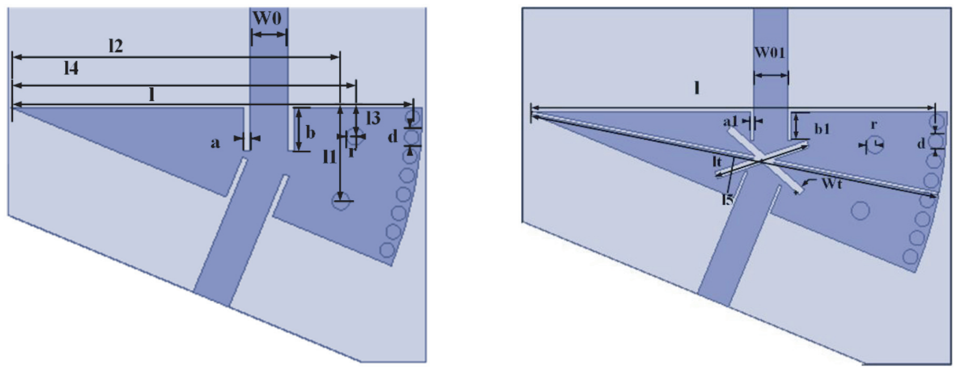
The resonant frequency of the dominant mode TM_{010} is calculated by Eq. (1) [8] as follows:

$$f = \frac{c \times 2.405}{\sqrt{\mu_r \times \varepsilon_r} \times 2 \times \pi \times R_{eff}} \tag{1}$$

where R_{eff} is the equivalent radius of the circular SIW cavity, and μ_r and ε_r are the permeability and relative dielectric constant, respectively.

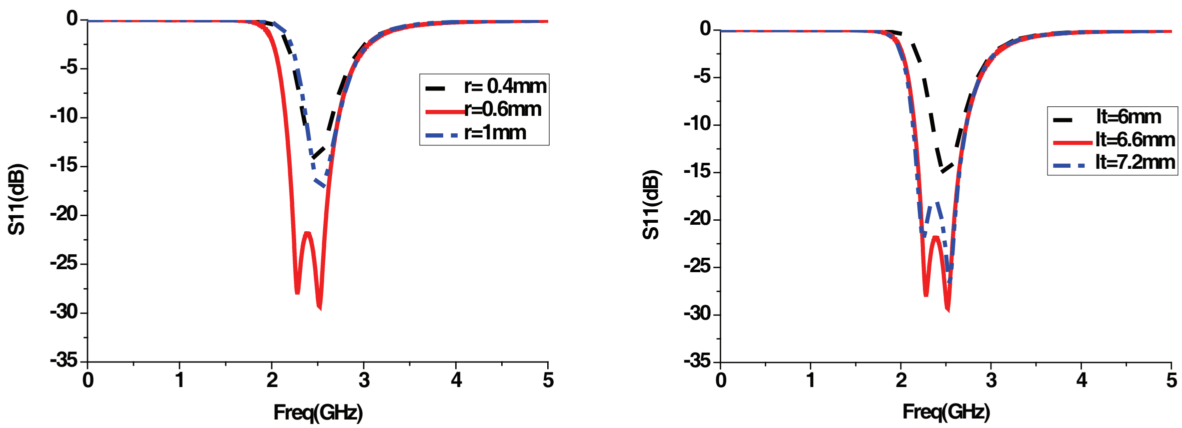
2.2. Design Procedure

Figure 2(a) shows the first-order filter (filter I) using SMSIW, where the filter is connected to two 50 Ω microstrip lines through a pair of coplanar waveguides. In order to compare, the second-order TMSIW filter (filter II) is also shown in Fig. 2(b). Two metallic vias are used to perturb the field distribution to increase the passband return loss, and the desired return loss can be obtained by suitably adjusting the size and position of the vias. Fig. 3 shows the simulated S-parameters for different r and lt. The radius r of the via is selected to improve the return loss of the second-order filter. As shown in Fig. 3(a), it can be seen that the metallized via-hole of the second-order filter affects return loss greatly. Fig. 3(b)



(a) (b)

Figure 2. Configuration of the proposed. (a) SMSIW filter, (b) TMSIW filter.



(a) (b)

Figure 3. Simulated S-parameters of the second-order filter for different (a) r values, and (b) lt values. (a) $lt = 6.6\,\text{mm}$, (b) $r = 0.6\,\text{mm}$.

demonstrates that the length of the rectangular slot also improves return loss. Therefore, an appropriate return loss can be reached by adjusting the metallized via-hole and the rectangular slot. Simulated S-parameters of the two filters are shown for comparison in Fig. 4. As shown in Fig. 4(a), obviously, filter I obtains a TZ at the upper stopband, but it possesses poor stopband performance because undesired spurious response is excited at 7.6 GHz. In order to extend the stopband region, a second-order TMSIW filter is proposed as shown in Fig. 2(b). Its whole size is the same as that of filter I. Two intersecting rectangular slots are etched between the two cavities. Wide stopband appears since one transmission zero is generated due to coupling between two cavities, where the angle between the two slots is 30°. In the presence of rectangular slots, two TMSIW cavities are coupled to each other, while the slit between the two cavities in the TMSIW filter is introduced to create two cavities. From Fig. 4(a), it is found that filter II obtains two TZs at the upper stopband and one TZ at the lower stopband. Hence, the out-of-band performance is greatly improved.

After the entire model is built, it is found that both lt and r have great impact on the return loss by scanning the two parameters within a range. The initial response is not very close to the desired without the need for optimization. A full-wave optimization is performed, and the final dimensions are attained. To obtain a desirable performance, all the parameters in Fig. 2 are optimized. The final dimensions of this filter are: $l = 28\,\text{mm}$, $W0 = 2.7\,\text{mm}$, $W01 = 2.3\,\text{mm}$, $d = 1\,\text{mm}$, $r = 0.6\,\text{mm}$, $a = 0.4\,\text{mm}$, $b = 3\,\text{mm}$, $a1 = 0.2\,\text{mm}$, $b1 = 2\,\text{mm}$, $Wt = 0.5\,\text{mm}$, $lt = 6.6\,\text{mm}$, $l1 = 6.5\,\text{mm}$, $l2 = 23\,\text{mm}$, $l3 = 2\,\text{mm}$, $l4 = 24\,\text{mm}$, $l5 = 28.7\,\text{mm}$.

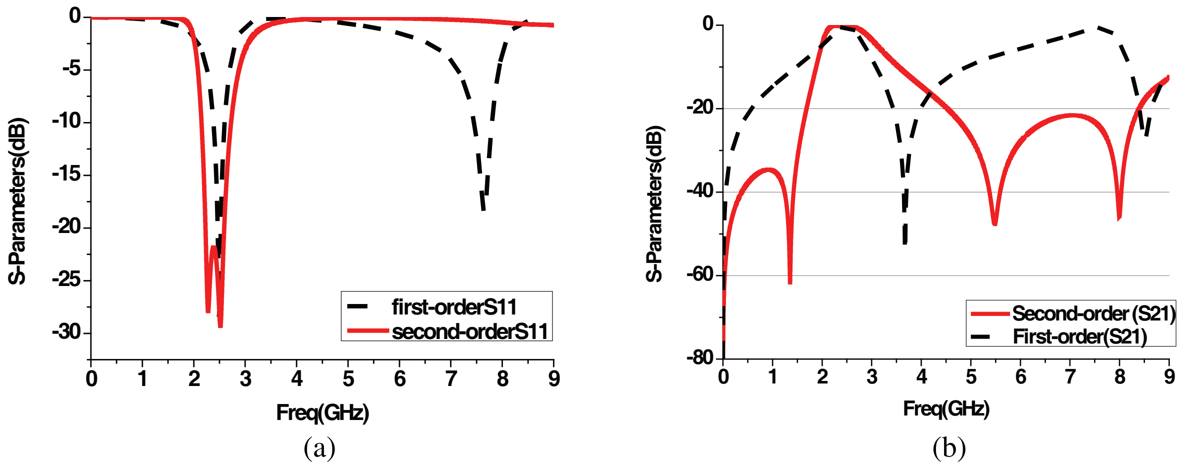


Figure 4. Comparison of S-parameters between filter I and filter II. (a) S_{11} and (b) S_{21}.

3. RESULTS AND DISCUSSION

Based on the above analysis, two compact bandpass SMSIW and TMSIW filters, respectively, are designed. They are both fabricated on a substrate of Rogers RT/Duroid 5880 with relative permittivity $\varepsilon_r = 2.2$, dielectric loss tangent $\tan\delta = 0.0009$, and thickness 0.508 mm. An HP 8722ES vector network analyzer was used for the measurements, and the comparisons between HFSS simulations and measurements are shown in Fig. 5. It is clear that good agreement for the in-band and out-of-band frequency responses is achieved except slight deviations due to processing and testing errors. As we can see from Fig. 5(a), the measured minimum insertion loss for filter I is approximately 0.38 dB with the center frequency of 2.45 GHz, whereas its return loss is better than 26 dB. As seen from Fig. 5(b), filter II is centered at 2.45 GHz with insertion loss of 0.25 dB, and passband return loss is larger than 18 dB. Three TZs located at the lower and upper stopbands are found, resulting in a high selectivity. However, the measured locations of transmission zeros show discrepancy compared with the simulation result. The measured TZs are at 1.12 GHz, 5.01 GHz and 6.99 GHz, respectively, which are shifted higher than the simulated ones. The upward shift in the TZs is mainly from the uncertainty about the permittivity and thickness, which are not perfectly constant. Photographs of the manufactured filter which is based on the design of Fig. 2, are presented in Fig. 6. The whole size of the filters is

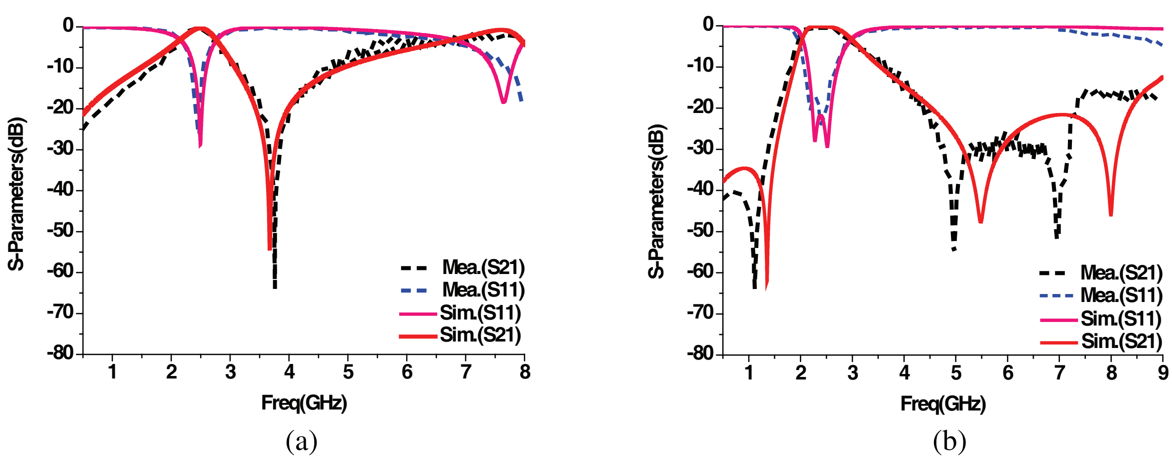
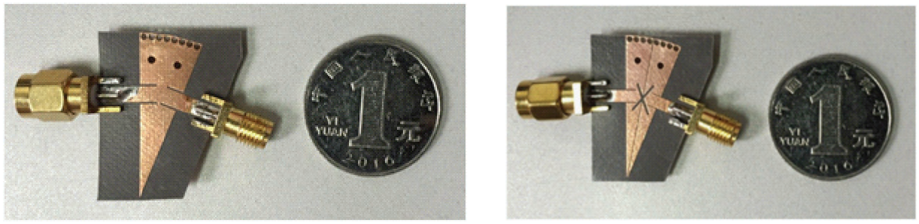


Figure 5. Simulated and measured frequency responses of the proposed (a) SMSIW filter, (b) TMSIW filter.



(a) (b)

Figure 6. Photograph of the fabricated filter. (a) SMSIW filter, (b) TMSIW filter.

approximately 24.2 mm × 29.1 mm × 0.508 mm.

Table 1 summarizes comparison between the proposed filters and other reported HMSIW, QMSIW, EMSIW and SMSIW filters in literatures. Compared with the proposed first-order filter, filter II has a wider stopband, and the passband performance is better than filter I. Compared with the HMSIW filter reported in [9] and QMSIW and EMSIW filters in [10], the proposed second-order filter not only has a better return loss and insertion loss, but also provides a wider passband. Compared with the SMSIW filter in [7], the return loss of the proposed second-order filter is not good enough, but it has a wider passband and lower insertion loss. It can be found that the proposed second-order filter is better than the referenced ones in terms of stopband.

Table 1. Comparison with the references.

	Basic unit	f_0 (GHz)	IL (dB)	RL (dB)	BW (%)	Stopband (> 25 dB)	Size ($\lambda_g \times \lambda_g \times \lambda_g$)
[9]	HMSIW	4.5	1.44	16	11.1	$2.22 f_0$	0.46×0.20×0.011
[10]	QMSIW and EMSIW	11.21	1.6	15	24	$1.43 f_0$	0.30×0.19×0.022
[7]	SMSIW	2.45	0.9	20	8.2	$2.45 f_0$	0.23×0.10×0.006
This work	SMSIW	2.45	0.38	26	24.1	$1.63 f_0$	0.24×0.20×0.004
	TMSIW	2.45	0.25	18	36.7	$2.94 f_0$	

4. CONCLUSION

Two compact bandpass filters centered at the frequency of 2.45 GHz have been designed using SMSIW and TMSIW cavities. Both of them have good insertion loss. Compared to the SMSIW filter with only one TZ, the TMSIW filter obtains two TZs at the upper stopband and one TZ at the lower stopband, and it improves the performance of the out-of-band. The bandwidth of the TMSIW filter is also wider than the SMSIW filter. The SMSIW filter achieves 24.1% of bandwidth while the bandwidth of the TMSIW filter is 36.7%. The whole size of the filters is 24.2 mm × 29.1 mm × 0.508 mm. Both the simulated and measured results are presented and discussed. The characteristics of designing the proposed filters indicate their potential to be utilized in microwave planar circuits.

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