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High-Order Triple-Mode Half-Mode Filter and Dual-Band Diplexer

Xiu Guang Chen*, Guo Hui Li, Zhi Wei Shi, and Shuo Dan Feng

Abstract—In this paper, a novel high-order triple-mode half-mode bandpass filter using a single perturbed substrate integrated waveguide (SIW) cavity and a dual-band diplexer are presented. Circular shape metal via-holes are added in the middle of a square SIW cavity as perturbation. The perturbed TE101, TE102, and TE201 resonant modes of the SIW cubic cavity are used to design the proposed filters, which can be shifted to the desired frequency by adjusting the position and size of via-holes. The proposed method reduces the size of the filter, and the measured results indicate that the bandwidth is higher than previous literatures. The dual-band diplexer with a half-mode SIW (HMSIW) structure can be easily implemented based on the proposed BPF through a T-junction, which decreases the number of resonating elements. A triple-mode half-mode filter using a single perturbed SIW cavity with center frequency of 7.43 GHz is obtained. The designed filter and dual-band diplexer are fabricated and measured to validate the present approach.

1. INTRODUCTION

A ever-accelerated modern multi-functional and multi-standard wireless communication system demands advanced microwave and millimeter-wave multiband components. Substrate integrated waveguide (SIW), as an attractive technique with the merits of low cost, compactness, and high performance, has been widely applied to the design of bandpass filters (BPFs) and diplexers.

Recently, multimode filters and multiplexers have received significant research attention for their attractive characteristics including the reduction of resonating elements, good passband selectivity, and advanced asymmetrical elliptic or quasi-elliptic response [1]. To date, several SIW dual-mode and triple-mode filters have been realized using a single perturbed circular cavity [2]. However, in some cases, slot perturbation approach can be used to design dual-band filters to independently tune the center frequencies (CFs) of passbands with only a single SIW cavity [3] A triple-mode filter using TE101, TE102, and TE201 resonant modes in a square cavity was proposed [4]. The modes in a cavity may be coupled to each other by introducing perturbation into the cavity through a coupling element, such as a screw in a cylindrical cavity or cubic dielectric resonator [5], corner cut in a rectangular cavity, and additional patch or corner cut in a microstrip cavity.

In this paper, we propose a novel planar triple-mode filter using a high-order half-mode cavity consisting of a square SIW cavity using a simple perturbation in the middle of the structure. The filter is realized by cutting the triple-mode resonator along its symmetrical axis.

The size of the filter remains almost half of the triple-mode SIW resonator. The dominant mode (TE101) is separated into two degenerated modes (TE102 & TE201), while modes 4 and 5 (TE220 & TM220) are not excited.

Based on multimode resonators concept, the first high-order half-mode filter is presented. A triple-mode half-mode bandpass filter using a single perturbed substrate integrated waveguide (SIW) cavity and a dual-band diplexer are fabricated, measured, and analyzed.

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This paper is organized as follows. In Section 2, comprehensive analysis procedures for the design of a band-pass filter and dual-band diplexer are provided. Section 3 demonstrates the fabrication and measurement including SIW triple-mode filter and multimode diplexer, and summarizes the comparison between the design and typical filter, and Section 4 comes to concise conclusions.

2. ANALYSIS AND DESIGN OF TRIPLE-MODE HALF-MODE FILTER AND DUAL-BAND DIPLEXER

The E-fields of resonant modes of a SIW cubic cavity can be perturbed by introducing circular shape metal via-holes, and the modes can be excited simultaneously. Moreover, the modes can be shifted to the desired frequency by adjusting the size of perturbation via-holes, and a triple-mode half-mode filter and dual-band diplexer can be designed. The specifications of the filter and diplexer are prescribed as follows:

1) Filter: center frequency $f = 7.4\,\mathrm{Hz}$ with 3-dB fractional bandwidth (FBW) of $\Delta_{\mathrm{I}} = 12\%$.
2) diplexer: center frequencies $f_{\mathrm{I}} = 4.3\,\mathrm{Hz}$, $f_{\mathrm{II}} = 6.9\,\mathrm{Hz}$ and $f_{\mathrm{III}} = 5.3\,\mathrm{Hz}$, $f_{\mathrm{IV}} = 8.4\,\mathrm{Hz}$ with 3-dB FBWs of $\Delta_{\mathrm{I}} = 5\%$, $\Delta_{\mathrm{II}} = 3\%$ and $\Delta_{\mathrm{III}} = 4\%$, $\Delta_{\mathrm{IV}} = 4\%$, respectively.

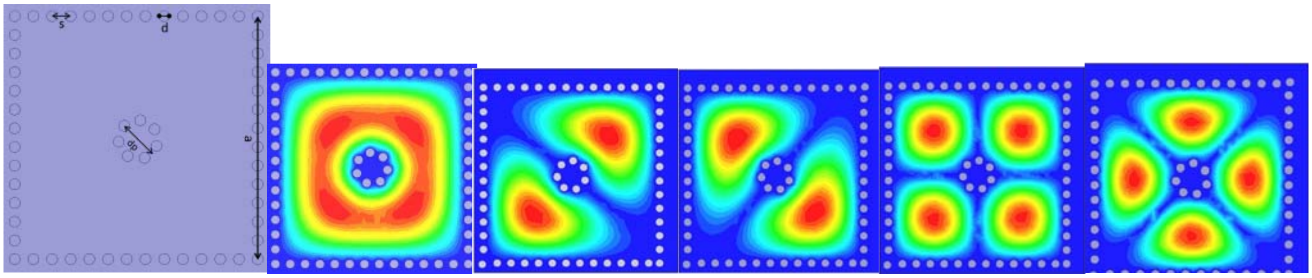
The filter and diplexer are fabricated on a Rogers RO5880 substrate with the relative dielectric constant $\varepsilon_r = 2.2$, thickness $h = 0.508\,\mathrm{mm}$, and $\tan\delta = 0.0009$. The diameter of via-holes and the center-to-center pitch are chosen as $dp = 5.54\,\mathrm{mm}$ and $d = 1.4\,\mathrm{mm}$. The simulations are based on Ansys Electromagnetics HFSS 15.0, while the measurements are executed by the Agilent N5227A vector network analyzer.

2.1. The Perturbed Cavity for Calculation of Resonant Frequencies

Several perturbation holes are added on the diagonal line of the SIW cavity to realize diagonal distribution modes. The geometry of the perturbed SIW cavity ($a = 30.7\,\mathrm{mm}$, $d = 1.4\,\mathrm{mm}$, $s = 2.4\,\mathrm{mm}$, and $dp = 5.54\,\mathrm{mm}$) is shown in Fig. 1(a). Metal via-holes arranged in a circle of radius dp are placed in the middle of the structure. Fig. 1(b) depicts the simulated E fields in the perturbed cavity at the resonant frequencies of the first five modes in the proposed cavity. The resonant frequencies of the empty cubic cavity (without perturbation) for the TEm0n modes are determined by

$$f_{m0n} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{a'}\right)^2 + \left(\frac{n}{a'}\right)^2} \tag{1}$$

where a' is the side length of the equivalent cavity, c the speed of light, and ε_r the relative dielectric constant. In the following, the effects of the metal perturbation diameter dp on the resonant frequencies are studied. The first three resonant modes of an empty cubic cavity (without perturbation) are TE101, TE102, and TE201. When the perturbation is introduced in the middle of the cavity, the electromagnetic



TE101 (Mode1) TE102 (Mode2) TE201 (Mode3) TE220 (Mode4) TM220 (Mode5)

(a) (b)

Figure 1. (a) Configuration of the perturbed SIW cavity and the filter. (b) Simulated E-fields of the first five resonant modes in the proposed cavity.

field of the original mode in the empty cavity is rapidly decreased or no longer exists. Meanwhile, the second-order resonant mode remains almost unchanged.

Resonant frequencies of modes 1, 2, and 3 are obtained by adjusting the radius of circular perturbation. The results obtained by eigenmode simulation are shown in Fig. 2. Owing to the symmetry of circular perturbation, the resonant frequencies of modes 2 and 3 are equal. The difference between the resonant frequencies of TE101 and TE102/TE201 modes becomes smaller when the diameter of the additional via increases. Therefore, a triple-mode half-mode filter can be created using proper size of the SIW cavity and additional single perturbation. The resonant frequencies of TE101 and TE102/TE201 modes of the empty cavity are $f_1 = 3.81$ and $f_2 = 6.03\,\mathrm{Hz}$, respectively. The frequency shift of mode TE101 is higher than that of mode TE102/TE201. As shown in Fig. 1(a), a perturbation in the middle of the square SIW cavity forces the resonant frequency of TE101 mode near that of TE102/TE201 modes. The resonant frequencies of modes 1 and 2/3 (f_1 and f_2) against dp are plotted in Fig. 2. It can be seen that f_1 increases rapidly, while f_2 varies smoothly. The main reason is that the effect of perturbation by the metal via-holes in the circle on mode 1 is greater than that on mode 2 metal. The simulated $|S_{21}|$ of filter validates this phenomenon. In addition, the electric field intensity of the dominant mode reaches its maximum at the center of the circular SIW cavity, while that of the other modes achieves minimum electric field. Then, a triple-mode SIW cavity resonator is created by adding circular metal via-holes at the center of a cubic dual-mode SIW cavity resonator.

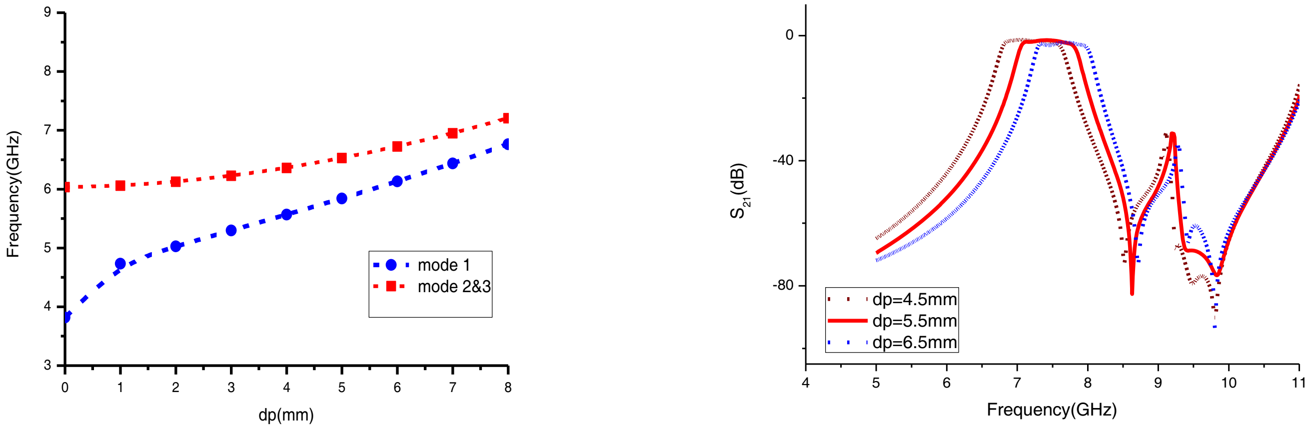


Figure 2. Resonant frequencies of mode 1, 2 and 3, and simulated $|S_{21}|$ of filter vs dp ($a = 30.7\,\mathrm{mm}$, $lp = 17.35\,\mathrm{mm}$).

2.2. Triple-Mode Half-Mode Filter

In order to design a triple-mode half-mode bandpass filter, perturbation is used to shift the frequency of dominant mode (TE101) close to that of the two degenerated modes (TE102 & TE201). The input and output ports are off centered, that is, metal via-holes arranged in a circle of radius dp/2 are placed at the center of the cavity. At the same time, high-order modecavities usually provide higher unloaded Q value and good tolerance for filter application [6].

Figure 3 shows the configuration of the high-order triple-mode half-mode bandpass filter. The inductive metal via windows between two cavities can be used to couple energy from one cavity to another. Return loss is optimized by choosing the proper coupling windows. Two $50\,\Omega$ microstrip lines through a pair of coplanar waveguides are adopted as input/output ports.

Figure 4 shows the coupling scheme of the proposed filter, where S and L in this scheme represent the source and load. Three modes in each resonator are adopted to couple with those in another resonator. For simplicity, only three couplings are considered by ignoring the minor couplings, for example: coupling between TE201 mode and TE102 mode. As shown in Fig. 4, three separate paths from source to load are provided. These three paths correspond to the three modes of the bandpass filter.

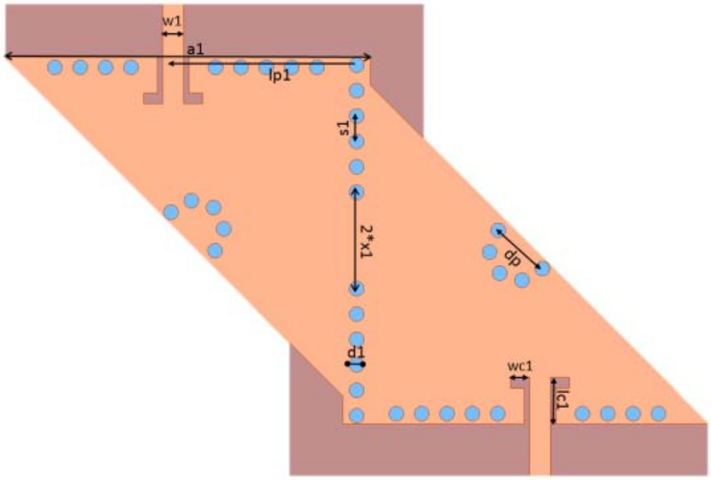


Figure 3. Structure of the proposed high-order triple-mode half-mode bandpass filter ($a = 30.7\,\mathrm{mm}$, $lp = 15.35\,\mathrm{mm}$).

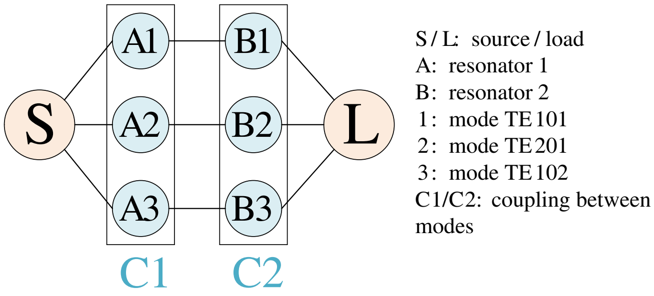
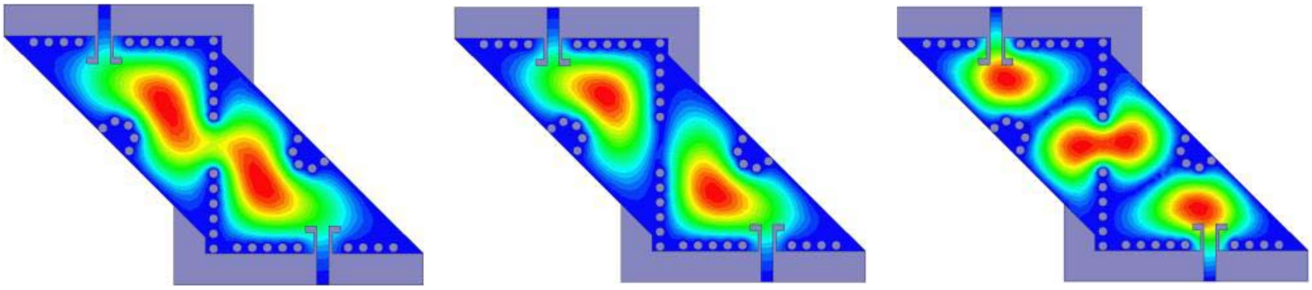


Figure 4. Coupling scheme of the triple-mode half-mode filter.



(a) Mode1 (b) Mode2 (c) Mode 3

Figure 5. Simulated E-fields of the first three resonant modes in the proposed cavity.

The electric field distributions of the dominant mode and two-similar degenerated modes are shown in Fig. 5(a), Fig. 5(b), and Fig. 5(c), respectively, which are named a, b and c, using the full-wave eigenmode analysis (HFSS). The perturbation of the metal vias arranged in circle can bring a most distinct change for mode1, while modes 2 and 3 are slightly perturbed.

The resonant frequencies of modes 1 and 2 (or 3) of the cavity are shown in Fig. 6 by full-wave electromagnetic simulations for $a = 30.7\,\mathrm{mm}$ and $\varepsilon_r = 2.2$. The design parameters are then synthesized and optimized as follows: $a = 30.7\,\mathrm{mm}$, $dp1 = 5.54\,\mathrm{mm}$, $lp1 = 17.45\,\mathrm{mm}$, $lp2 = 15.35\,\mathrm{mm}$, $lc1 = 4.4\,\mathrm{mm}$,

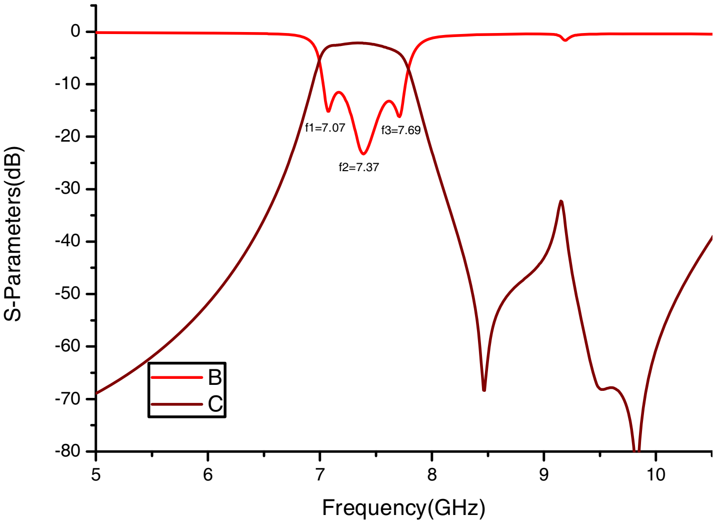


Figure 6. Simulated frequency responses of the SIW triple-mode half-mode bandpass filter.

$l2 = 1.8\,\text{mm}$, $d = 1.4\,\text{mm}$, $s = 2.4\,\text{mm}$, $h = 0.508\,\text{mm}$, $w1 = 1.5\,\text{mm}$, $l1 = 5\,\text{mm}$, $w2 = 1.5\,\text{mm}$, $l2 = 5\,\text{mm}$, $wc1 = 0.5\,\text{mm}$, $wc2 = 1\,\text{mm}$, $x1 = 4.1\,\text{mm}$, $x2 = 3.6\,\text{mm}$, $x3 = 3.48\,\text{mm}$, $l3 = 16.98\,\text{mm}$. As we can see from Fig. 6, for triple-mode half-mode bandpass filter, the simulation result shows that the center frequency and 3-dB FBW are 7.43 Hz and 12%, respectively.

2.3. Dual-Band Diplexer

Based on the design filter described in the previous section, the proposed structure for diplexer is shown in Fig. 7, which is composed of a lower dual-band filter, an upper dual-band filter, and a T-junction. The lower dual-band filter consists of two triple-mode half-mode cavities that are coupled with each

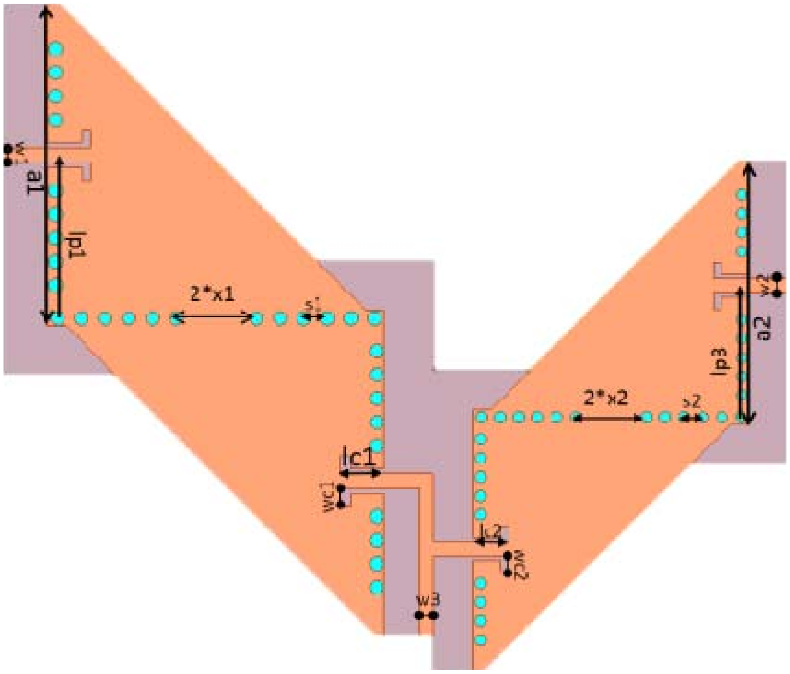


Figure 7. Structure of the proposed dual-band diplexer.

other through a SIW section. Actually, such a coupling structure is not the only possible option. Classical inductive coupling window can also function well when the square cavities become rectangle to force the two resonating nodes within the cavity to the desired external coupling quantity. Hence, a classical inductive coupling window is adopted for the upper channel filter. Compared with SIW, microstrip T-junction can acquire more compact size, easier design complexity, and better out-band performance, so it is usually employed by SIW diplexer. As stated previously, the proposed dual-band diplexer possesses the following advantages: 1) more compact and easier design, since bulky SIW T-junction is replaced by compact microstrip T-junction; 2) better isolation between the two channels because of the steeper rejection. The final optimized parameters of the diplexer are: $a = 30.7\,\text{mm}$, $dp1 = 5.54\,\text{mm}$, $lp1 = 17.45\,\text{mm}$, $lp2 = 15.35\,\text{mm}$, $l1 = 4.4\,\text{mm}$, $l2 = 1.8\,\text{mm}$, $d = 1.4\,\text{mm}$, $s = 2.4\,\text{mm}$, $h = 0.508\,\text{mm}$, $w1 = 1.5\,\text{mm}$, $l1 = 5\,\text{mm}$, $w2 = 1.5\,\text{mm}$, $l2 = 5\,\text{mm}$, $wc1 = 0.5\,\text{mm}$, $wc2 = 1\,\text{mm}$, $x1 = 4.1\,\text{mm}$, $x2 = 3.6\,\text{mm}$, $x3 = 3.48\,\text{mm}$, $l3 = 16.98\,\text{mm}$, $a1 = 24.56\,\text{mm}$, $l4 = 4\,\text{mm}$, $dp1 = 4.8\,\text{mm}$, $lp3 = 13.38\,\text{mm}$, $lp4 = 12.08\,\text{mm}$, $l3 = 3.61\,\text{mm}$, $l4 = 1.62\,\text{mm}$, $d1 = 1.12\,\text{mm}$, $s2 = 1.92\,\text{mm}$, $l5 = 4\,\text{mm}$, $wc3 = 0.4\,\text{mm}$, $wc4 = 0.8\,\text{mm}$, $l0 = 7\,\text{mm}$. Fig. 8 shows the specifications of the dual-band diplexer which are: CFs of $f_{\text{I}} = 4.3\,\text{Hz}$, $f_{\text{II}} = 6.9\,\text{Hz}$ and $f_{\text{III}} = 5.3\,\text{Hz}$, $f_{\text{IV}} = 8.4\,\text{Hz}$ with 3-dB FBWs of $\Delta_{\text{I}} = 5\%$, $\Delta_{\text{II}} = 3\%$ and $\Delta_{\text{III}} = 4\%$, $\Delta_{\text{IV}} = 4\%$. The simulated return losses are above 12 dB.

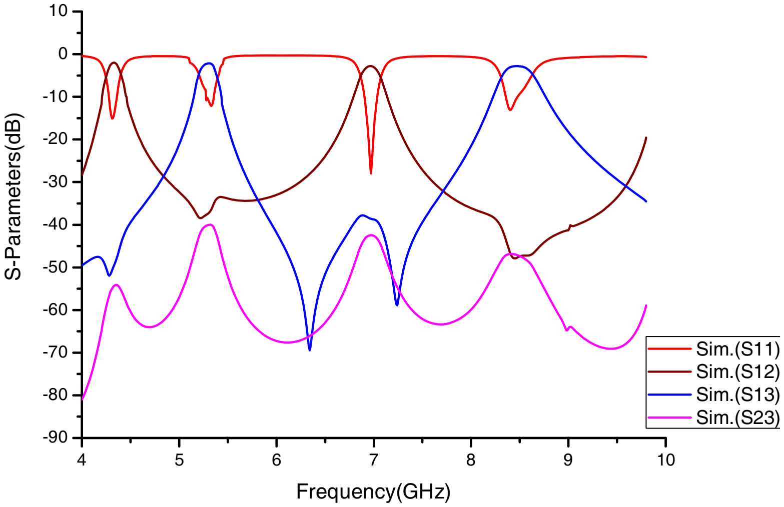
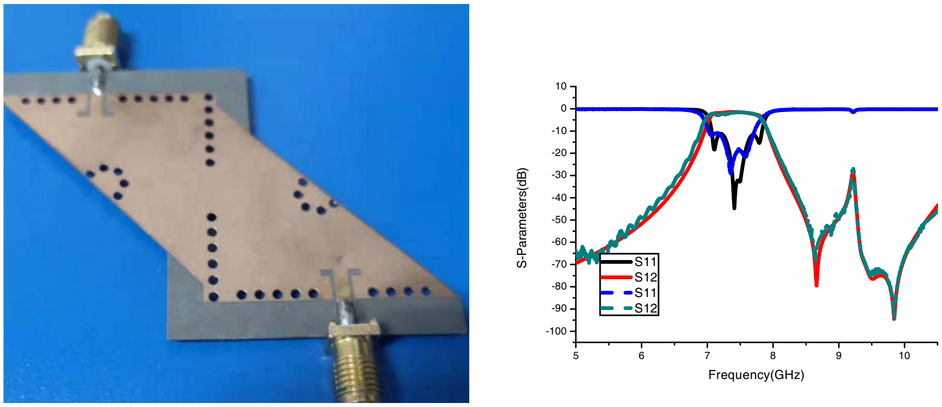


Figure 8. Simulated frequency responses of the proposed dual-band diplexer.

3. FABRICATION AND MEASUREMENT

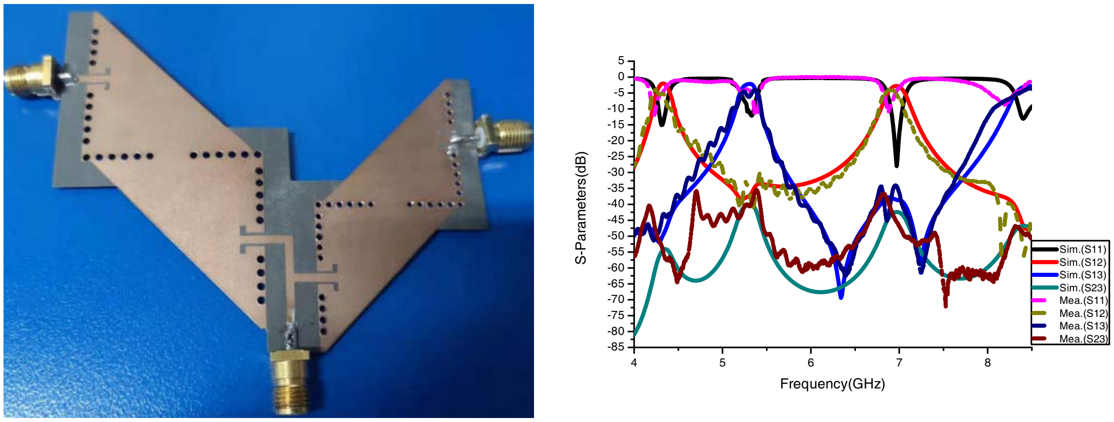
In order to verify the accuracy of the above analysis triple-mode half-mode bandpass filter using a single perturbed substrate integrated waveguide (SIW) cavity is fabricated, and the simulation and measurement results are depicted in Fig. 9. As we can see from Fig. 9(b), for the triple-mode half-mode bandpass filter, the measured results are in good agreement with the simulated ones. The measurement shows that the CF of filter is 7.43 Hz, and the 3-dB FBW is 13%. The measured minimum in-band insertion loss is nearly 1.8 dB, and passband return loss is better than 12 dB. It is also found that one transmission zero is located at 8.6 Hz above the passband, and the location of the transmission zeros can be controlled by changing the dimension of the slots, so the stopband rejection in the upper band of this filter is greatly improved.

For dual-band diplexer, the specifications of the diplexer are: CFs of $f_{\text{I}} = 4.3\,\text{Hz}$, $f_{\text{II}} = 6.9\,\text{Hz}$ and $f_{\text{III}} = 5.3\,\text{Hz}$, $f_{\text{IV}} = 8.2\,\text{Hz}$ with 3-dB FBWs of $\Delta_{\text{I}} = 5\%$, $\Delta_{\text{II}} = 3\%$ and $\Delta_{\text{III}} = 4\%$, $\Delta_{\text{IV}} = 4\%$. Fig. 10(a) shows its photograph. The measured return losses are above 12 dB. Moreover, the simulated and measured results agree well with each other. Despite high-order modes, the filter and diplexer are still very compact due to the folded structure with only two cavities. The total sizes of the filter and diplexer are $45\,\text{mm}\times 67.9\,\text{mm}\times 0.508\,\text{mm}$, $80.2\,\text{mm}\times 64.4\,\text{mm}\times 0.508\,\text{mm}$, respectively. The performance of the proposed BPFs is compared with previous works, as indicated in Table 1. The proposed work achieves the maximum bandwidth compared to those in [3, 7, 8], while keeping merits of low-insertion loss and compact circuit size.



(a) (b)

Figure 9. Photograph and comparison of the simulated and the measured results of the SIW triple-mode half-mode bandpass filter. (a) Photograph. (b) $|S_{11}|$ and $|S_{21}|$. Dimensions in mm: $a = 30.7$, $dp = 5.35$, $lp = 17.35$, $d = 1.4\,\mathrm{mm}$.



(a) (b)

Figure 10. Photograph and comparison of the simulated and the measured results of the dual-band diplexer. (a) Photograph. (b) $|S_{11}|$, $|S_{21}|$, $|S_{31}|$, and $|S_{23}|$. Dimensions in mm: $\mathrm{a}_1 = 30.7$, $\mathrm{dp}_1 = 5.54$, $\mathrm{lp}_1 = 16.55$, $\mathrm{d}_1 = 1.4$, $\mathrm{a}_2 = 24.56$, $\mathrm{dp}_2 = 4.8$, $\mathrm{lp}_2 = 13.38$, $\mathrm{d}_2 = 1.12$.

Table 1. Comparison between the proposed filter and the references.

	f (Hz)	IL (dB)	Bandwidth	Size (λ_g^2)
[3]	7.71	<1.9	6.2%	1.05*0.83
[7]	2.45	<1.0	8.2%	1.22*0.65
[8]	6.88	<2.0	10.0%	2.35*0.72
This work	7.37	<1.8	13%	1.67*1.10

4. CONCLUSION

In this paper, based on the mode-shifting technique, a triple-mode half-mode bandpass filter using a single perturbed SIW cavity and a multimode diplexer are presented. With the circular perturbation, the resonant frequency of the first mode of a SIW square cavity is shifted to near that of the second and third modes. A single-layer triple-mode SIW filter has been realized by this triple-mode cavity. The three center frequencies and bandwidths can be flexibly controlled by properly arranging the higher order harmonics of all cavities. In order to validate the simulation results, triple-mode half-mode bandpass filter using a single perturbed SIW cavity and multimode diplexer prototypes have been fabricated with standard PCB technology. All the simulated and measured results are in good agreement, demonstrating the feasibility of the proposed design method.

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