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High-Isolation Diplexer With High Frequency Selectivity Using Substrate Integrate Waveguide Dual-Mode Resonator

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ABSTRACT Two novel substrate integrated waveguide (SIW) high-isolation dual-mode diplexers based on electromagnetic perturbation technology have been presented in this paper. The capacitive perturbation and inductive perturbation have been introduced in the presented dual-mode diplexers. Furthermore, this perturbation can produce two transmission zeros in the real frequency axis, and those transmission zeros in the real frequency axis can improve the frequency selectivity of each channel of the diplexer and the isolation between two channels. Two different SIW dual-mode diplexers have been designed, fabricated, and measured. The measured insertion losses at each center frequency are 2.2 and 2.4 dB for the diplexer 1, 1.8, and 1.5 dB for the diplexer 2, with the fractional bandwidths of 1.95% and 2.08% for the diplexer 1 and 1.94% and 2.05% for the diplexer 2. The isolation is greater than 45 dB. Reasonable agreement between the simulated and measured results is achieved for the proposed dual-mode SIW diplexers.

INDEX TERMS Diplexer, high isolation, substrate integrated waveguide (SIW), high frequency selectivity, dual-mode resonator.

I. INTRODUCTION

The Diplexer is an important component of the electronic systems with single input and two completely different output frequency ports. It can be used to separate or merge the signals of different frequency bands. Good performance, including high isolation and low insert loss, as well as easy processing and compact size are the main concerns of microwave devices.

Diplexers with two independent filters connected to a common end through a T-junction are introduced in [1]–[8]. T-junctions in diplexers made by SIW are presented in [1]–[3]. Filters made by circular and elliptic cavities [1] and rectangle cavities [2] are presented. In [3], the filters are made by four corner cavities coupled using inductive irises. T-junctions made by microstrip [4]–[8] are consider as miniaturized, comparatively. With microstrip T-junction, various filters can be used in diplexers. Two second-order bandpass filters using dual-mode capacitance loaded square meander loop resonators are presented in [4]. Two sets of slotline stepped impedance resonators [5], are used as filters. In [6], the filters are independently designed using three-pole circular substrate integrated coaxial resonators. In [7], SIW and antipodal finlines are used as filters. In [8], dual-mode SIW filters, which are made by square cavity with via perturbation, are used in diplexer. The T-junctions made by quarter wavelength transmission line used in the diplexers mention above, both microstrip type and SIW type, cost large area in the diplexers.

In order to reduce the area of the connection part between two circuits with different frequency bands, a dual-mode resonator is used as the common end of the circuit [9]–[16]. The additional dual mode resonator makes the whole circuit increase an area of the resonator, but in fact it does not reduce the size of the common end much more compared to bended T-junction [6].

Multilayer SIW diplexers [9], [17]–[19] are also research hotspot, which at least contains three layers of dielectric substrates. The main difference between multilayer diplexer and single-layer is that the resonators and filters are distributed on

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different layers which connected and coupled through vertical holes in multilayer diplexer. Compared with single-layer diplexers, the overall area is reduced, but the insert loss is increased and manufacturing difficulty increased either.

In [20], complementary split-ring resonators etched on the SIW surface are used as filters, and a short section of microstrip insert the SIW are used as input port. The T-junction is made of a section of microstrip and two sections of SIW, which is smaller than quarter wavelength transmission line. Without considering the impedance of resonator and port, the insertion loss of the diplexer is too large.

Filters made by dual mode SIW are easy to design and fabricate. By virtue of additional perturbation vias [8], [10], [17], [21], [22], dual mode SIW filter are made. In order to enhance the perturbation strength, the triangular resonator [9] is made, based on two pole perturbation model. In [23], the filter characteristic is made by magnetic coupling between input port made by coplanar waveguide (CPW) and slots etched on the surface of SIW, and inductive perturbation caused by slots.

In this paper, the high-isolation diplexers have been designed by using the dual-mode SIW resonator. The dual-mode resonator, which resonate at two resonance frequencies, have been used in filters to reduce the number of resonators and reduce the size of filters. The two kinds of coupling-topology diplexers can be minimized with dual-mode resonator simultaneously. One of them is H-slot type circuit, and the other is horizontal slot type circuit. These type of filters occupy similar area in comparison with conventional two-pole SIW counterparts, but exhibits better frequency selectivity. Each of the two circuits can produce one transmission zero on both side of passband. It can achieve high selectivity and high isolation characteristics of diplexers. With the insertion T-junction, which reduce area of common end and increase isolation, the high isolation with high frequency selectivity diplexers are presented.

This paper is organized as follows. Section II describes characteristics of the SIW dual-mode resonator. Section III designs two kinds of the diplexers. Section IV gives the simulated results and measured results of the two diplexers. Section V is the conclusion.

II. CHARACTERISTICS OF THE SIW DUAL-MODE RESONATOR

Fig. 1 illustrates the electric distribution of the SIW dual-mode resonators. It can be seen that the electric field of the two degenerate modes are mutually orthogonal. There is no energy coupled between the two degenerate modes without perturbation and the resonant frequency does not split. The resonant frequency f_{m0n} of TE_{m0n} mode of the SIW resonator can be calculated by [24]:

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

where L and W are the length and width of the resonator, respectively. The dimension of resonator can be calculated by (1) that $L = W = 36.8$ mm where the permittivity $\varepsilon_r = 3.5$ and the resonant frequency is 5 GHz. By commercial electromagnetic simulation software HFSS, we can get the electric field distribution of two degenerate modes in 5 GHz which showed in Fig. 1.

The coupling topology of the dual-mode resonator, namely perturbation coupling topology, is shown in Fig.2. S and L are the source and load, respectively. Resonator 1 and resonator 2, represent TE_{102} (Odd mode) and TE_{201} (Even mode), respectively.

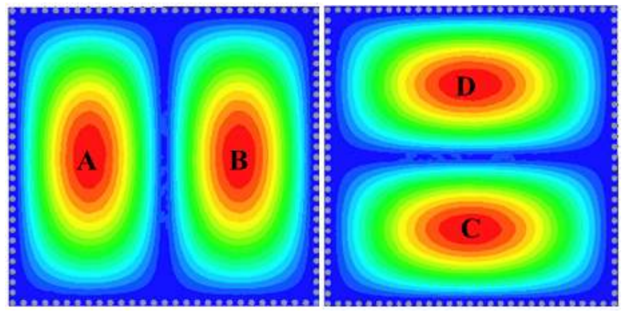

FIGURE 1. Electric filed distribution of the two degenerate modes of the SIW dual-mode resonator (a) TE_{102} mode, (b) TE_{201} mode.

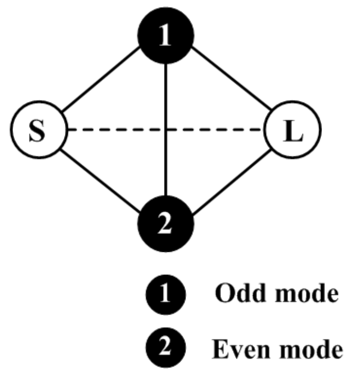

FIGURE 2. Coupling topology of the dual-mode resonator (perturbation coupling topology).

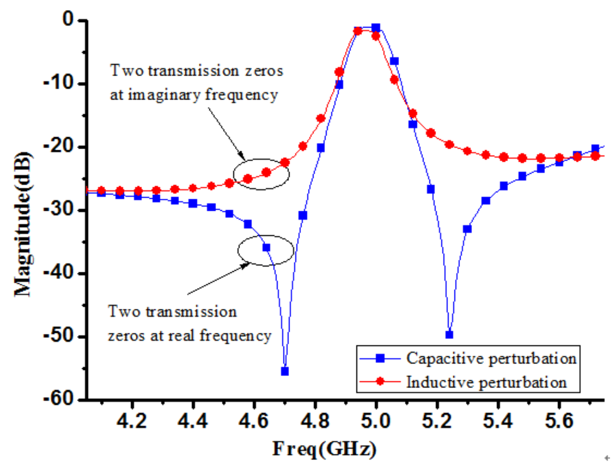

FIGURE 3. Frequency response of the perturbation coupling topologies of the dual-mode resonator.

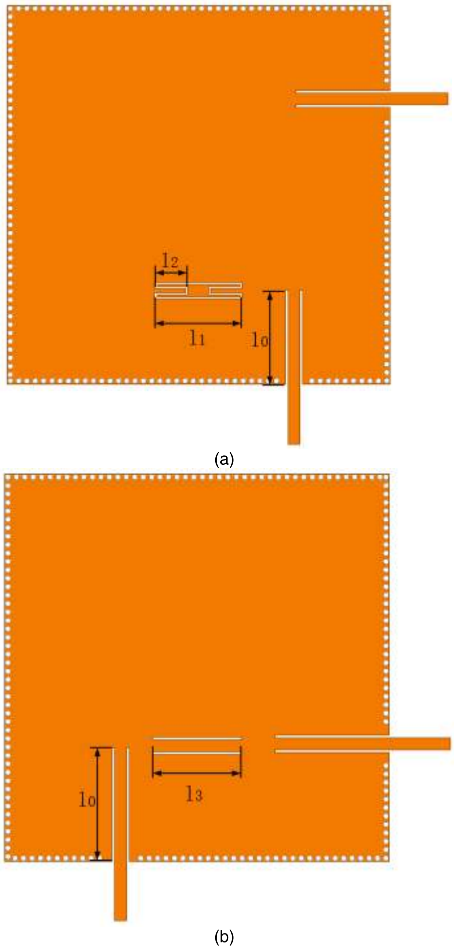

FIGURE 4. Two perturbation coupling circuits, (a) capacitive perturbation, (b) inductive perturbation.

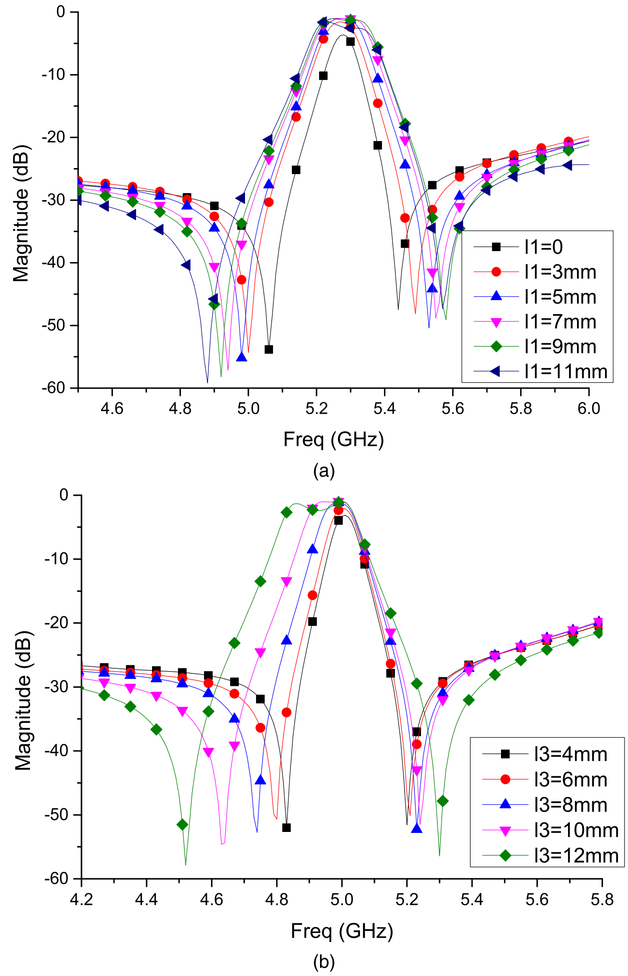

FIGURE 5. Passband frequency response with (a)l_1 and (b) l_3.

Fig. 2 shows the electromagnetic perturbation coupling topology, which can be used to separate the two degenerate modes. The odd-mode frequency can be changed by the perturbation and coupled with the even mode. There are two kinds of perturbation: one is capacitive perturbation, and the other is inductive perturbation. The two degenerate modes can be separated by both of them. However, the frequency response is different. The capacitive perturbation can produce two transmission zeros in the real frequency axis, while the inductive perturbation can produce two transmission zeros in the imaginary frequency axis, as shown in Fig. 3. In general, it is important for the filter design to generate the transmission zero in real frequency axis, which can improve the frequency selectivity of the passband.

$$M = \begin{bmatrix} 0 & M_{S1} & M_{S2} & M_{SL} \\ M_{S1} & M_{11} & M_{12} & M_{1L} \\ M_{S2} & M_{12} & M_{22} & M_{2L} \\ M_{SL} & M_{1L} & M_{2L} & 0 \end{bmatrix} \quad (2)$$

The perturbation coupling topology can be denoted by a coupling matrix where M_{S1} and M_{S2} are the coupling between source and resonator 1/resonator 2. M_{1L} and M_{2L} are the coupling between resonator1/resonator 2 and load. M_{12} is the coupling between resonator 1 and resonator 2, while M_{SL} is the coupling between source and load.

It can be seen from the above analysis that the two transmission zeros in real frequency axis can be obtained by using capacitive perturbation, which can improve the frequency selectivity of the passband. Fig. 4 shows two perturbation coupling circuits. A H-type slot is located on A or B of the electric field distribution (shown in Fig. 1), as shown in Fig. 4. According to the schematic diagram of electric field in the resonator, the H-type slot is placed in the place where the electric field is strongest, meanwhile the horizontal type slot is placed in the place where the magnetic field is strongest. It is obvious that the H-type slot in this case is a capacitive perturbation and can change the electric distribution of TE_{102} mode (odd mode) and has less impact on TE_{201} mode (even mode). If the position of the two structures is exchanged mutually, the perturbation of horizontal slot to odd mode is an inductive perturbation, as shown in Fig. 4. Two transmission zeros in imaginary frequency axis will generate, as shown in Fig. 3.

The passband width can be changed by adjusting the perturbation for the capacitive perturbation coupling circuit,

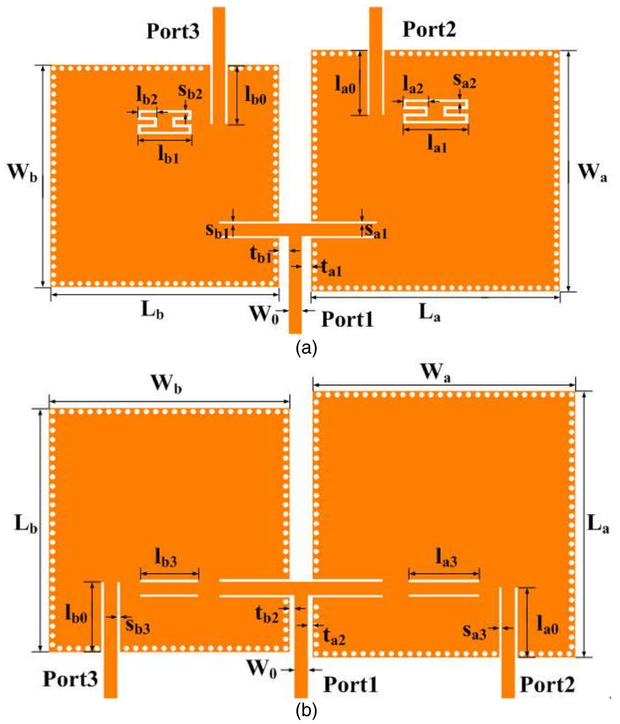

FIGURE 6. Two kinds of the diplexers (a) diplexer 1, (b) diplexer 2.

as shown in Fig. 4(a), the perturbation of TE_{102} mode will become large with increasing $l1$, and the coupling between odd mode and even mode will be great. Then, the passband width will become wide, as shown in Fig. 5(a). In the same way, the perturbation of TE201 mode will become large with increasing $l3$, and the coupling between odd mode and even mode will be great. The TZ will be change when the l1/l3 change.

III. SIW DUAL-MODE DIPLEXER

The diplexer is designed by using the above SIW dual-mode resonator. Two kinds of coupling circuits are employed to achieve the two passband diplexer. Two kinds of diplexer circuits are showed in Fig. 6. The diplexer 1 and the diplexer 2 are designed by capacitive perturbation and inductive perturbation, respectively. One diplexer includes two different channel filters (namely the low-bandpass filter and the high-passband filter), each channel filter is realized by using the dual-mode SIW resonator, which is mainly decided by the resonator size. The two center frequencies (5GHz for the low-bandpass filter and 5.25 GHz for the high-passband filter) of the channel filter is different, so the two resonators for one diplexer have different sizes.

The center frequencies and relative bandwidth of the two passbands are 5/5.25 GHz and 1.94/2.05%, respectively. Fig. 7 illustrated the simulation results. To achieve high isolation between two channel filters, the out-of-band transmission zero of the low-passband filter has been designed at the center frequency of the high-passband filter, and vice versa. The high out-of-band suppression of each channel filter can

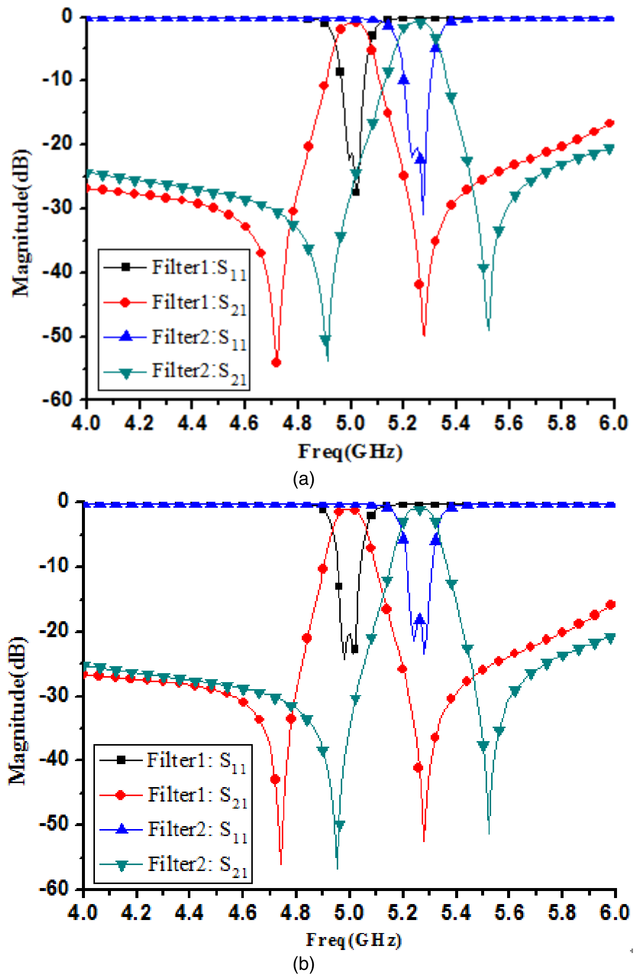

FIGURE 7. Simulation results of (a) diplexer 1, (b) diplexer 2.

be seen in Fig. 7. So high isolation can be easily get. The filters are designed by two kinds of the coupling circuits, which center frequency are 5 GHz and 5.25 GHz, respectively. Obviously, the passband has a transmission zero on the each side. It means the good frequency selectivity can be obtained for the SIW dual-mode bandpass filter.

The zero-degree feeding technologies are used to design the diplexer. If the group delay of the port1 GD(1,1) meets the following equation,

$$\begin{cases} GD(1,1)\big|_{f_1} = CH1\_GD(1,1)\big|_{f_1} \\ GD(1,1)\big|_{f_2} = CH2\_GD(1,1)\big|_{f_2} \end{cases} \quad (3)$$

the two passband filters can be designed independently, where CH1_GD(1, 1) and CH2_GD(1, 1) are the group delay of the two pass-bands. When equation (3) is met, the design of the diplexer can be simplified to the design of the passband filters. In addition, the flat group delay within the passband of the filter can be desired according to Equ.(3).

The design process of the diplexer is as follows:

Firstly, the external quality and the coupling coefficient of the two passbands are determined by coupling circuits, respectively. The dimension of resonator can be calculated

TABLE 1. The dimensions of diplexer (unit: mm)

parameter	value	parameter	value	parameter	value
W_0	1.11	S_{a2}	0.25	l_{b3}	7.4
W_a	18.2	t_{a1}	0.9	S_{b0}	0.25
L_a	18.4	t_{a2}	0.45	S_{b1}	0.25
l_{a0}	10.8	t_{a3}	0.65	S_{b2}	0.25
l_{a1}	7.8	W_b	17.3	t_{b1}	0.9
l_{a2}	3.4	L_b	17.5	t_{b2}	0.45
l_{a3}	7.6	l_{b0}	10.4	t_{b3}	0.65
S_{a0}	0.25	l_{b1}	7.6		
S_{a1}	0.25	l_{b2}	3.4		

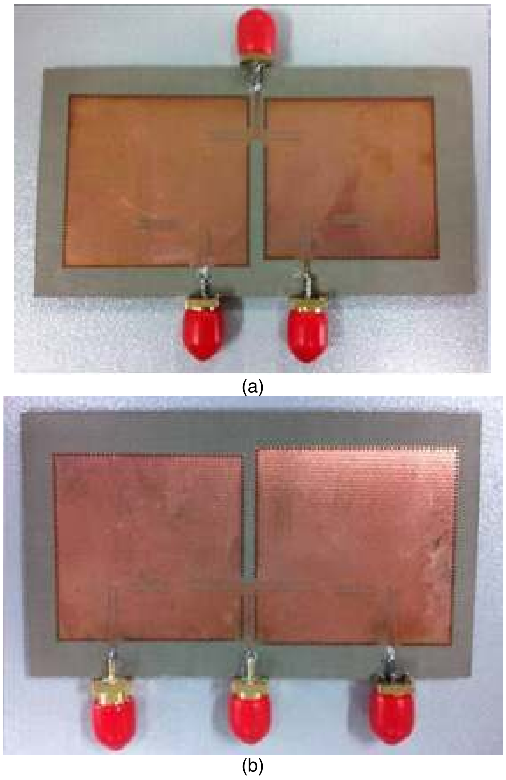

FIGURE 8. Two kinds of diplexers (a) diplexer 1 (b) diplexer 2.

by using (1), and the perturbation sizes can be determined according to the operating bandwidth of the channel filters.

Then, the two passbands are connected with a T-junction and combined into a diplexer, the T-junction can be obtained from (3);

Finally, the diplexer can be simulated and optimized by using the HFSS when the total circuit initial sizes of the diplexer are obtained according to above analysis and design.

The two branches of T-junction are inserted into the position where the electric field is strongest and the insertion length, which followed Equ.3, is adjusted to achieve the best impedance matching. The proposed T-junction structure still keeps the ability of divide electromagnetic field into two different resonators. In other words, this structure proposed in this paper has lower cost, more miniaturized size, more convenience, and better performance.

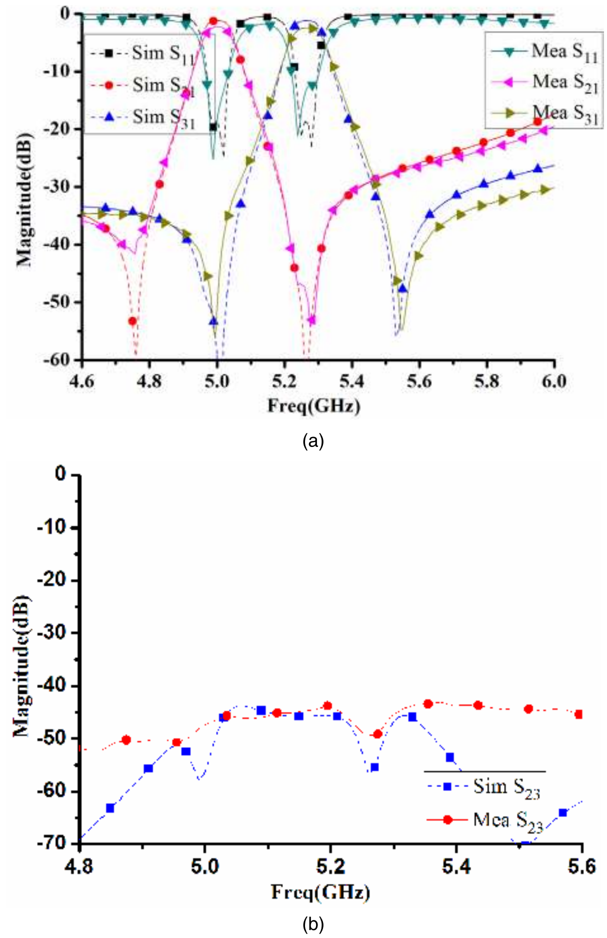

FIGURE 9. Simulated and measured results of the diplexer1 (a) insert loss and return loss (b) isolation.

IV. RESULT AND DISCUSSION

The presented two SIW dual-mode diplexers have been simulated and optimized by using HFSS. For the diplexer1, the external quality factors for the two channel filter are 51.2 and 48.1, respectively. For the diplexer2, the external quality factors for the two channel filter are 51.5 and 48.7, respectively. Table 1 gives the dimensions of the two diplexers. The fabricated diplexers are shown in Fig. 8, which are fabricated by using Taconic RF-35 with permittivity $\varepsilon_r = 3.5$ and thickness $H_s = 0.508$ mm. The dimensions of the two diplexers both are 37 mm×75 mm approximately ($1.02\lambda_g \times 2.08\lambda_g$, where λ_g is the guided-wave wavelength at center frequency of the first passband.).

The simulated and measured results of the diplexer1 are shown in Fig.9. The simulated and measured center frequency of the two passbands are 5 GHz and 5.25 GHz, while the simulated and measured return loss of the two passbands are both larger than 20 dB. The simulated insert loss of the two passbands are both less than 1.3 dB, and the measured

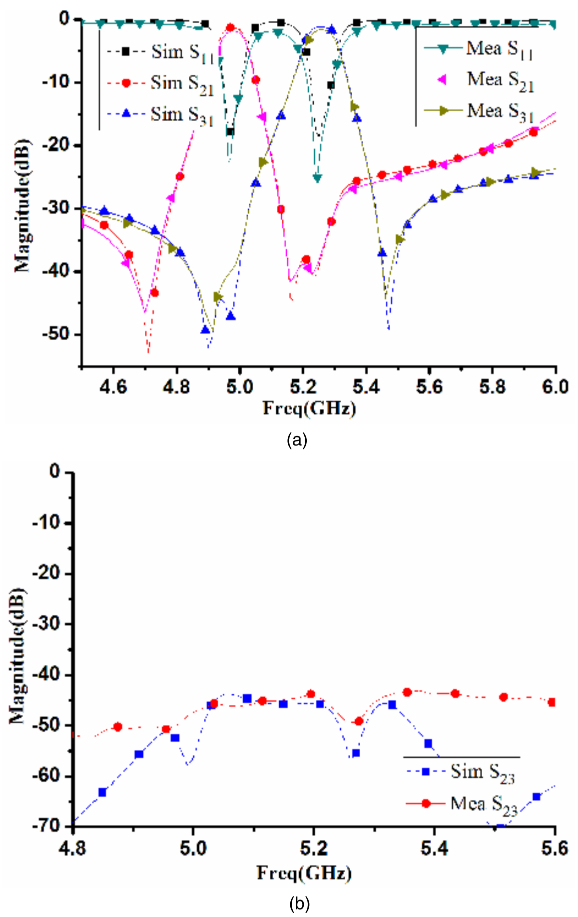

FIGURE 10. Simulated and measured results of the diplexer2 (a) insert loss and return loss (b) isolation.

insert loss of the two passbands are 2.2 dB and 2.4 dB. The simulated and measured isolation between two passbands are greater than 50 dB and 45 dB, respectively.

The simulated and measured results of the diplexer2 are shown in Fig.10. The simulated and measured center frequency of the two passbands are 5 GHz and 5.25 GHz, while the simulated and measured return loss of the two passbands are both larger than 20 dB. The simulated insert loss of the two passbands are less than 1.4 dB and 1.2 dB, and the measured insert loss of the two passbands are 1.8 dB and 1.5 dB. The simulated isolation between two passbands are larger than 50 dB and 45 dB, while the measured ones are larger than 50 dB and 40 dB. With the processing error, the measured results of both two kinds of diplexer didn‘t show two poles in each passband as simulated results. Fortunately, all the measured center frequencies are in good agreement with the simulation results.

The comparison between the proposed and the references are shown in Table 2. It is observed that the measured results agree well with the simulated ones, as shown in Fig. 9 and Fig. 10. The difference between the simulated and measured results is due to the fabrication errors, the measuring errors and the loss of the SMA connectors.

TABLE 2. Comparison between the proposed and the references.

Diplexer	f_0 (GHz)	FBW (%)	IL (dB)	Isolation (dB)	Size (λ_g^2)	NL
[1]	25/26	5.4/ 5.2	1.95/ 2.09	>40	5.8*5	1
[2]	20/21	2/1.9	2.75/ 3.05	>36.7	3*8	1
[6]	9.5/10. 5	3.2/ 2.8	1.6/ 2.1	>35	2.04* 0.65	1
[8]	25/26.8	2.8/ 1.8	1.7	>30	3*3	1
[9]	8/9	3.66/ 3.62	2.86/ 3.04	>40	1.66* 1.66	3
[10]	9.75/ 10.25	1/ 0.97	5/6	>30	1*3	1
[14]	12/14	4.9/ 5.65	1.34/ 1.4	>27	2.77* 2.77	1
[17]	10.5/11 .43	1.9/ 1.7	3.1/ 2.7	>35	1.38* 1.44	3
[19]	20/30	17/ 3.3	3.2/4	>30	0.9*0.5	5
Diplex er 1	5/5.25	1.95/ 2.08	2.2/ 2.4	>45	1.02* 2.08	1
Diplex er 2	5/5.25	1.94/ 2.05	1.8/ 1.5	>40	1.02* 2.08	1

f_0: Center Frequency, FBW: Fractional Bandwidth, IL: Insert Loss, NL: number of layers

Compared with the references, the proposed diplexers not only optimize the T-junction size to minimize the overall size, but also make the frequency selectivity superior to other diplexers which using square cavity with via perturbation, through H-type and horizontal type. Moreover, the proposed diplexers have higher isolation than the references.

V. CONCLUSION

In this paper, the dual-mode diplexers with high isolation are designed, fabricated and measured. Firstly, the two degenerate modes of the dual-mode resonator are analyzed. Then the perturbation coupling topology for the SIW dual-mode resonator is introduced. Two transmission zeroes on the two sides of the passband can be generated by this coupling structure, which can improve the frequency selectivity of the passband. Finally, two diplexers have been designed and fabricated by using the above dual-mode SIW resonator. The measured results agree well with the simulated results. The proposed technique should become a competitive candidate for the development of RF/microwave circuits and systems.

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