IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received August 29, 2020, accepted September 11, 2020, date of publication September 18, 2020, date of current version October 7, 2020.

*Digital Object Identifier 10.1109/ACCESS.2020.3024682*

# Design of Filtering Crossover and Diplexer on SIW Quadruple-Mode Resonators in a Single Cavity

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This work was supported in part by the Ministry of Science and Technology of China under Grant 2013YQ200503.

**ABSTRACT** This paper at first presents the proposal and design of a filtering crossover and diplexer with two second-order filtering channels on substrate integrated waveguide (SIW) quadruple-mode resonators (QMRs) and in single cavities. The proposed method has an interesting application in the overall size miniaturization design. The proposed resonator is yielded with four perturbed modes (TE103, TE104, TE201 and TE202) featuring distinct electric field distributions by inserting metal via-holes in the center of a rectangular SIW cavity. Next, a pair of resonances is applied to form a second-order filter channel while TE201 and TE202 modes are implemented to realize the other, thereby integrating the whole circuit in a single cavity. Besides, the transmission responses between the channels are isolated only by the perturbed via-holes. Slots are introduced in the metal surface to further increase each channel design flexibility. In this way, controllable frequencies and compact size have been well achieved. Two examples including a crossover and diplexer with two second-order filter channels are designed, fabricated, and measured to verify. Good agreement between simulation and measurement can be observed.

**INDEX TERMS** Crossover, diplexer, quadruple-mode resonator (QMR), single cavity, substrate integrated waveguide (SIW).

## I. INTRODUCTION

Microwave diplexers and crossovers with frequency selective become increasingly popular in modern multiservice wireless communications and multimode radar systems owing to their advantages of technology convergence [1]–[3]. The substrate integrated waveguide (SIW) technology featuring advantages of low cost, high quality factor and easy integration with planar circuits has been widely used in the designs of microwave devices [4]–[16]. Thus, lots of SIW passive devices have been proposed in the last few years [5]–[16].

Nevertheless, few works have been proposed to realize crossovers in SIW technology, which are able to make two bandpass filters (BPFs) and crossovers coexist in one system [6]–[8]. The most popular approach is to cascade multiple SIW cavities simultaneously to construct two multi-order BPF channels, and use dual-mode SIW cavities' modal orthogonality in the intersecting cavity to conduct crossovers, thus allowing two BPFs cross each other while remaining high isolation [6]–[8]. For instance, in [6], a planar crossover is composed of five identical dual-mode cavities for two triple-order BPF channels, and the TE102 and TE201 modes in the intersecting cavity are utilized for isolation. Moreover, to introduce additional characteristics, the cavities have been stacked according to different topologies [7], [8]. In [7], seven dual-mode SIW cavities are cascaded to realize a SIW crossover, and stacked in a non-planar structure to introduce common mode rejection characteristics. In [8], a six-channel crossover is presented based on six SIW dual-mode resonant cavities with controllable frequencies. However, since the realization of the SIW crossovers presented in these reports not only rely on the application of dual-mode SIW resonators, but are also limited by them conversely, the entire design processes focus on circuit implementation, but ignore their large-scale structures. Usually, multi-mode resonators (MMRs) have been extensively studied in the field of compact SIW devices owing to the more effective circuit reduction while maintaining design flexibility and performance improvement [9]. However, up to the authors' knowledge, crossover based on MMRs has been unexplored

The associate editor coordinating the review of this manuscript and approving it for publication was Feng Lin.

so far, and the main restricted factors lie in difficulty of isolation design among multiple resonance modes. Therefore, it's extremely challenging for the miniaturization of SIW crossovers. In this paper, for the first time, we propose a SIW crossover based on quadruple-mode resonator (QMR) technology overcoming all the problems. Meanwhile, benefiting from the proposed method, the whole circuit of the proposed crossover at first operates in a single cavity, thereby reducing the footprint extremely efficient.

In addition, as an indispensable part of the frequency selective devices for connecting two independent filters to a common end through a T-junction, diplexers have attracted much attention [9]–[15]. However, desirable diplexer performances are generated at the expense of expanded whole footprints, because two or more SIW cavities are still required to generate respective dual-, triple- or multi-order filtering channels. Based on microstrip T-junctions, the diplexers occupy two [9], three [10], four [11], five [12] and six [13] SIW cavities to meet the channel requirements. Common dual- and triple-mode SIW cavities act as T-junctions, as well as three [14], six [15] and seven [16] cavities are cascaded to realize respective channels. Although a three-state diplexer we have reported [17] using a triple-mode resonator in a single SIW cavity, it produces one-order filtering channel responses, which will be solved unless multiple cavities are cascaded. Thus, the improvement on the miniaturization design method is urgent to be solved. Except for the dual- and triple-mode resonators, QMRs are also investigated to minify circuit scales [18], [19]. However, no diplexers have been reported based on SIW QMRs, because the modes are difficult to isolate. In this paper, a diplexer is firstly reported using QMR technology. Moreover, it is also the first time that the diplexer with two second-order channels is integrated in a single SIW cavity.

In design, the key point is to produce four resonant modes in a SIW cavity with distinct electric field (E-field) distributions. To meet the requirements, metal via-holes' perturbation has been introduced in a conventional SIW rectangular cavity to obtain a novel QMR. By dividing four modes into two pairs, two second-order BPF channels are generated, and isolations between them are realized owing to orthogonal characteristics. In addition, flexible controllable frequencies are implemented by embedding two slots on the SIW top metal surface. Detailed analyses are presented in the following content. Section II conducts the investigation of the proposed method. Section III analyzes the resonance characteristics of the proposed QMR. Section IV demonstrates the comprehensive design procedures of the examples, including SIW crossover and diplexer. Section V is the conclusion.

## II. INVESTIGATION OF THE PROPOSED METHODOLOGY

The conventional crossover and diplexer working mechanisms are shown in Figure 1(a) and 1(b). Each circle represents a cavity, $k$ is on behalf of a cavity number ($k = 2, \ldots, n$), $T$ represents a T-junction, and 1 and 2 represent two resonant modes (Mode 1 and Mode 2). As shown

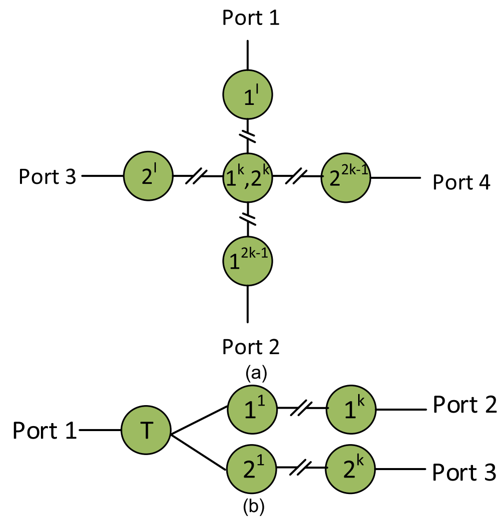


**FIGURE 1. Conventional working mechanisms of the SIW (a) crossover, (b) diplexer.**

in Figure 1(a), the input source, port 1, excites Mode 1, and couples Mode 1 to $2k$-1 cavities to port 2, thereby resulting in a multi-order BPF channel, while Mode 2 in $2k + 1$ SIW cavities would be coupled sequentially to support signal flow path from port 3 to port 4. The isolation between two channels depends on the intersecting cavity, $k$. In this way, a crossover can be well achieved. Meanwhile, Figure 1(b) illustrates the working concept of a diplexer. A common dual-mode SIW cavity is utilized as a T-junction for isolation, as well as providing a one-order filtering response. $2k$ cavities are cascaded to form two second-, triple- and multi-order filtering channels. According to these concepts, designing a crossover requires $4k$-3 SIW cavities, while a diplexer at least occupies $2k + 1$ SIW cavities. Therefore, the aforementioned concepts exist some dilemmas for compact crossover and diplexer implementations. To solve this problem, a new method is firstly proposed, which designs a crossover and diplexer with two second-order BPF channels by employing QMR and single cavity technology. Figure 2 displays the working mechanism. As can be observed, four resonant modes (represented by node 1, 2, 3 and 4) are excited in a single SIW cavity, and are divided into two groups to form two second-order BPF channels. Mode 1 and 2 are transmitted from port 1 to port2, while another pair implements the other signal path, port 3 to port 4. The isolation between two paths is preferred by the typical electric distributions.

## III. RESONANCE CHARACTERISTICS OF THE PROPOSED SIW QMR

For implementation, a QMR derived from a conventional SIW rectangular resonator is proposed to meet the above requirements. As the schematic depicted in Figure 3, a conventional SIW rectangular resonator is designed on a single-layer Taconic RF-35 substrate with a thickness of 0.508 mm, a relative permittivity of 3.5, and a dielectric loss tangent of 0.0018. The resonator is analyzed using the even-odd mode theory owing to standard rectangular

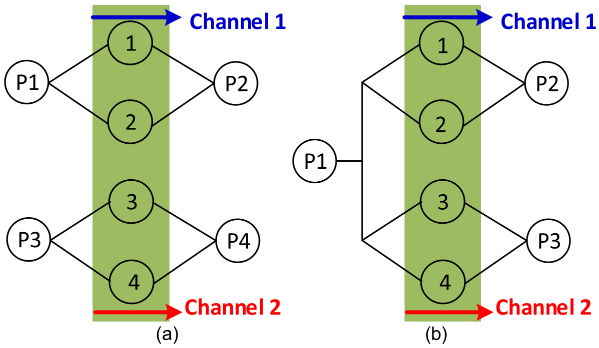


**FIGURE 2.** Proposed design mechanisms of the SIW (a) crossover, (b) diplexer.

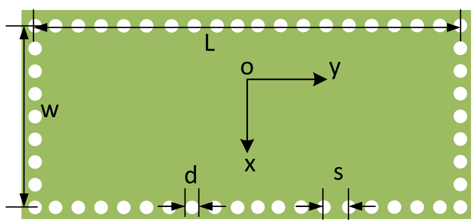


**FIGURE 3.** Conventional SIW rectangular resonator analyzed using even-odd mode theory.

structure, and excites TEm0n modes [12]. The even-mode resonance frequencies can be calculated according to [17]:

$$f_{e\_m0n} = \frac{C}{2\pi\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m\pi}{W-\frac{d^2}{0.95S}}\right)^2+\left(\frac{n\pi}{L-\frac{d^2}{0.95S}}\right)^2} \quad (1)$$

while that of odd mode employing

$$f_{o\_m0n} = \frac{C}{2\pi\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m\pi}{W-\frac{d^2}{0.95S}}\right)^2+\left(\frac{n\pi}{\frac{L}{2}-\frac{d^2}{0.95S}}\right)^2} \quad (2)$$

can be obtained. C is the speed of light in free space, and $\varepsilon_r$ is the relative permittivity of the dielectric substrate. W, L, d and S represent dimensions of the resonator, respectively. m and n are the mode indices along the respective X- and Y- axes, directions, respectively. The E-field distributions of four resonance modes, TE103, TE104, TE201 and TE202, are displayed in Figure 4. In view of X-axis direction, the E-field distribution, in the cavity center, of TE103 and TE104 modes feature extensive, while that of TE201 and TE202 are almost vanished. As seen in Y-axis direction, TE201 and TE202 modes share the common strong E-field area, but the common vanished E-field area between TE103 and TE104 modes is nonexistent. Thus, conventional SIW cavities cannot meet the isolation requirements between two channels.

Redistributing E-field distribution could solve this problem. Then, a resonator is proposed using perturbance technology by inserting a row of metal via-holes into the center along the SIW-based longitudinal direction, as shown in Figure 5. Based on the E-fields shown in Figure 4, the perturbance technology has great effect on the even resonant modes, but almost no influence on the odd modes. In this way, the E-field vanished area of TE103 mode shown in Figure 4(a) can be moved (Figure 6(a)) to coincide with that of TE104 (Figure 6(b)). Meanwhile, the common strong E-field area formed by TE201 and TE202 modes still exists. To explain more intuitive, these specific areas are marked in Figure 6 as follows: Region A, Region B, Region C and Region D. In X-axis direction, we can find Region A and Region B are the strong E-field areas of TE103 and TE104 modes, but the vanished areas of TE201 and TE202 modes. As seen in Y-axis direction, TE201 and TE202 modes possess common strong E-field areas, Region C and Region D, where distribute null E-fields of TE103 and TE104 modes. In this way, desired isolation between two channels can be well obtained. Then, without interaction, TE103 and TE104 modes can flow from Region A to Region B, as well as the Region C to Region D path transmits TE201 and TE202 modes, thus a crossover is realized. Region E is the area co-existing the E-fields of the four resonance modes. Likewise, a diplexer is designed employing the two signal paths, Region A to Region E (TE 103 and TE104 modes) and Region C to Region E (TE201 and TE202 modes).

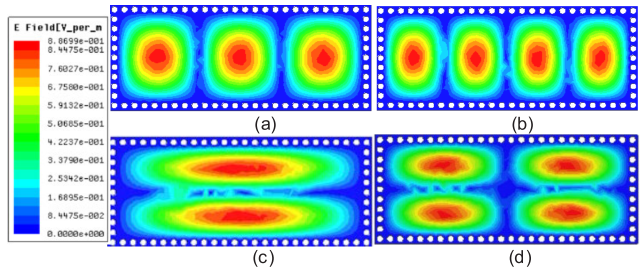


**FIGURE 4.** E-field distributions in the rectangular SIW cavity: (a) TE103 mode, (b) TE104mode, (c) TE201 mode, (d) TE202mode.

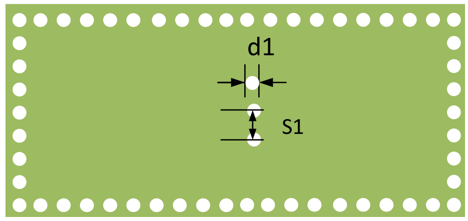


**FIGURE 5.** Perturbed SIW cavity with four distinct resonance modes.

Based on E-fields, the frequencies of TE103 and TE201 modes can be controlled by adjusting the metal via-hole length, l1, without affecting TE104 and TE202 modes. Meanwhile, because the E-filed of TE 201 mode is extremely weak in the center, several via-holes can be deleted, l2, to adjust the resonant frequency of TE103 without affecting the other three modes. Figure 7 verify the above analysis in cures simulated by ANYSIS 15.0, and the trends are consistent with analysis. However, these changes are limited, only in a small range. Next, two slots are embedded on the SIW cavity top metal surface to enlarge current flow paths to lower frequencies. Figure 8(a)-8(d) show the current direction of the proposed resonator, respectively. It can be observed that the current directions of TE103 and TE104 modes are perpendicular to

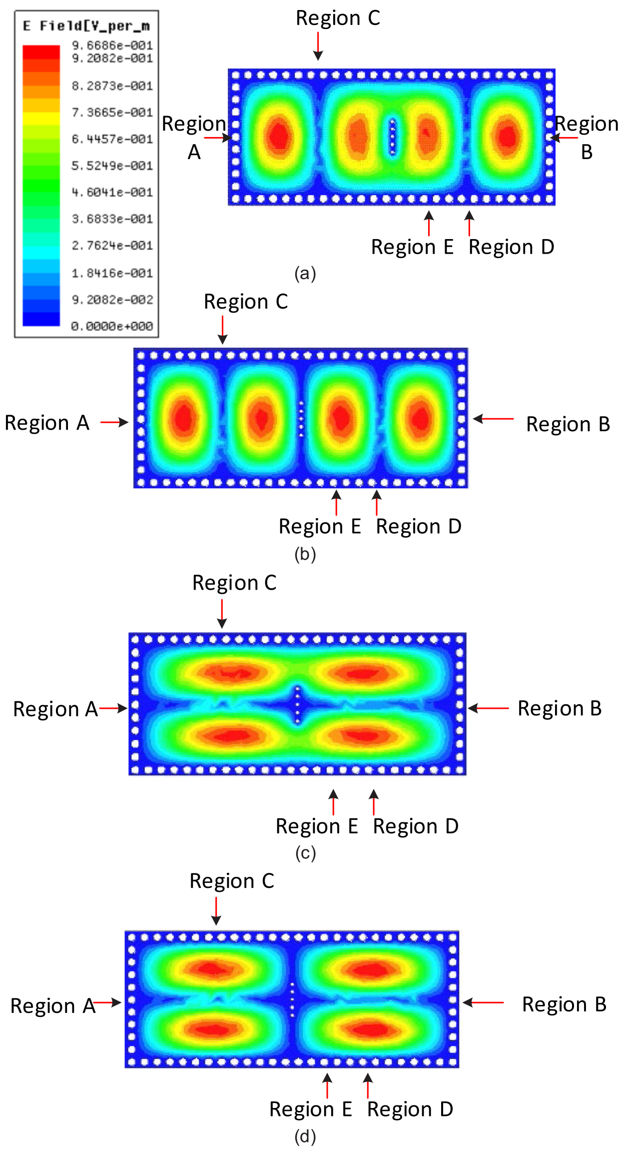


**FIGURE 6.** E-field distributions in the perturbed SIW cavity: (a) TE103 mode, (b) TE104mode, (c) TE201 mode, (d) TE202mode.

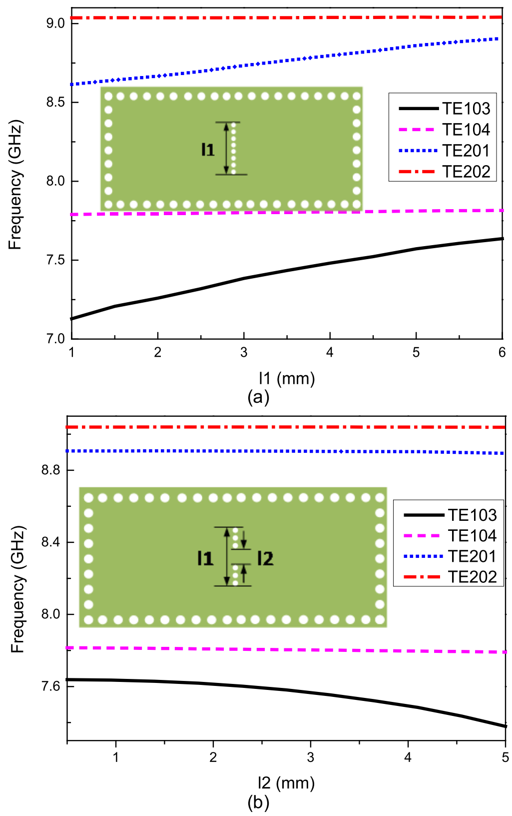


**FIGURE 7.** Simulated resonant frequency of the modes versus metal via-hole lengths, (a) l1, (b) l2.

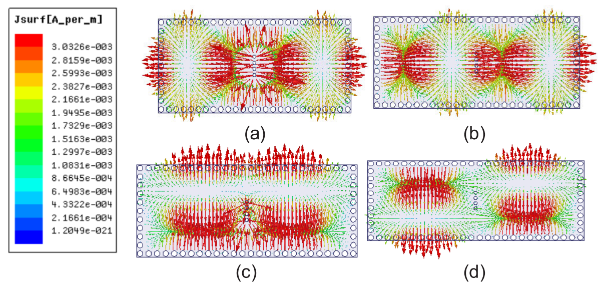


**FIGURE 8.** Current distributions in the perturbed SIW cavity: (a) TE103 mode, (b) TE104mode, (c) TE201 mode, (d) TE202mode.

that of TE201 and TE202 mode in $L/4$ and $3L/4$ area. Hence, embedded slots can change the current path of TE103 and TE104 without affecting TE201 and TE202 modes, thereby further increasing the design flexibility. The curves in Figure 9 verify the above analysis' validity. Based on the results, the overall frequency design steps are summarized as follows:

First, determine the frequency of TE202 mode. Then, the frequency of TE201 mode is obtained by adjusting $l1$ without affecting TE202 mode. Next, generate the desired TE104 mode frequency with an appropriate $l3$ without affecting the TE202 and TE201 modes. Finally, specific $l2$ is chosen to realize the frequency of TE103 mode without affecting the other three modes. Benefiting from the flexibility, single cavity technology has been realized to construct two channels using TE103 and TE104 modes, TE201 and TE202 modes, respectively.

## IV. CROSSOVER INTEGRATED IN A SINGLE CAVITY

### A. DEMO FOR CROSSOVER

#### 1) CROSSOVER ARCHITECTURE

A demo for SIW crossover is designed, as shown in Figure 10. Four coplanar waveguide (CPW) feedlines are utilized for inputs and outputs [8]. According to the analysis in Section II, it can be inferred TE103 and TE104 modes form a channel when signals are injected from port 1 to port 2. Meanwhile, another channel, port3 to port 4, can be realized employing TE201 and TE202 modes. To verify, the E-field distributions of the proposed crossover are shown in Figure 11(a)-11(d). As seen, the signals (TE103 and TE104 modes) are transmitted from port 1 to port 2 while isolated between port3 and port 4, and vice versa. Therefore, a crossover with two second-order channels can be well realized using the proposed concept in a single SIW cavity.

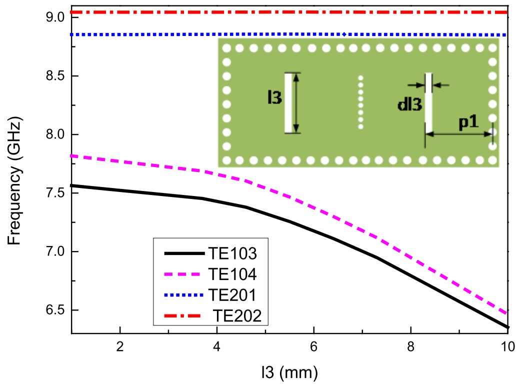


**FIGURE 9. Simulated resonant frequency of the modes versus slot length, l3.**

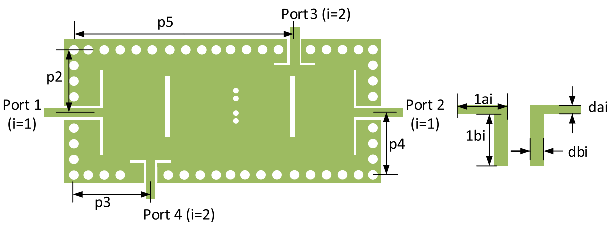


**FIGURE 10. Configuration of the demo crossover.**

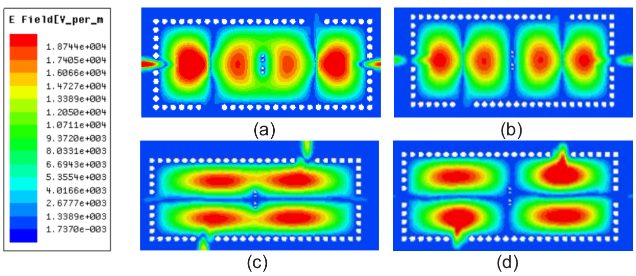


**FIGURE 11. E-field distributions in the demo crossover: (a) TE103 mode, (b) TE104mode, (c) TE201 mode, (d) TE202mode.**

## 2) RESONANCE CHARACTERISTICS

Corresponding to the above analysis, the channel filtering response flexibility can be forecasted, and has been shown in Figure 12 for demonstration. Figure 12(a) shows the center frequency of the lower channel moves downwards with the increase of l3 within a large range, while that of the upper is almost fixed. In this way, the center frequencies of two channels can be controlled independently. Moreover, the center frequencies of two channels shift slightly with varied s1 (corresponding to two varied parameters, l1 and l2), as shown in Figure 12(b). This inherent feature helps to control the bandwidth of two channels, and required bandwidths can be obtained by fine optimizing of l1, l2 and s1. Thus, we can conclude that although the crossover is designed utilizing a single simple SIW cavity, its flexibility has not been restricted.

## 3) EXTERNAL COUPLING

As investigated in [9], the external factor, $Q_e$, could be extracted from the phase and group delay responses of

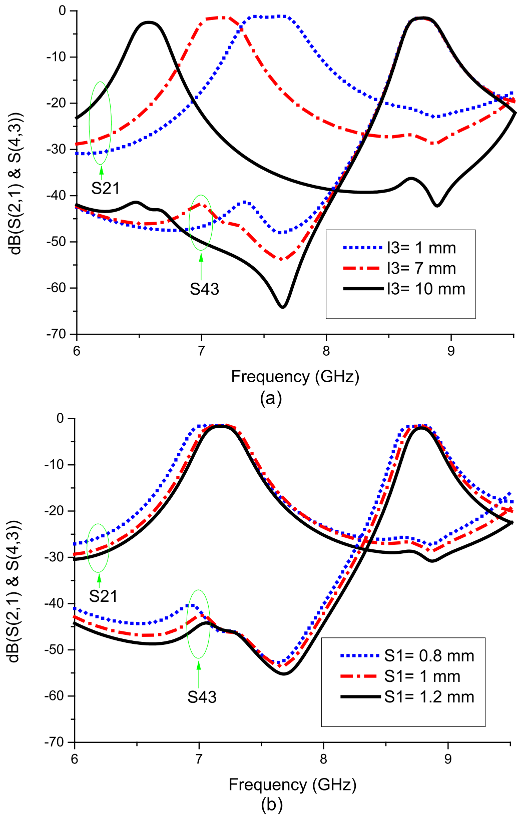


**FIGURE 12. Simulation response of the demo crossover adjusted by (a) l3, (b) s1.**

S11 using the following formula

$$Q_e = \frac{f_0}{\Delta f_{\pm 90^\circ}} \tag{3}$$

$f_0$ accounts for the frequency at which the group delay of S11 reaches the maximum, and $\Delta f$ is on behalf of the absolute bandwidth between ±90° points relative to the absolute phase at $f_0$. Notably, the external coupling of the lower channel (TE103 and TE104 modes) comes from the feedlines (port 1 and port 2). Similarly, the upper channel external coupling is determined via the other two CPW feedlines. After determining the channel frequencies, a proper coupling at the QMR and the input/output CPW feedlines and good impedance matching among the input and the output of the two channels could be realized by controlling the dimensions of the feedlines.

## 4) IMPLEMENATION AND RESULTS

Figure 13(a) prints the photograph of the fabricated SIW crossover. Optimized dimensional parameters are listed as follows: W = 20, L = 50, S = 2, d = 1.3, l1 = 4.34, l2 = 1.42, l3 = 7, dl3 = 0.2, S1 = 0.96, d1 = 0.5, p1 = 12.5, p2 = 12.5, p3 = 12.5, p4 = 10, p5 = 37.5, la1 = 5.2, da1 = 0.2, lb1 = 1.8, db1 = 0.4, la2 = 4, da2 = 0.2, lb2 = 1 and db2 = 0.2. Figure 13(b) and 13(c) give the simulated and measured results respectively, showing good agreement. Small inconsistency mainly comes from the practical processing and testing. In two channels,

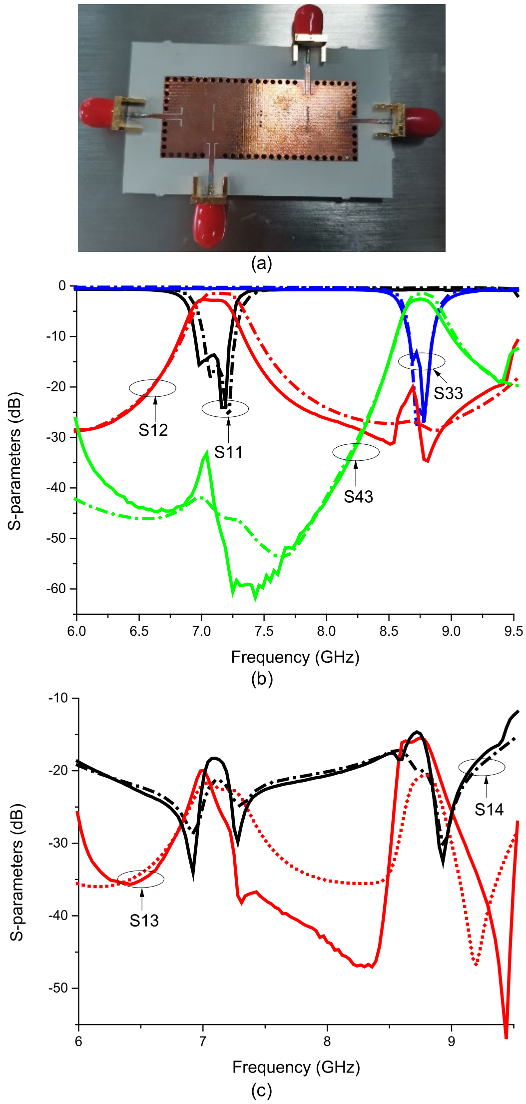


**FIGURE 13.** The demo crossover, (a) photograph, (b) simulation (dotted line) and measured (solid line) response, (c) simulation (dotted line) and measured (solid line) response.

the measured center frequencies operate at 7.11 GHz and 8.77 GHz, exhibit return losses (RLs) within the two channels all better than 13.1 dB and isolations between two channels all better than 14.65 dB, while the minimum insertion losses are 2.7dB and 2.57 dB, respectively. The measured 3-dB bandwidths are 0.36 and 0.27 GHz, corresponding to 3-dB fractional bandwidths (FBWs) of 5.06% and 3.07%.

## B. DEMO FOR DIPLEXER

### 1) DIPLEXER ARCHITECTURE

Figure 14 shows the layout of the proposed SIW filtering diplexer using the proposed concept in a single SIW cavity. Three CPW feedlines are placed at the corresponding sidewalls shown in Figure 6. Figure 15 display the corresponding E-field distributions on the bottom surface of the four operated modes. As observed in Figure 15 (a) and 15(b), the E-field of TE103 and TE104 modes are at high intensities when port 1 and port 2 are excited, but exhibit null at port 3. In addition, the energy of TE201 and TE202 modes transmits

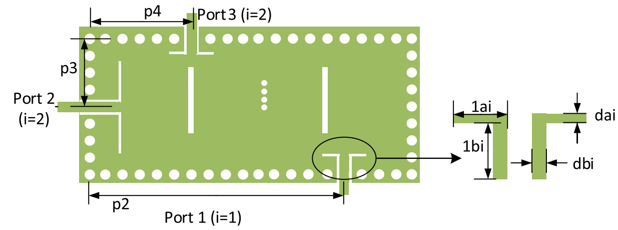


**FIGURE 14.** Demo for SIW diplexer structure.

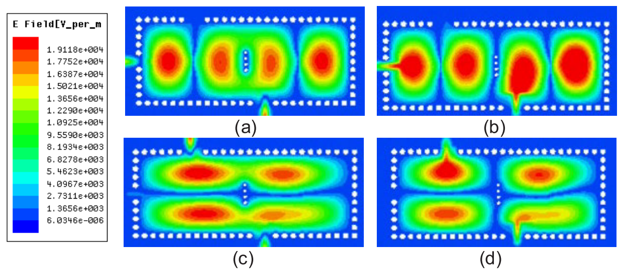


**FIGURE 15.** E-field distributions in the demo diplexer: (a) TE103 mode, (b) TE104mode, (c) TE201 mode, (d) TE202mode.

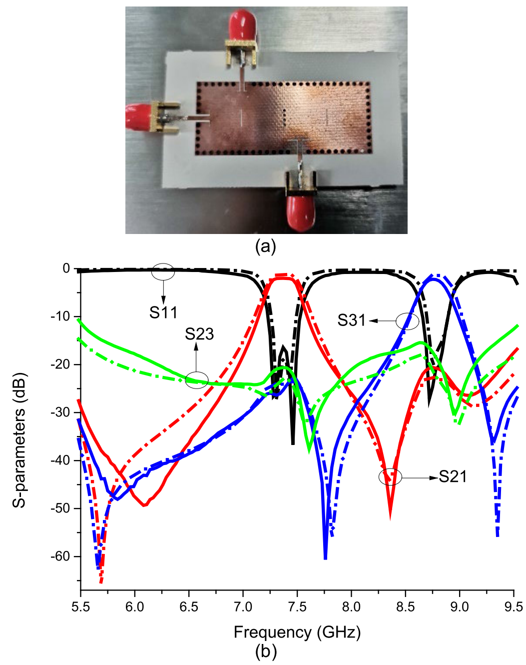


**FIGURE 16.** The diplexer, (a) photograph, (b) measured (solid) and simulated (dashed) responses.

between port 1 and port 3, but is isolated at port 2. Thus, the diplexer generates desirable isolations and two second-order channels successfully.

Moreover, in order to make the resonator operate at the required frequencies, the parameters, l1, l2 and l3, are chosen and compromised. In this way, the center frequencies of the two channels can be controlled independently. Since only the feedline positions have been changed, the frequency change trends are basically consistent with Figure 12. And, the external quality factors also can be generated and analyzed as above.

### 2) IMPLEMENATION AND RESULTS

To demonstrate, Figure 16(a) prints the photograph of the fabricated SIW crossover. Optimized dimensional parameters are listed as follows: W = 20, L = 50, S = 2, d = 1.3, l1 = 5.06, l2 = 0, l3 = 5, dl3 = 0.1, S1 = 1.42, d1 = 0.8, p1 = 12.5, p2 = 31.25, p3 = 12.5, p4 = 10, la1 = 4.3, da1 = 0.2, lb1 = 3.2, db1 = 0.3, la2 = 5, da2 = 0.3, lb2 = 2, db2 = 0.2, la3 = 3, da3 = 0.2, lb3 = 1 and db3 = 0.2 (all in mm). Figure 16(b) gives the simulated and measured results, showing good agreement between them. The two channels center at 7.37 GHz and 8.78 GHz, exhibit RLs within the two channels all better than 15.41 dB and isolations between two channels all better than 15.426 dB, while the minimum measured insertion losses are 2.3 and 2.13 dB, respectively. The measured 3-dB bandwidths are 0.33 and 0.29 GHz, corresponding to3-dB FBWs of 4.47% and 3.3%, respectively.

## V. CONCLUSION

The design and implementation of a novel crossover and diplexer with two second-order channels design method based on SIW QMR technology has been proposed and presented. By utilizing the proposed method, the crossover and diplexer operate in single cavities, which reduce the whole circuit size extremely efficient, and realize flexible control channels, thereby improving design freedom. To verify, the crossover and diplexer have been designed and fabricated. The good agreement between simulated and measured results demonstrates the validity. Thus, the proposed method can be a good candidate for compact planar microwave circuits and systems.

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