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A Novel Triple-Band Filter Based on Triple-Mode Substrate Integrated Waveguide

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Abstract—A novel triple-band filter using triple-mode substrate integrated waveguide (SIW) resonator is presented in this paper. The proposed resonator consists of a square cavity with two additional metallic vias that split the first pair of degenerate modes (TE_{201} and TE_{102}) at the diagonal of the cavity. Triple-band response is achieved by TE_{101}, TE_{201} and TE_{102}. The center frequencies of the first band and the third band can be controlled by appropriately adjusting the location of perturbation vias, while the second band keeps almost unchanged. A two-pole triple-band filter with two transmission zeros utilizing the coupled triple mode cavity resonators is designed and fabricated. The measured results agree very well with the simulated ones.

1. INTRODUCTION

Microwave filters play an important role in the communication system. Modern communications require microwave filters with small size, low cost, high power capability and high performance, such as high selectivity, low insertion loss, sharp skirt behavior and spurious characteristics. Multi-band SIW filter perfectly satisfies these requirements. In the past years, most of the researchers focused on the realization of microstrip dual-band and triple-band filters based on SIR structure [1–4]. Many of these filters are designed by multi-mode [4]. Moreover, a conventional approach in triple-mode filter designs is based on the degenerate modes of a cavity. In [5], a triple-mode filter using $TE_{101}/TE_{011}/TM_{110}$ modes in a cubic cavity was proposed. However, this is a band-pass filter with a single band. Few triple-band filters using SIW cavities with multi-mode have been reported.

The properties of low cost, high Q-factor, compact size and easy manufacture make SIW technology attractive for planar filter design by using planar circuit fabrication process. Since SIW is a three-dimensional periodic structure, it has the ability to control the transmission path of electromagnetic waves by metal vias on the dielectric substrate. In a certain range it can replace rectangular metal waveguide [6–9]. This concept was first proposed by a Japanese scholar Shigeki in 1994 [10]. In 1998, Uchimura et al. studied this waveguide structure systematically and fully [11]. Thereafter, many scholars have done a lot of deep researches about SIW.

Recently, the study about dual-mode resonators based on SIW is increasing [12–15], and most of them utilized the high-order resonances of SIW cavity (TE_{201} and TE_{102}). The filter designed by this method has poor rejection, because TE_{101} mode in lower frequency is near the first degenerate modes. In this paper, a novel method for designing a substrate integrated waveguide triple-mode triple-band filter is presented, and the triple-band response is achieved by TE_{101} mode and the first degenerate modes (TE_{201} and TE_{102}). A perturbation method by placing two additional vias at the diagonal of a square dual-mode SIW cavity resonator is designed to adjust the resonant frequencies of two modes while keeping the resonant frequency of the other mode unchanged. The perturbation splits the first

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pair of degenerate modes, resulting in three resonant frequencies. Then, the proposed triple-mode bandpass filter is analyzed and designed using full-wave EM simulator software (Ansoft HFSS). A two-pole Chebyshev filter is designed, fabricated and measured, which verifies the design principle.

2. CHARACTERISTICS OF THE SIW SQUARE RESONANT CAVITY

2.1. Structure of SIW Resonant Cavity

Figure 1 shows the structure of a substrate integrated waveguide square resonant cavity. Two metallic perturbation vias with diameter d are located along the diagonal line of the square, where a and t are the side length and height of the cavity, respectively, p is the distance between the center of two adjacent vias, c is the distance from the center of the perturbation vias to the nearest sides of the square.

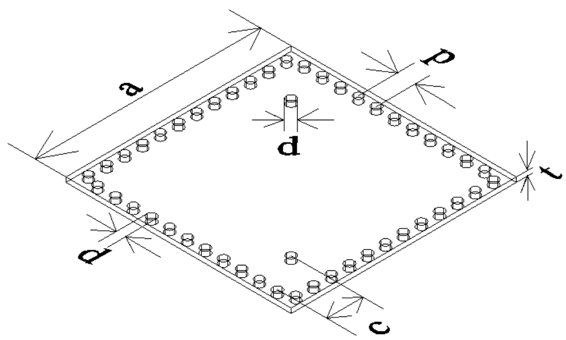

Figure 1. Structure of the square SIW cavity.

2.2. Property of the Perturbation

The perturbation can split degenerate modes, and then dual- or triple-mode in one cavity is achieved. In this paper, SIW square cavity is perturbed by metallic vias at the diagonal of the structure. Fig. 2 shows the electric distribution of TE_{101} mode and the first split degenerate modes. At the center of the SIW cavity, the electric field strength of TE_{101} mode reaches its maximum, and those of the other modes are minimal. As shown in Fig. 2(a) and Fig. 2(c), TE_{101} (Fig. 2(a)) and TE_{102} (Fig. 2(c)) are significantly influenced by the perturbation vias. But the perturbation vias have little effect on the diagonal TE_{201} mode (Fig. 2(b)) since the electric field is weak at the diagonal of the square. As an example, considering a triple-mode SIW cavity resonator with $a = 23\,\text{mm}$, $d = 1\,\text{mm}$, $p = 3\,\text{mm}$, $t = 0.508\,\text{mm}$, its resonant frequencies versus c are shown in Fig. 3(a). It can be seen that the first pair of the two degenerate modes resonates at the same frequency, which is higher than that of TE_{101} mode, when there is no perturbation ($c = 0$). As c increases, the electromagnetic field of the TE_{101} mode and TE_{102} mode are greatly changed, and the corresponding resonant frequency increases rapidly. Fig. 3(a) also shows that the c value does not affect the resonant frequency of TE_{201} mode which agrees well with the above analysis. Hence, a pair of perturbation vias causes the spacing between the two resonant frequencies to increase gradually, as shown in Fig. 3(a), leading to splitting the resonant frequencies of the degenerate modes. Fig. 3(b) illustrates the transmission coefficients against frequency of the square SIW with different cs. As c increases, the resonant frequencies of TE_{101} mode and TE_{102} mode move to a higher value gradually, while TE_{201} mode remains nearly invariable. Therefore, by properly choosing the distance c, the lowest and the highest resonant modes can be controlled to resonate at two desired frequencies. It is clear from Fig. 3 that the difference among the resonant frequencies of the three modes becomes smaller as the distance of the additional via increases. Thus, a triple-mode SIW cavity resonator can be generated by selecting the proper size of the SIW cavity and the additional perturbation via.

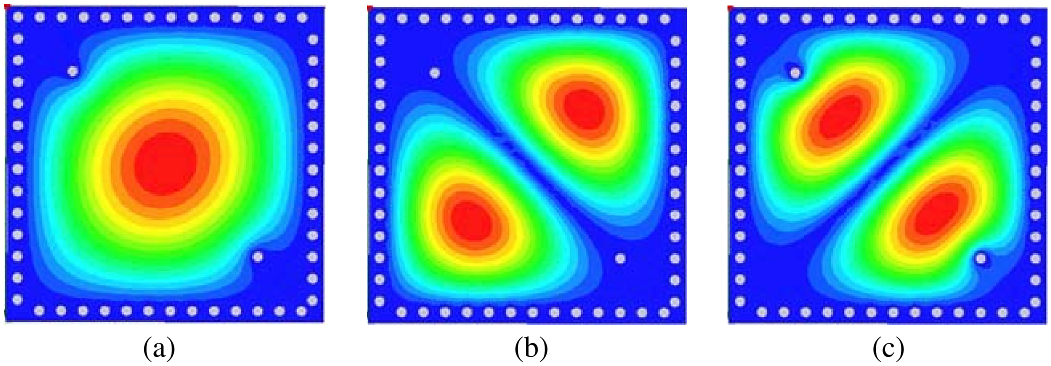

Figure 2. Electric field distributions of the mode TE_{101} and the first degenerate modes, (a) mode TE_{101}, (b) mode TE_{201}, (c) mode TE_{102}.

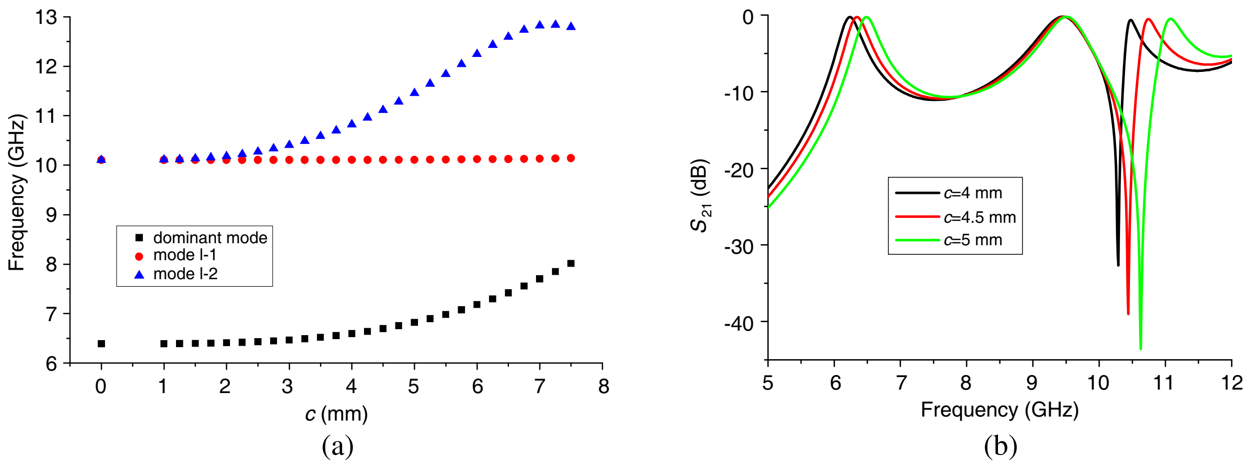

Figure 3. (a) Resonant frequencies versus vias' position c, (b) simulated transmission coefficients against frequency of the square SIW.

3. DESIGN OF THE TRIPLE-MODE TRIPLE-BAND SIW FILTER

To demonstrate the application of the proposed triple-mode square SIW resonator, a bandpass filter with two resonators is investigated. Fig. 4 shows the proposed triple-band SIW filter working at 6.4 GHz, 9.8 GHz, 10.7 GHz. The 50 Ω microstrip lines are transited to the SIW through coplanar waveguide (CPW) structures at the input and output ports. And the width of the port is W_s. There are two vias in each cavity which are splitting the first degenerate mode. Two square cavities are coupled to each other through a coupling window, whose size is W_{12}. To get strong coupling, the aperture should be placed to ensure that more energy is allowed to transfer through the aperture as possible. L and W are the length and width of the SIW filter, and W_{ls} and L_{sot} are the width and length of the gap of the coplanar waveguide, respectively.

Figure 5 shows the transversal coupling scheme of the proposed filter based on the fundamental mode and the first splitting degenerate mode of the perturbed cavity, where empty circles S and L in this scheme represent the source and load, respectively. 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 TE_{201} mode and TE_{102} mode. As shown in Fig. 5, three separate paths from source to load are provided. These three paths, corresponding to the lower, middle and higher bands of the triple band filter, respectively, can be easily designed and realized.

To verify the proposed structure above, a triple-band SIW filter is also designed and fabricated on a 0.508 mm-thickness F4B substrate with a relative permittivity of 2.2. Its design specifications are

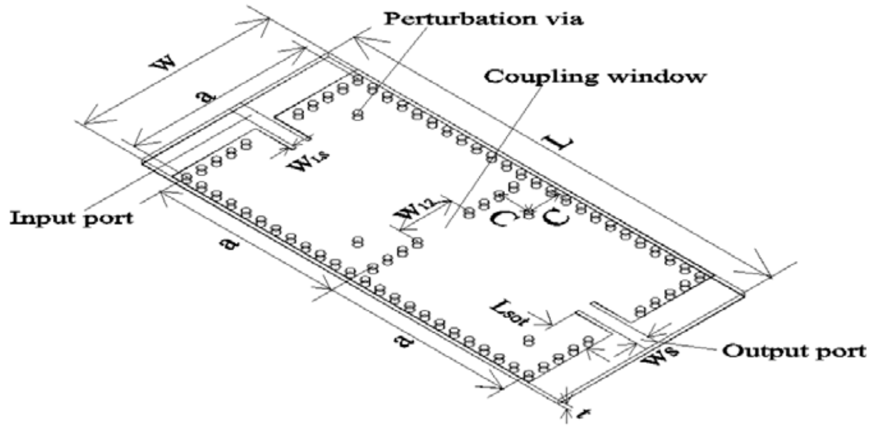

Figure 4. Configuration of the proposed triple-mode triple-band SIW filter.

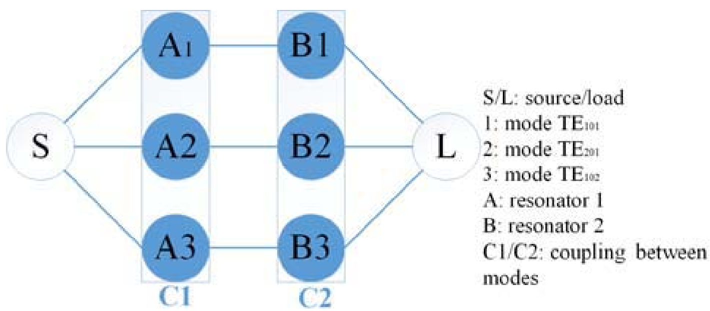

Figure 5. Coupling scheme of the triple-mode triple-band SIW filter.

Table 1. The design specifications of triple-band SIW filter.

	f_0 (GHz)	Bandwidth (MHz)	Return Loss (dB)
First band-pass	6.4	150	-20
Second band-pass	9.8	300	-20
Third band-pass	10.7	150	-20

shown in Table 1. The design procedure of the filter is summarized as follows. Firstly, let the center frequency of the second bandpass $f_0 = 9.8$ GHz, so the size of the cavity can be determined. Then, the resonant frequencies of the first and third pass-bands are finely tuned by changing the position of the perturbation vias. Fig. 6 shows the simulated response of the filter with different c. The value of c should be determined by the resonant frequency 6.4 GHz and 9.8 GHz. Finally, according to the required bandwidth, the coupling matrix is calculated. The size of the rectangular coupling window is determined by coupling coefficients. Coupling matrix of the first band based on the coupling scheme shown in Fig. 5 is written as

$$M_1 = \begin{bmatrix} 0 & 1.658 \\ 1.658 & 0 \end{bmatrix} \tag{1}$$

In this paper, full wave software HFSS is used for simulation. The corresponding dimensions are listed in Table 2. Fig. 7 shows photographs of the fabricated filter. The fabricated filter was measured using Agilent network analyzer 8722ES. Measured results are plotted together with those simulated ones in Fig. 8, where good agreement between the measured and simulated results is observed. Although the agreement of the measured response with the simulated frequency responses is acceptable, discrepancies

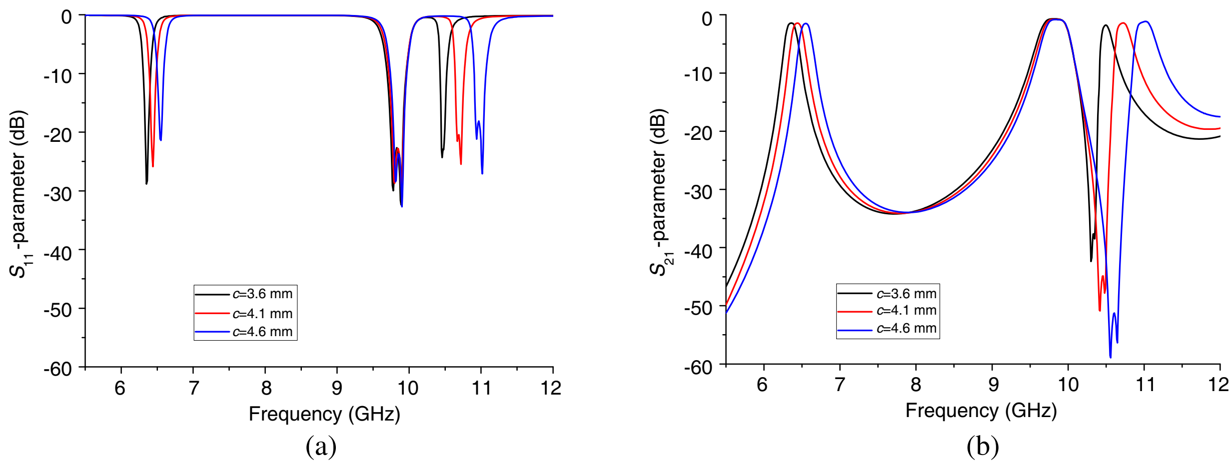

Figure 6. Simulated response of the filter with different c. (a) S_{11}, (b) S_{21}.

Table 2. Dimensions of the filter.

Symbol	Size (mm)	Name	Size (mm)
W	25	W_s	1.56
L	56	L_{sot}	5
a	23	W_{12}	6.96
W_{ls}	0.5	c	4.1

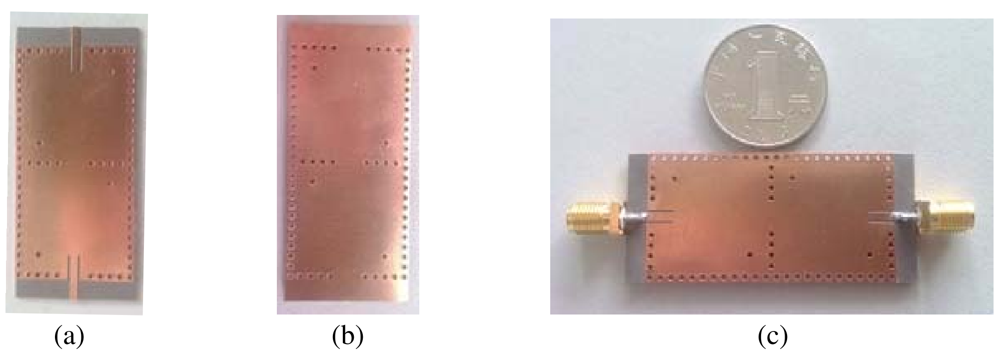

Figure 7. Photographs of the fabricated filter. (a) Top metal layer, (b) bottom metal layer, (c) the filter with SMA.

are also observed. From Table 3 it can be seen that the measured in-band return losses are below -14 dB with three center frequencies at 6.47 GHz, 9.9 GHz and 10.8 GHz. The measured minimum insertion losses of the three pass-bands are 2.47 dB, 2.04 dB and 3.26 dB, about 2 dB larger than the simulation ones. It is conjectured that slight impedance mismatch between the feeding section and the SMA connectors contributes to the insertion loss. Another reason should be the effective conductivity of fabricated filters less than that of the simulation. In addition, two adjacent transmission zeros can be clearly observed at 10.39 GHz with a 49 dB rejection, 10.57 GHz with a 39.31 dB rejection, respectively, which increase the selectivity of the filter. The proposed design method and detailed structures can be easily applied in similar filters using LTCC, where much better performances will be obtained, and the assembly errors might be reduced. This will lead to a low insertion loss. It should be pointed out that the proposed triple-mode filter has some limitations on its narrow bandwidth and narrow stopband between the second and third bands due to its simple structure and compact size.

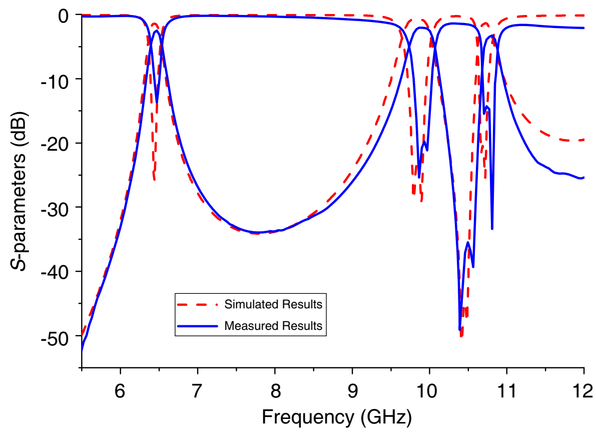

Figure 8. Simulated and measured results.

Table 3. The measured results of triple-band SIW filter.

	f_0 (GHz)	Bandwidth (MHz)	Return Loss (dB)
First band-pass	6.47	160	−14.73
Second band-pass	9.9	310	−19.79
Third band-pass	10.8	160	−14.76

4. CONCLUSION

A novel triple-mode triple-band SIW filter using two square cavity resonators is proposed in this paper. For achieving triple-mode, TE_{101} mode and the first degenerate modes are excited by placing two additional vias at the diagonal of a resonator. The resonant frequencies and electric field distributions have then been simulated for a resonator. Finally, a compact planar triple-band filter with three center frequencies at 6.47 GHz, 9.9 GHz and 10.8 GHz (over C-band and X-band) has been designed and fabricated on a 0.508 mm-thickness F4B substrate based on the proposed SIW resonator. By shifting the position of the perturbation vias, the center frequencies of the first and third pass-bands can be adjusted while that of the second pass-band remains unchanged. This character can be used to control the resonant frequency ratio of the three pass-bands within limits. Both simulated and measured results suggest that the proposed SIW resonator is an attractive candidate to design compact planar triple-mode filters. The proposed design method and structure can be easily achieved in similar filters using LTCC to improve the operation bandwidth of filter and even better frequency response selectivity. Since the coupling matrix is frequency independent, the proposed filter suffers from a very narrow frequency band. To improve this limitation, frequency-dependent coupling technique should be taken into account, which will be presented in our future work.

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