A Three-Pole Substrate Integrated Waveguide Bandpass Filter Using New Coupling Scheme

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Abstract. *A novel three-pole substrate integrated waveguide (SIW) bandpass filter (BPF) using new coupling scheme is proposed in this paper. Two high order degenerate modes (TE$_{102}$ and TE$_{201}$) of a square SIW cavity and a dominant mode (TE$_{101}$) of a rectangular SIW cavity are coupled to form a three-pole SIW BPF. The coupling scheme of the structure is given and analyzed. Due to the coupling between two cavities, as well as the coupling between source and load, three transmission zeros are created in the stopband of the filter. The proposed three-pole SIW BPF is designed and fabricated. Good agreement between simulated and measured results verifies the validity of the design methodology well.*

Keywords

Transmission zero, substrate integrated waveguide (SIW), degenerate mode, coupling matrix

1. Introduction

Substrate integrated waveguide (SIW) has gained wide attention for its advantages of low cost, high Q, and easy connection with planar devices. SIW components, such as filters, couplers, diplexers and so on, have been widely used in various microwave and millimeter wave systems [1], [2]. Traditionally, SIW filters can be implemented by inserting irises in a SIW. Desired inductor and capacitor effect can be realized by controlling the irises [3]. In [4], a four-pole bandpass filter (BPF) is realized by using four side-by-side horizontally oriented SIW cavities. Each cavity acts as a resonator and they are coupled to form a bandpass characteristic. Cavities also can be arranged in an extended box configuration with dispersive coupling on a main signal path, which produces an extra zero in comparison to classical approaches [5]. Dominant resonant mode (TE$_{101}$ mode) of the SIW cavities is applied in these SIW filters. Degenerated modes of SIW cavity can also be used in the filter. In [6], a dual-mode SIW BPF has been proposed by using orthogonal feed lines and two slot lines for disturbing two degenerate modes. To realize a sharp transition band and improve selectivity of the filter, high order or multi-pole filters are needed. In [7], a planar SIW elliptic BPF is investigated by cascading two extend

doublets. Multi-pole BPFs are realized by etching a multi-mode microstrip resonator on the top metal layer or on the bottom ground layer of a SIW resonator in [8] and [9]. Although it can achieve multi-pole bandpass characteristic, slot on the metal layer of the SIW cavity may cause radiation and worsen characteristic of the filter. In [10], an in-line and a folded three-pole dual-mode SIW filters with asymmetric transmission response are presented. Unlike the SIW filters with resonant cavities [11], the signal is coupled to different modes by eccentrically fed SIW, which provides a new way to realize multi-pole SIW BPF.

In this paper, a novel three-pole SIW BPF is proposed by using two SIW cavities with dissimilar sizes. Two degenerate modes (TE$_{102}$ and TE$_{201}$) of the bigger square SIW cavity and a dominant mode (TE$_{101}$) of the smaller rectangular SIW cavity are coupled together to form a three-pole SIW BPF. By virtue of source-load coupling and the coupling between two SIW cavities, three transmission zeros are realized, which improve the performance of the proposed SIW BPF. Finally, the SIW BPF is designed, fabricated and measured. Good agreement between simulation and measurement verifies the validity of the design methodology.

2. Analysis and Design

2.1 Analysis of the SIW Filter

Figure 1 shows the configuration of the proposed three-pole SIW BPF. It mainly consists of a square SIW cavity (Cavity 1) and a rectangular SIW cavity (Cavity 2). The filter is fed by a pair of microstrip lines via the coplanar waveguide (CPW) transition structure.

The size of SIW cavity is determined by the corresponding resonant frequency. The resonant frequency of the resonant modes (TE$_{m0n}$) of the SIW dual-mode filter can be calculated using the following equation [12]:

$$f_r = \frac{c_0}{2\sqrt{\varepsilon_r}} = \sqrt{(\frac{m}{W_{eff}})^2 + (\frac{n}{L_{eff}})^2} \tag{1}$$

where

$$W_{eff} = L_{eff} = W - \frac{D^2}{0.95 \cdot S} = L - \frac{D^2}{0.95 \cdot S} \tag{2}$$

where m and n are the indices of the modes, ε_r is the permittivity of the substrate material, and c_0 is the velocity of the light in free space, D is the diameter of the metal via, W and L are the width and length of the cavity, respectively, S is the space between metal vias, W_{eff} and L_{eff} are the equivalent width and length of the rectangular cavity, respectively.

As to a square SIW cavity, its TE_{201} mode and TE_{102} mode has the same resonant frequency. To ensure that the dominant mode of cavity 2 has the same resonant frequency with the high order mode of cavity 1, according to (1), side length of cavity 2 is set about half of longitudinal dimension.
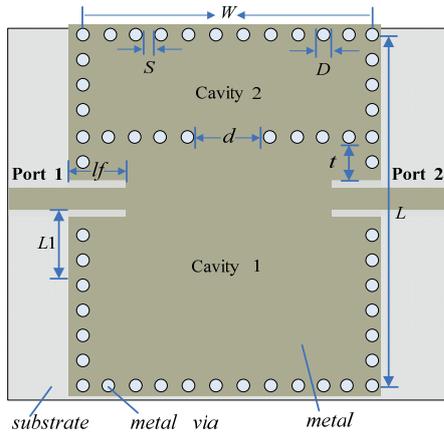
Fig. 1. Layout of proposed three-pole SIW BPF.
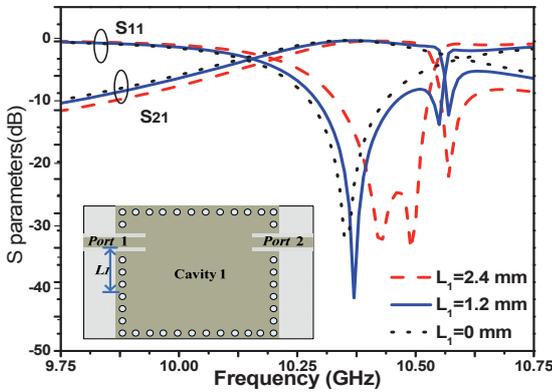
Fig. 2. Simulated characteristics of cavity 1 against L_1.
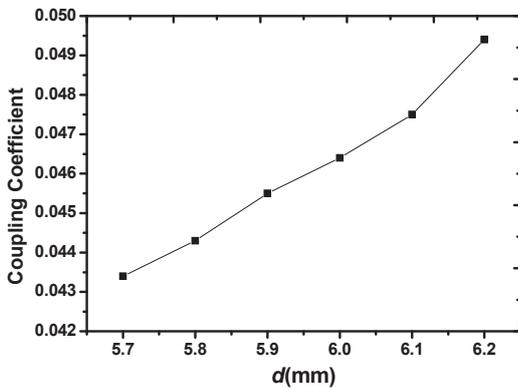
Fig. 3. The coupling between cavity 1 and cavity 2 versus d.

In order to excite the degenerate modes of cavity 1, feed lines of the dual-mode SIW resonator offset from the center of cavity 1 [13]. Figure 2 illustrates the bandpass characteristics of the dual-mode SIW cavity against offset length L_1. When $L_1 = 0$ mm, two degenerate modes of cavity 1 coincide with each other and only one resonant peak can be observed. When L_1 increases from 0 to 2.4 mm, its two degenerate modes are split and the other resonant peak can also be seen. The coupling strength between cavity 1 and cavity 2 is controlled by the width of iris d. Figure 3 gives the simulated coupling coefficient between cavity 1 and cavity 2 versus d. When d increases from 5.7 to 6.2 mm, the coupling coefficients increases from 0.0435 to 0.0495. In addition, because two degenerate modes of cavity 1 are coupled with each other, the coupling scheme of the proposed filter can be affirmed.

Figure 4 shows the coupling scheme of the proposed three-pole SIW BPF. Two degenerated modes of cavity 1 are directly coupled to both source and load, and the dominant resonant mode of cavity 2 is coupled to one degenerated mode of cavity 1. Corresponding coupling matrix of coupling scheme of the proposed filter can be written as

$$M = \begin{bmatrix} 0 & M_{s1} & M_{s2} & 0 & M_{SL} \\ M_{s1} & 0 & M_{12} & 0 & M_{1L} \\ M_{s2} & M_{12} & 0 & M_{23} & M_{2L} \\ 0 & 0 & M_{23} & 0 & 0 \\ M_{SL} & M_{1L} & M_{2L} & 0 & 0 \end{bmatrix} \quad (3)$$

where M_{S1} and M_{S2} represent the coupling between source and degenerate modes of cavity 1, M_{1L} and M_{2L} indicate the coupling between load and degenerate modes of cavity 1, M_{12} indicates the mutual coupling between the two degenerate modes, and M_{23} denotes the coupling between the main mode of the cavity 2 and one degenerate mode of cavity 1. Coupling matrix of the filter is synthesized as [14]:

$$M = \begin{bmatrix} 0 & 0.5249 & 0.4545 & 0 & -0.021 \\ 0.5249 & 0 & -0.09 & 0 & -0.61 \\ 0.4545 & -0.09 & 0 & -0.76 & 0.5249 \\ 0 & 0 & -0.76 & 0 & 0 \\ -0.021 & -0.61 & 0.5249 & 0 & 0 \end{bmatrix}. \quad (4)$$

Figure 5 presents the synthesized scattering characteristics of the proposed filter. The in-band return loss is about 16 dB. Two transmission zeros are achieved in the transition band, improving the selectivity of the filter. Out-of-band rejection at both sides is higher than 15 dB.
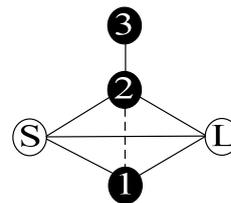
Fig. 4. Coupling scheme of the proposed three-pole SIW BPF.
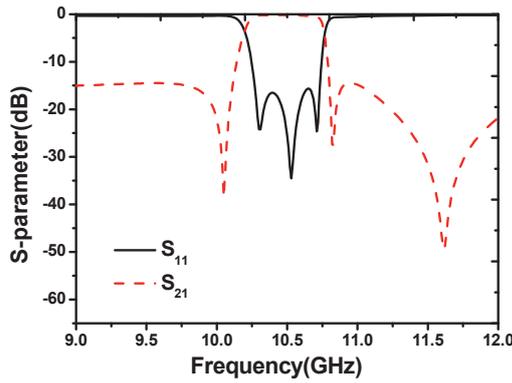
Fig. 5. The synthesized scattering characteristics of the proposed filter.

2.2 Discussion on Characteristics of the Filter

Figure 6 gives a comparison of transmission characteristics between dual-mode SIW filter, original three-pole filter, and the proposed filter with source-load (SL) coupling. Three transmission zeros are clearly observed in the stopband of the proposed filter with SL coupling. Comparing the transmission characteristics of these structures, a conclusion can be drawn that a transmission zero, namely TZ_2, will be created in the higher stopband of the filter by virtue of dual-mode SIW cavity [14]. Extended coupled cavity 2 produce a transmission zero (TZ_1) in the lower stopband of the filter. And the third transmission zero TZ_3 is mainly attributed to the coupling between source and load. To verify the above-mentioned analysis, the relation between transmission zeros and parameters of the filter are studied.

Originally, when two degenerated modes of cavity 1 are split, it provides two signal paths from source to load. It should be noted that when the signal from two paths are of same magnitude but opposite phase, transmission zero TZ_2 will be created. When cavity 2 is attached and coupled to cavity 1, additional transmission zero TZ_1 is achieved. Figure 7(a) depicts the transmission characteristics of the filter against iris width d. When iris width d increases from 5.4 mm to 6 mm, TZ_1 shifts down from 10.16 GHz to 9.97 GHz, while TZ_2 and TZ_3 almost keep unchanged. Obviously, TZ_1 can be controlled by changing iris width d. Meanwhile, it is clearly observed that the low edge of the passband moves down and the bandwidth of the filter increases with the increment of d.

Figure 7(b) presents the transmission characteristics of the filter against l_f, the probe depth of the CPW. When l_f increases from 4 mm to 6 mm, transmission zero TZ_3 moves from 11.9 GHz to 11.4 GHz, and TZ_1 decreases from 10.1 GHz to 10 GHz, while TZ_2 keeps almost unchanged. The CPW transition structure provides a coupling between source and load, which increases with increment of l_f. Furthermore, the increment of l_f will change the coupling between degenerated modes and source/load, which leads to the shift of TZ_1, but has a slight effect on the bandwidth of the filter.
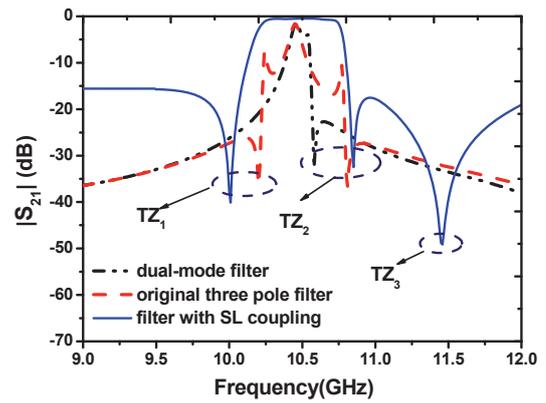
Fig. 6. A comparison of transmission characteristics between dual-mode SIW filter, original three-pole filter, and the proposed filter with source-load (SL) coupling.

(a)

(b)
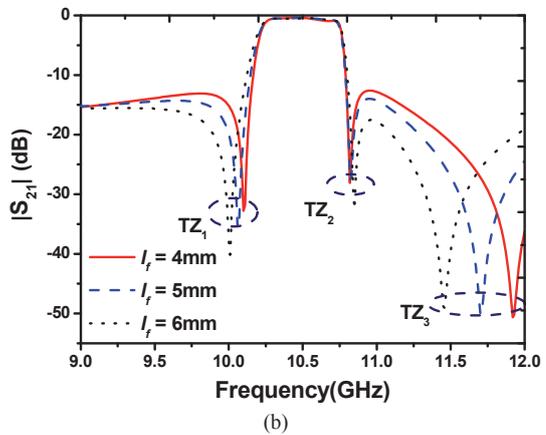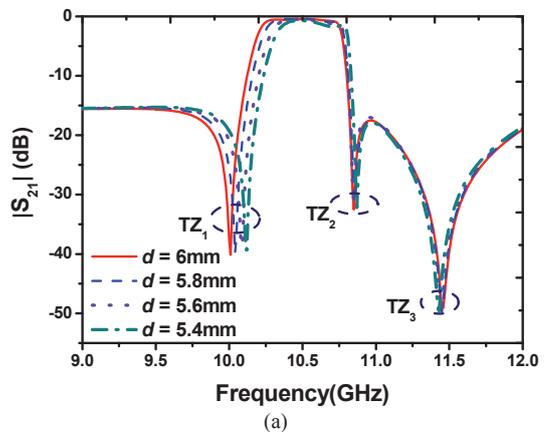
Fig. 7. Simulated transmission characteristics of the filter against (a) d, and (b) l_f.

Figure 8 presents the reflection characteristics of the filter against t. When t increases from 5.6 mm to 6 mm, transmission poles move away from each other and the bandwidth of the filter enlarged accordingly.

Obviously, from the coupling structure and the coupling matrix of the filter, the larger coupling between resonant modes will cause larger bandwidth [14]. Parametric study also shows that the bandwidth of the filter can be tuned by modifying d and l_f [15].
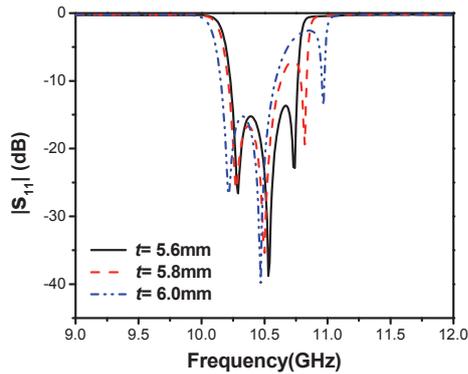
Fig. 8. Simulated reflection characteristics of the filter against *t*.

3. Experimental Results

Based on the proposed structure and coupling scheme, a novel three-pole SIW BPF with central frequency of 10.5 GHz is designed and fabricated. The designed filter has an equal ripple of 0.15 dB in the passband and fractional bandwidth is 4.8%. The filter is fabricated on a Rogers RT/duroid 5880 substrate with a relative dielectric constant of 2.2, thickness of 0.508 mm, and loss tangent of 0.0009. Finally, the obtained parameters of the filter shown in Fig. 1 are: $D = 0.6$ mm, $S = 0.3$ mm, $W = 22$ mm, $L = 32.65$ mm, $L_1 = 2.2$ mm, $l_f = 5.8$ mm, $d = 5.9$ mm, and $t = 5.6$ mm.

The filtering performance is measured by using Network Analyzer AV3926. A comparison between EM simulated results and measured results are shown in Fig. 9. Solid lines and dashed lines indicate the simulated and
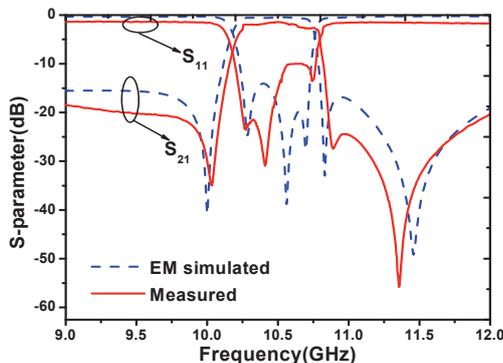
Fig. 9. A comparison between EM simulated results and measured results.
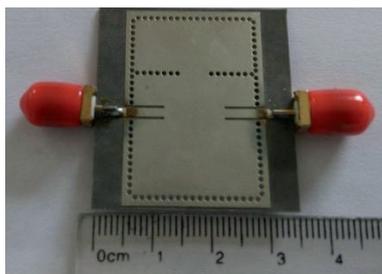
Fig. 10. A photograph of the fabricated filter.

measured results, respectively. The passband of the proposed filter covers from 10.25 GHz to 10.75 GHz, and its return loss is better than 15 dB. Three transmission poles are clearly observed at 10.28 GHz, 10.57 GHz, and 10.78 GHz. Three transmission zeros are created at 9.97 GHz, 10.86 GHz, and 11.35 GHz, which improve the stopband characteristics of the filter. Simulated and measured insertion loss in the passband is 0.76 dB and 1.39 dB, respectively. The relatively large insertion loss is mainly attributed to the SMA connections and the test transitions used in the measurement. Two 3.5 mm-to-2.4 mm transitions are additionally used while performing transition from 2.4 mm of Network Analyzer to 3.5 mm SMA. A photograph of the fabricated filter is shown in Fig. 10.

4. Conclusion

In this article, a novel three-pole SIW BPF with new coupling scheme is proposed. The filter is consisted by a square SIW cavity and a rectangular SIW cavity. Two degenerate modes of the square SIW cavity and a main mode of the rectangular SIW cavity are coupled together to form a BPF. Three transmission zeros are created in the stopband of the filter, which improve the stopband characteristics of the proposed filter.

Acknowledgments

References

[1] CHE, W. Q., LEI, X., WANG, D. P., et al. Equivalence between substrate-integrated (SIRW) rectangular waveguide short-circuit load and its equivalent rectangular waveguide short-circuit load. *Microwave and Optical Technology Letters,* 2006, vol. 48, no. 9, p. 1694–1698. DOI: 10.1002/mop.21805

[2] CHE, W. Q., DENG, K., YUNG, E. K. N., et al. H-plane 3-dB hybrid ring of high isolation in substrate integrated rectangular waveguide. *Microwave and Optical Technology Letters,* 2006, vol. 48, no. 3, p. 502–505. DOI: 10.1002/mop.21392

[3] CHEN, X. P., DROLET, D., WU, K. Substrate integrated waveguide filters for airborne and satellite system applications. In *Canadian Conf. on Electrical and Computer Engineering*. Vancouver (Canada), 2007, p. 659–662. DOI: 10.1109/CCECE.2007.169

[4] SHEN, W., YIN, W. Y., SUN, X. W., et al. Compact coplanar waveguide-incorporated substrate integrated waveguide filter. *Journal of Electromagnetic Waves and Application,* 2010, vol. 24, no. 7, p. 871–879. DOI: 10.1163/156939310791285164

[5] SZYDLOWSKI, L., LESZCZYNSKA, N., LAMECKI, A., et al. A substrate integrated waveguide (SIW) bandpass filter in a box configuration with frequency-dependent coupling. *IEEE*

Microwave and Wireless Components Letters, 2012, vol. 22, no. 11, p. 556–558. DOI: 10.1109/LMWC.2012.2221690

[6] LI, R. Q., TANG, X. H., XIAO, F. Substrate integrated waveguide dual-mode filter using slot lines perturbation. *Electronics Letters*, 2010, vol. 46, no. 12, p. 845–846. DOI: 10.1049/el.2010.0629

[7] SHEN, K., WANG, G. M., FU, S. H., GU, G. D., Highly selective bandpass filter based on substrate integrated waveguide. *Electronics Letters*, 2009, vol. 45, no. 14, p. 746–748. DOI: 10.1049/el.2009.0785

[8] CHEN, X. P., HONG, W., CUI, T., CHEN, J., WU, K. Substrate integrated waveguide (SIW) linear phase filter. *IEEE Microwave and Wireless Components Letters*, 2005, vol. 15, no. 11, p. 787 to 789. DOI: 10.1109/LMWC.2005.859021

[9] SHEN, W., YIN, W. Y., SUN, X. W. Compact substrate integrated waveguide (SIW) filter with defected ground structure. *IEEE Microwave and Wireless Components Letters,* 2011, vol. 21, no. 2, p. 83–85. DOI: 10.1109/LMWC.2010.2091402

[10] CHEN, X. P., HAO, Z. C., HONG, W., et al. Planar asymmetric dual-mode filters based on substrate integrated waveguide (SIW). In *IEEE MTT-S International Microwave Symposium Digest.* USA, 2005, p. 12–17. DOI: 10.1109/MWSYM.2005.1516782

[11] CHEN, X.-P., WU, K., LI, Z.-L. Dual-band and triple-band substrate integrated waveguide filters with Chebyshev and quasi-elliptic responses. *IEEE Transactions on Microwave Theory and Technique*, 2007, vol. 55, no. 12, p. 2569–2578. DOI: 10.1109/TMTT.2007.909603

[12] DESLANDES, D., WU, K. Substrate integrated waveguide dual-mode filters for broadband wireless systems. In *Proceedings of Radio and Wireless Conference RAWCON*. Boston (USA), 2003, p. 385–388. DOI: 10.1109/RAWCON.2003.1227973

[13] ALMALKAWI, M., ZHU, L., DEVABHAKTUNI, V. Dual-mode substrate integrated waveguide (SIW) bandpass filters with an improved upper stopband performance. In *Proceedings of 36th International Conference on Infrared, Millimeter and Terahertz Waves IRMMW-THz 2011*. Houston (USA), 2011, p. 1–2. DOI: 10.1109/irmmw-THz.2011.6105128

[14] AMARI, S., ROSENBERG, U., BORNEMANN, J. Adaptive synthesis and design of resonators with source/load-multiresonator coupling. *IEEE Transactions on Microwave Theory and Technique*, 2002, vol. 50, no. 5, p. 1969–1978. DOI: 10.1109/TMTT.2002.801348

[15] SHEN, W., YIN, W. Y., SUN, X. W. Miniaturized dual-band substrate integrated waveguide filter with controllable bandwidths. *IEEE Microwave and Wireless Components Letters*, 2011*,* vol. 21*,* no. 8, p. 418–420. DOI: 10.1109/LMWC.2011.2158412

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