Compact Substrate Integrated Waveguide BPF for Wideband Communication Applications

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Abstract— A new compact substrate integrated waveguide (SIW) bandpass filter (BPF) is presented in this paper as a candidate for use in wide bandwidth X-band applications. The proposed filter is constructed by embedding two semi-circular slots have been in the SIW structure from the input and the output sides. The simulation and performance evaluation of the proposed filter have been carried out using Microwave Studio Suite of Computer Simulation Technology CST. A parametric study reveals that the insertion of these slots has successfully led to the compact size and the wide bandwidth. The cavity dimensions are $13.6 \times 10.6\,\text{mm}^2$ while the overall filter dimensions are $28.5 \times 16\,\text{mm}^2$ using a substrate with relative permittivity of 2.2 and thickness of 0.245 mm. The resulting filter exhibits a return loss less than -15 dB and insertion loss approaching to 0 dB over the passband. The proposed filter offers a -3 dB fractional bandwidth of about 68.4% centered at 11.7 GHz. The compact size offered by this filter makes it a suitable for use in designing microwave and millimeter-wave circuits.

1. INTRODUCTION

The features that characterize the waveguide, which is the possibility of dealing with handling high power capacity, high quality factor and a few losses, but this does not enough to make waveguides familiar in planar devices environment due to their large size, difficulty of manufacturing and the difficulty of compatibility with integrated applications that are widely spread and have become popular in wireless applications. On the contrary, we find that the planar structures characterized by their small size and ease of manufacturing and ease of compatibility with integrated circuits and other tools. However, we still encounter the difficulty of dealing with high capacity and high losses. The introduction of the substrate integrated waveguide, SIW, represents a planar structure which combines the good features of the previous structures.

An SIW is a synthesized non-planar waveguide that is transformed into planar form. It can then be integrated into any planar dielectric substrate with any planar fabrication or processing technique. This will include the printed circuit boards (PCBs), and low-temperature co-fired ceramic (LTCC) technologies, among others [1]. The basic idea of the substrate integrated waveguide technique is the allocation of rows of cylindrical holes with certain radius and specific spacing. This led to emerging guided-wave structure and it looks like two parallel walls that have a specific spacing in which EM waves are well confined [1]. The purpose of the application of this technique is to make the planar structures behave as a waveguide. Therefore; all the concepts of waveguide theory can be applied to these planar structures. It is worth mentioning that SIW technique has been applied to many of microwave structures such as antennas, filters, power dividers, couplers, etc..

Due to the advantages offered by the SIW techniques, it has been attractive for microwave circuits and antenna designers. To illustrate more, the published research works can be classified into more than one category depending on how this technique has been applied. The first category includes distribution of via holes linearly on the sides of the substrate [2–5]. The second category included via holes distribution in particular certain pattern on the top layer of the planar structure [6–11]. While in the third category, defected ground structures, DGSs, and complementary single split resonators CSSRs have been applied in the ground planes of the SIW structures included in the previous two categories [12–16].

In this paper, a semi-circular slots loaded SIW based BPF is presented. The proposed BPF offers a compact size and wide bandwidth.

2. THE PROPOSED FILTER DESIGN

The structure of the proposed SIW BPF represents an improvement of that adopting the bow-tie resonator, reported in the literature [17], as a starting step. The relationship between the cut-off frequency, f_c, and the dimensions of any waveguide filled with a dielectric material can be related together, and this relationship can be considered as the starting points of a SIW design. For a rectangular waveguide, the cut-off frequency of a dominant TE mode is given by [18]:

$$f_c = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \tag{1}$$

where c is the speed of light in free space, m and n are mode numbers, a and b are the longer and the shorter dimensions of the waveguide respectively. For the dominant TE_{10} mode, Equation (1) is simplified to:

$$f_c = \frac{c}{2a} \tag{2}$$

For dielectric filled waveguide with same cut off frequency, dimension "a_d" is found to be:

$$a_d = \frac{a}{\sqrt{\varepsilon_R}} \tag{3}$$

where $\varepsilon_{\mathit{eff}}$ is the effective dielectric constant, and can be calculated by empirical expressions reported in the literature [19].

Having determined the dimension "a" for the dielectric filled waveguide; we can now pass to an empirical design equation of the SIW correlating its width, a_s, and is given by [20]:

$$a_s = a_d + \frac{d^2}{0.95p} \tag{4}$$

where d is the diameter of the vias, and p is the center to center separation between the vias along the longitudinal direction. A general rule of thumb for the choice of d and p is given in (5) and (6), respectively [20]:

$$d < \lambda_g/5 \tag{5}$$

$$p < 2d \tag{6}$$

where λ_g is the guided wavelength [21] which is given by:

$$\lambda_g = \frac{2\pi}{\sqrt{\left(\frac{\varepsilon_r(2\pi f)^2}{c^2}\right) - \left(\frac{\pi}{a}\right)^2}} \tag{7}$$

The proposed filter is constructed by embedding two semi-circular slots in the SIW structure from the input and the output sides as shown Figure 1.

3. PARAMETRIC STUDY AND SIMULATION RESULTS

The proposed filter is constructed by embedding two half-circular slots in the SIW structure from the input and the output sides as shown in Figure 1. The proposed SIW cavity dimensions are $13.09 \times 9.945\,\text{mm}^2$ while the overall dimensions are $26.625 \times 14\,\text{mm}^2$ using a substrate with relative permittivity of 2.2 and thickness of 0.245 mm. The complete parameters are finely tuned by using Microwave Studio Suite of Computer Simulation Technology CST. The detailed and optimum dimensions of the proposed filter are illustrated in Table 1.

Many parameters have studied to get more insight about their effects on the proposed filter performance. For this it is found that the most influential of these factors is the radius of the half-circular slot in the resonator. A parametric study has been conducted to explore the effect of the embedded semi-circular slot radius, r, on the presented filter performance. The effect of varying the slot radius r, while keeping the other filter parameters unchanged, has been shown in Figures 2(a) and (b).

Table 1: Summary of the dimensions of the proposed filter structure.

Parameters	l	w	a_s	r	b	y	d	p
Values (mm)	10.63	26.63	13.09	5	0.76	6.12	0.50	0.765

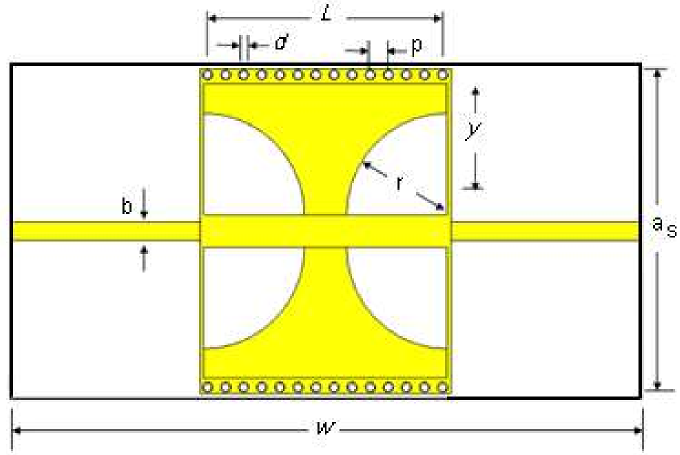
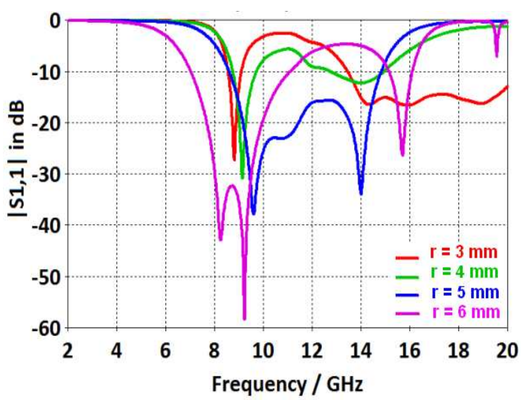
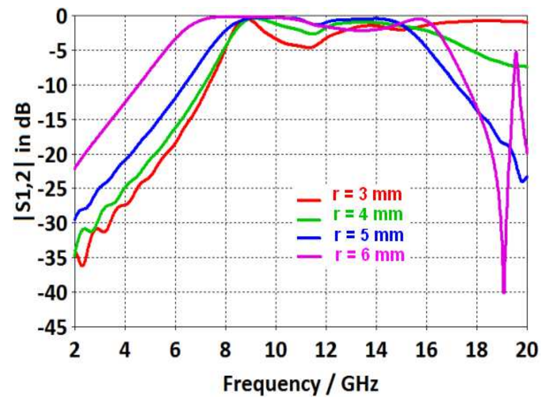


Figure 1: The front view of the simulated BPF.



(a)



(b)

Figure 2: The simulated S_{11} and S_{12} responses of the proposed BPF with r as a parameter.

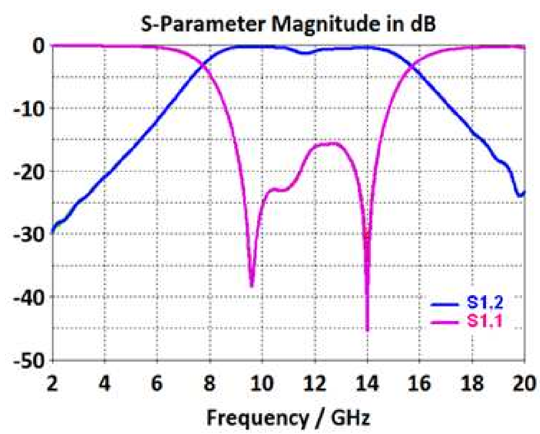


Figure 3: The simulated S_{11} and S_{12} responses of the proposed BPF with $r = 5\,\mathrm{mm}$.

Examining the results of Figure 2, it is clear that the increase of r leads to reduce the lower cut-off frequency. As r becomes larger, up to r equal to 5 mm, this will expand the filter bandwidth. Beyond this value reduction of lower cut-off frequency continues. However, the effect of varying r on the filter performance can be described as follows. As r increases, the position of the lower transmission zero has been shifted away from the lower edge cut-off frequency resulting in a low selectivity and roll-off rate. Furthermore, the increase of r makes the upper transmission zero approaches the upper edge cut-off frequency resulting in higher selectivity and higher roll-off rate at the upper passband. The resulting increase in the filter bandwidth is at the expense of the in-band performance.

There must be some compromise between the various requirements of the wide bandwidth, higher selectivity at both the lower and the upper edges of the passband, besides the low ripple in the filter passband. Figure 3 shows the performance responses of the resulting filter responses with the dimensions summarized in Table 1. The filter have exhibited a return loss less than −15 dB at the center of the passband, insertion loss approaching to 0 dB over the passband and offers a −3 dB fractional bandwidth of about 68.4% centered at 11.7 GHz. The results reveal that the dimensions of the proposed filter represent only (69.9%) lower than those reported in [17].

4. CONCLUSIONS

A new compact substrate integrated waveguide (SIW) bandpass filter (BPF) is presented in this paper as a candidate for use in wide bandwidth X-band applications. Two semi-circular slots have been embedded in the structure from the input and the output sides. The simulation and performance evaluation of the proposed filter have been exhibited a return loss less than −15 dB, insertion loss approaching to 0 dB over the passband and offers a −3 dB fractional bandwidth of about 68.4% centered at 11.7 GHz. A parametric study reveals that the insertion of these slots has successfully led to the compact size and the wide bandwidth. The results reveal that the dimensions of the proposed filter represent a considerable size reduction as compared with those reported in the relevant literature. The compact size offered by this filter makes it a suitable for use in designing microwave and millimeter-wave circuits.

REFERENCES

1. Chen, X. and K. Wu, "Substrate integrated waveguide filters: Practical aspects and design considerations," *IEEE Microwave Magazine*, Vol. 15, No. 7, 75–83, 2014.
2. Liu, C. and K. Huang, "A compact substrate integrated waveguide band-pass filter," *PIERS Proceedings*, 1135–1138, Cambridge USA, Jul. 5–8, 2010.
3. Xu, Z., G. Zhang, H. Xia, and M. Xu, "Novel hexagonal dual-mode substrate integrated waveguide filter with source-load coupling," *The Scientific World Journal*, Vol. 2014, Article ID 915740, Apr. 2014.
4. Xu, Z., Y. Shi, C. Xu, and P. Wang, "A novel dual mode substrate integrated waveguide filter with mixed source-load coupling (MSLC)," *Progress In Electromagnetics Research*, Vol. 136, 595–606, 2013.
5. Huang, Y., Z. Shao, and L. Liu, "A substrate integrated waveguide bandpass filter using novel defected ground structure shape," *Progress In Electromagnetics Research*, Vol. 135, 201–213, 2013.
6. Dong, Y., W. Hong, H. Tang, J. Chen, and K. Wu, "Planar realization of a Q-band triple-mode filter using high order resonances," *Microwave and Optical Technology Letters*, Vol. 51, No. 3, 600–603, 2009.
7. Shen, K., G.-M. Wang, S.-H. Fu, and G.-D. Gu, "Highly selective bandpass filter based on substrate integrated waveguide," *Electronics Letters*, Vol. 45, No. 14, 746–748, 2009.
8. Zheng, B., Z. Zhao, and Y. Lv, "A K-band SIW filter with bypass coupling substrate integrated circular cavity (SICC) to improved stopband performance for satellite communication," *Progress In Electromagnetics Research C*, Vol. 17, 95–104, 2010.
9. Zou, X., C. Tong, and D. Yu, "Design of an X-band symmetrical window bandpass filter based on substrate integrated waveguide," *Proceedings of Cross Strait Quad-Regional Radio Science and Wireless Technology Conference*, Harbin, China, Jul. 2011.
10. Chen, L.-N., Y.-C. Jiao, Z. Zhang, and F.-S. Zhang, "Miniaturized substrate integrated waveguide dual-mode filters loaded by a series of cross-slot structures," *Progress In Electromagnetics Research C*, Vol. 29, 29–39, 2012.
11. Zhu, X., W. Hong, and K. Wu, "Design and implementation of a triple-mode planar filter," *IEEE Microwave and Wireless Components Letters*, Vol. 23, No. 5, 243–245, 2013.
12. Deng, K., Z. Guo, C. Li, and W. Che, "A compact planar bandpass filter with wide out-of-band rejection implemented by substrate integrated waveguide and complementary split-ring resonator," *Microwave and Optical Technology Letters*, Vol. 53, No. 7, 1483–1487, 2011.
13. Guo, Z., K. Chin, W. Che, and C. Chang, "Substrate integrated waveguide quasi-elliptic bandpass filter with meander-slot coupling structures," *Proceedings of 2012 Asia Pacific Microwave Conference, APMC 2012*, Kaohsiung, Taiwan, Dec. 2012.

14. Guo, Z., K.-S. Chin, W. Che, and C. Chang, "Cross-coupled bandpass filters using QMSIW cavities and S-shaped slot coupling structures," *Journal of Electromagnetic Waves and Applications*, Vol. 27, No. 2, 160–167, 2013.
15. Zhang, Q., W.-Y. Yin, and S. He, "Evanescent-mode substrate integrated waveguide (SIW) filters implemented with complementary split ring resonators," *Progress In Electromagnetics Research*, Vol. 111, 419–432, 2011.
16. Szydlowski, L., A. Jedrzejewski, and M. Mrozowski, "A trisection filter design with negative slope of frequency-dependent cross coupling implemented in substrate integrated waveguide (SIW)," *IEEE Microwave and Wireless Components Letters*, Vol. 23, No. 9, 456–458, 2013.
17. Zhang, X., J. Xu, Z. Yu, and Y. Dong, "Microstrip wide band-pass filter based on substrate integrated waveguide (SIW)," *Proceedings of IEEE International Symposium on Microwave, Antenna, Propagation, and EMC Technologies for Wireless Communications*, Hangzhou, China, Aug. 2007.
18. Pozar, D. M., *Microwave Engineering*, John Wiley & Sons, New York, 2005.
19. Hong, J. S., *Microstrip Filters for RF/Microwave Application*, Wiley, New York, 2001.
20. Wu, K., D. Deslandes, and Y. Cassivi, "The substrate integrated circuits — A new concept for high-frequency electronics and optoelectronics," *Proceedings of 6th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Service, TELSKIS 2003*, Nis, Serbia and Montenegro, Oct. 2003.
21. Rayas-Sanchez, J. E. and V. Gutierrez-Ayala, "A general EM-based design procedure for single-layer substrate integrated waveguide interconnects with microstrip transitions," *IEEE MTT-S International Microwave Symposium Digest*, 983–986, Atlanta, USA, Jun. 2008.