Progress In Electromagnetics Research B, Vol. 7, 321–329, 2008

SUBSTRATE INTEGRATION OF DUAL INDUCTIVE POST WAVEGUIDE FILTER

A. Adabi and M. Tayarani

Electrical Engineering Department
IUST University
Narmak, Tehran, Iran

Abstract—Integration of planar circuits to non-planar ones has been recently considered as a credible technique for low-cost mass production of microwave and millimeter-wave circuits and systems. This paper regards these concepts that provide for a complete integration of planar circuits and waveguide filters synthesized on a single substrate by means of metalized post (via-hole) arrays. A method of designing a waveguide filter derived from a synthesis technique using dual array of inductive posts is presented. An experimental five-pole Chebyshev filter which has 2.5 dB insertion loss and return loss better than 10 dB is demonstrated. Such a technique of integration of planar and non-planar circuits on the same substrate shows a significant reduction in size, weight and cost.

1. INTRODUCTION

Rectangular waveguide has been one of the best candidates to design a high-Q component in microwave and millimeter-wave systems during decades. One of the difficulties that engineers will encounter in integrating such a component with planar circuits is the requirement of a 3-D complex transition. Several studies of transitions between microstrip line and rectangular waveguide have been reported [13–16, 24, 25]. However, typical integration designs from rectangular waveguide filters with planar structures are voluminous and expensive to manufacture, due to the fact that rectangular waveguide components intrinsically are bulky and costly. Moreover, high precision mechanical adjustment or a subtle tuning mechanism is needed to obtain satisfying performance of filters for mass production.

A novel planar circuit technique called substrate integrated waveguide (SIW) has been recently proposed that inherits many of the advantages of printed circuits such as low cost, small size etc. and has the benefits of being waveguide such as high quality factor (Q-factor), low insertion loss, etc. The SIW is synthesized and realized with two arrays of metalized posts or via-holes on two sides of the PCB that is simulating the side walls of the standard rectangular waveguide. Due to the fact that two metal planes cover the up and down surfaces of the SIW components, there will be no anxiety of outside interference that may come from the planar circuit is integrating with SIW. The rapid development and great influence of SIW technique in designing of many passive components and active devices such as antennas [7], filters [8], diplexers [9], oscillators [10], and couplers [11] indicates the promising capabilities of this technology for designing microwave and millimeter-wave devices and systems. In this paper a dual inductive post waveguide filter design process and fabrication data at X-band are presented. Initially, we begin with a brief analysis of integrated-waveguide in Section 2 and continue in Section 3 by presenting the design process of (dual) inductive post waveguide filters and the finally the physical parameters for implementing the filter on PCB are tabled. Also, the simulation and measurement results are included in Section 4.

2. ANALYSIS OF INTEGRATED WAVEGUIDE

Figure 1 shows the schematic view of the integrated waveguide. This waveguide consists of two parallel arrays of metalized posts (or via-holes) that resemble the side walls of a real standard waveguide. Generally, a rectangular waveguide has horizontal length, a and vertical length, b and its cut-off frequencies depend on a and b as (1),

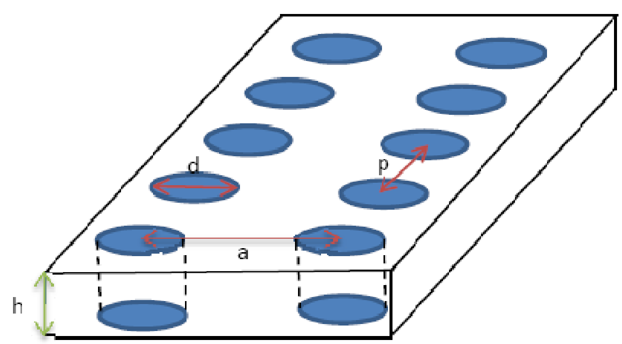


Figure 1. The basic structure of substrate integrated waveguide (SIW).

which, μ and ε are permeability and permittivity of the substrate, respectively [15].

$$f_{C_{mn}} = \frac{K_C}{2\pi\sqrt{\mu\epsilon}} = \frac{1}{2\pi\sqrt{\mu\epsilon}} \times \sqrt{(m\pi/a)^2 + (n\pi/b)^2} \rightarrow f_{C_{10}} = \frac{1}{2a\sqrt{\mu\epsilon}} \tag{1}$$

Since the height of substrate in SIW is the same as vertical wall and as long as the substrate thickness (h or b) is much smaller than a, the cut-off frequency of the dominant mode in rectangular waveguide (TE_{10}) is determined only by a.

According to the analysis reported in [2], to realize the minimum radiation loss as well as the return loss, the parameters of via-holes "d" and "p" should be kept as $\frac{d}{p} \geq 0.5$ and $\frac{d}{a} < 0.4$. Also, the distance between via-holes (p) has to be smaller than 0.2λ.

3. DUAL INDUCTIVE POST-FILTER DESIGN

Bandpass waveguide filters can be realized with different structures like E-plane or H-plane, irises, and metalized cylindrical inductive posts [16–21]. Metalized cylindrical inductive post filter surpasses the other techniques for ease of implementation in SIW technology. Marcuwitz proposed two methods for designing single inductive post filters as Off-Centered post and Centered post filters [5]. The former usually result in vias of same diameter while the latter gives vias of different diameters. Two symmetrically placed posts have some advantages over a single post. Intuitively, the extent of the higher-order fields might be expected to be smaller in the symmetrical case for the same given susceptance. This is due to the fact that no second-order mode is excited in this case. It is thus possible to put the matching structure closer to the load impedance without affecting its susceptance [1]. The geometry of the problem is shown in Fig. 2.

As illustrated in Fig. 2(b) the susceptance is to be found for the dominant mode (TE_{10}) with electric vector parallel to the posts. By assuming that the current in the post is uniform and that for the purpose of calculating the fields excited in the guide, the currents are concentrated along the axis of each post, Gruenberg developed some formulas for calculating the susceptance [1]. Also, it has been shown that the equivalent network is then transformed into a K-inverter using (2) [6].

$$\begin{aligned} K &= Z_0 \tan|\phi/2| \\ \phi &= -\tan^{-1}\frac{2X}{Z_0} \end{aligned} \tag{2}$$

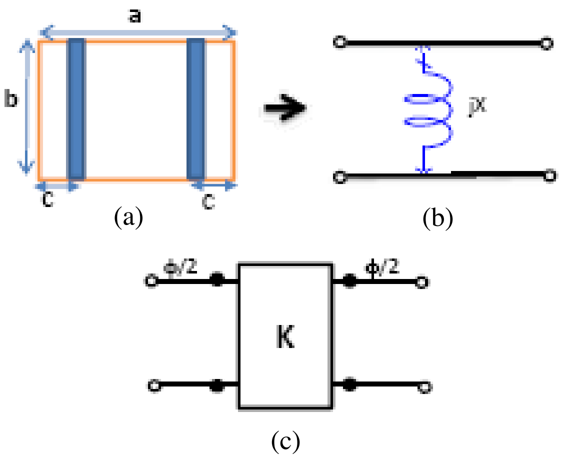


Figure 2. Dual inductive post filters design process. (a) Posts in waveguide. (b) Equivalent lumped circuit (c) Equivalent K-inverter network.

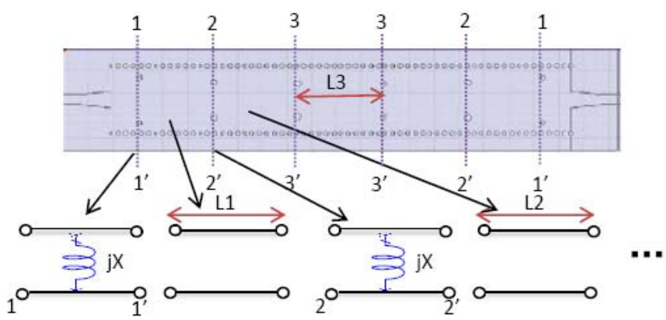


Figure 3. Equivalent circuit of waveguide filter.

In Fig. 3, the equivalent circuit of the whole filter is shown. It is clear that the cavity between the posts behaves as a half-wavelength resonator and the posts play their the role of the K-inverter.

It should be noted that, at the beginning of designing filter using SIW technique, the integrated waveguide should be mapped to a rectangular waveguide as described in [2] by considering that the total size of air-filled waveguide-filter must be inversely proportional to $\sqrt{\epsilon_r}$ like (1). Then, using the model has been shown in Fig. 2, and the theory developed by Gruenberg for calculating the susceptance of dual inductive posts in a waveguide, filter is designed on the basis of the renowned synthesis techniques for inductive posts in the rectangular waveguide, as depicted in [6]. Usually, inductive post filters that use a number of posts of different diameter located at the same distance from the side walls will result in some unfeasible via-holes on the PCB process. So, to resolve the problem, we considered both the distance from sidewalls and the diameter of the posts as variable parameters. The geometry of the filter is shown in Fig. 3.

4. EXPERIMENTAL RESULTS

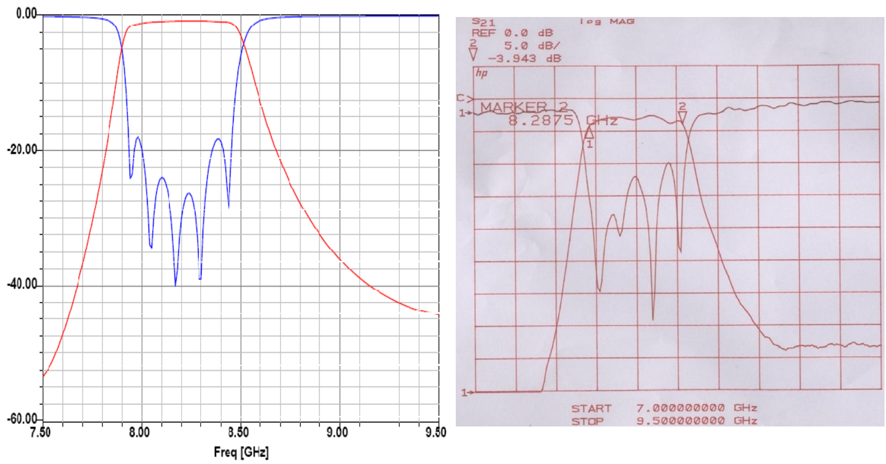
Following the rule presented in Section 3, a five-pole Chebyshev filter of 500 MHz bandwidth centred at 8.2 GHz has been designed, fabricated and measured. We used a 0.7874 mm-thick dielectric substrate with $\epsilon_r = 2.6$ and $\tan\delta = 0.0006$ (Taconic, TLT) to construct the circuit. The dimensions of the structure according to Fig. 1 are selected as, $a = 14.9$ mm, $p = 1.5$ mm, $h = 0.7874$ mm and the post diameter $d = 0.8$ mm. A well-known tapered microstrip transition has been designed and employed as described perfectly in [4]. The dimensions of the transition regarding Fig. 1 of [4] are, $w = 2.2$ mm, $d = 3.8$ mm, and $l = 6.5$ mm. Also the dimensions of the filter's posts are summarized in Table 1.

Table 1. Dimensions of the deigned filter. All the dimensions are in mm.

d1	**c1**	**L1**	**d2**	**c2**
0.9	2.46	15.21	1.1	3.47
L2	**d3**	**c3**	**L3**	
16.95	1.1	3.76	17.24	

Figure 4. Photograph of the manufactured five-pole Chebyshev filter.

Moreover, the manufactured prototype of the filter is shown in Fig. 4 and all results including the HFSS simulated and measured ones are shown in Fig. 5. The measurement shows the insertion loss around 2.5 dB and the return loss is better than 10 dB in the pass band. The insertion loss discrepancy between the simulated result and the measured one is because of that the commercial package used for simulation is not accurate for small thickness conductors, so the conductor losses were not modelled in the simulation. Also, the best manufacturing precision that we could apply is 100 microns and as it can be seen in Fig. 4 we filled all the via-holes since we were not sure that the posts have been metalized completely, so a sensible discrepancy was expected.



(a) (b)

Figure 5. (a) Simulated and (b) measured results for five-pole Chebyshev filter with two transitions of microstrip to integrated waveguide.

5. CONCLUSION

This paper deals with the dual inductive post filter design method applicable to PCB substrate integrated waveguide (SIW) filters on the basis of the design rule of the conventional air-filled waveguide filter. The advantages of this kind of structures are easily found by comparing the overall size of this structure with standard air-filled waveguide filter. Since the wave propagation characteristics in rectangular waveguide at dominant mode (TE_{10}) is only dependent on a, the proposed filter are very useful for small-sized millimetre and microwave systems.

REFERENCES

1. Gruenberg, H., "Symmetrical placed inductive posts in rectangular wave guide," Radio and Electrical Engineering Division, National Research of Canada, Ottawa, Canada, December 1951.
2. Deslandes, D. and K. Wu, "Single-substrate integration technique of planar circuits and waveguide filters," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 51, No. 2, February 2003.
3. Kim, B. S., J. W. Lee, K. S. Kim, and M. S. Song, "PCB substrate integrated waveguide-filter using via fences at millimeter-wave," *IEEE MTT-S Digest*, 2004.
4. Deslandes, D. and K. Wu, "Integrated microstrip and rectangular waveguide in planar form," *IEEE Microwave and Wireless Components Letters*, Vol. 11, No. 2, February 2001.
5. Marcuvitz, N., *Waveguide Handbook*, Peter Peregninus Ltd., 1985.
6. Matthaei, G. L., et al., *Microwave Filters, Impedance Matching and Coupling Structures*, Artech House, 1980.
7. Sanz Izquierdo, B., P. R. Young, N. Grigoropoulos, J. C. Batchelor, and R. J. Langley, "Substrate-integrated folded waveguide slot antenna," *IEEE International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials*, 2005.
8. Chen, X., W. Hong, T. Cui, J. Chen, and K. Wu, "Substrate integrated waveguide (SIW) linear phase filter," *IEEE Microwave and Wireless Components Letters*, Vol. 15, No. 11, November 2005.
9. Hao, Z. C., W. Hong, J. X. Chen, X. P. Chen, and K. Wu, "Planar diplexer for microwave integrated circuits," *IEE Proc.-Microw. Antennas Propag.*, Vol. 152, No. 6, December 2005.
10. Cassivi, Y. and K. Wu, "Low cost microwave oscillator using substrate integrated waveguide cavity," *IEEE Microwave and Wireless Components Letters*, Vol. 13, No. 2, February 2003.
11. Hao, Z. C., W. Hong, J. X. Chen, H. X. Zhou, and K. Wu, "Single layer substrate integrated waveguide directional couplers," *IEE Proc. - Microw. Antennas Propag.*, Vol. 153, No. 5, October 2006.
12. Deslandes, D. and K. Wu, "Integrated microstrip and rectangular waveguide in planar form," *IEEE Microwave Wireless Comp. Lett.*, Vol. 11, 68–70, February 2001.
13. Deslandes, D. and K. Wu, "Integrated transition of coplanar to rectangular waveguides," *IEEE MTT-S Int. Microwave Symp. Dig.*, Vol. 2, 619–622, 2001.
14. Jain, N. and N. Kinayman, "A novel microstrip mode to waveguide mode transformer and its applications," *IEEE MTT-S*

Int. Microwave Symp. Dig., Vol. 2, 623–626, 2001.

15. Nam, H., T.-S. Yun, K.-B. Kim, K.-C. Yoon, and J.-C. Lee, "Ku-band transition between microstrip and substrate integrated waveguide (SIW)," *IEEE APMC 2005 Proceedings*, 2005.
16. Sotoodeh, Z., F. H. Kashani, and H. Ameri, "A novel bandpass waveguide filter structure on SIW technology," *Progress In Electromagnetics Research Letters*, Vol. 2, 141–148, 2008.
17. Ghorbaninejad, H. and M. Khalaj-Amirhosseini, "Compact bandpass filters utilizing dielectric filled waveguides," *Progress In Electromagnetics Research B*, Vol. 7, 105–115, 2008.
18. Deslandes, D. and K. Wu, "Millimeter-wave substrate integrated waveguide filters," *IEEE CCECE2003*, 1917–1920, 2003.
19. Bahrami, H., M. Hakkak, and A. Pirhadi, "Analysis and design of highly compact bandpass waveguide filter using complementary split ring resonators (CSRR)," *Progress In Electromagnetics Research*, PIER 80, 107–122, 2008.
20. Khalaj-Amirhosseini, M., "Microwave filters using waveguides filled by multi-layer dielectric," *Progress In Electromagnetics Research*, PIER 66, 105–110, 2006.
21. Mohammad Amjadi, S. and M. Soleimani, "Design of bandpass waveguide filter using frequency selective surfaces loaded with surface mount capacitors based on split-field update FDTD method," *Progress In Electromagnetics Research B*, Vol. 3, 271–281, 2008.
22. Zhang, X.-C., Z.-Y. Yu, and J. Xu, "Novel band-pass substrate integrated waveguide (SIW) filter based on complementary split ring resonators (CSRRs)," *Progress In Electromagnetics Research*, PIER 72, 39–46, 2007.
23. Li, G. and C.-H. Liang, "Design techniques for microwave diplexers," *Progress In Electromagnetics Research B*, Vol. 2, 103–113, 2008.
24. Lee, Y., "CPW-to-stripline vertical via transitions for 60 GHz LTCC SOP applications," *Progress In Electromagnetics Research Letters*, Vol. 2, 37–44, 2008.
25. Eldek, A. A., "Wideband 180 degree phase shifter using microstrip-CPW-microstrip transition," *Progress In Electromagnetics Research B*, Vol. 2, 177–187, 2008.
26. Ranjkesh, N. and M. Shahabadi, "Loss mechanisms in SIW and MSIW," *Progress In Electromagnetics Research B*, Vol. 4, 299–309, 2008.
27. Che, W.-Q., C.-X. Li, D.-P. Wang, L. Xu, and Y. L. Chow,

"Investigation on the ohmic conductor losses in substrate-integrated waveguide and equivalent rectangular waveguide," *J. of Electromagn. Waves and Appl.*, Vol. 21, No. 6, 769–780, 2007.

28. Zhu, Y.-Z. and Y.-J. Xie, "Novel microstrip bandpass filters with transmission zeros," *Progress In Electromagnetics Research*, PIER 77, 29–41, 2007.
29. Prabhu, S., J. Mandeep, and S. Jovanovic, "Microstrip bandpass filter at S band using capacitive coupled resonator," *Progress In Electromagnetics Research*, PIER 76, 223–228, 2007.
30. Zhao, L.-P., X. Zhai, B. Wu, T. Su, W. Xue, and C.-H. Liang, "Novel design of dual-mode bandpass filter using rectangle structure," *Progress In Electromagnetics Research B*, Vol. 3, 131–141, 2008.
31. Wang, Y.-X., B.-Z. Wang, and J. P. Wang, "A compact square loop dual-mode bandpass filter with wide stop-band," *Progress In Electromagnetics Research*, PIER 77, 67–73, 2007.
32. Chen, J., Z.-B. Weng, Y.-C. Jiao, and F.-S. Zhang, "Lowpass filter design of Hilbert curve ring defected ground structure," *Progress In Electromagnetics Research*, PIER 70, 269–280, 2007.
33. Hasan, A. and A. E. Nadeem, "Novel microstrip hairpinline narrowband bandpass filter using via ground holes," *Progress In Electromagnetics Research*, PIER 78, 393–419, 2008.
34. Wu, G.-L., W. Mu, X.-W. Dai, and Y.-C. Jiao, "Design of novel dual-band bandpass filter with microstrip meander loop resonator and CSRR DGS," *Progress In Electromagnetics Research*, PIER 78, 17–24, 2008.
35. Ansoft Corporation, Ansoft HFSS ver.10, Ansoft Designer ver.3.5.