A General Design Method for Band-pass Post Filters in Rectangular Waveguide and Substrate Integrated Waveguide

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***Abstract*—This paper presents an efficient design approach for band-pass post filters in waveguides, based on mode-matching technique. With this technique, the characteristics of symmetrical cylindrical post arrangements in the cross-section of the considered waveguides can be analyzed accurately and quickly. Importantly, the approach is applicable to post filters in waveguide but can be extended to Substrate Integrated Waveguide (SIW) technologies. The fast computations provide accurate relationships for the *K* factors as a function of the post radii and the distances between posts, and allow analyzing the influence of machining tolerances on the filter performance. The computations are used to choose reasonable posts for designing band-pass filters, while the error analysis helps to judge whether a given machining precision is sufficient. The approach is applied to a Chebyshev band-pass post filter and a band-pass SIW filter with a center frequency of 10.5 GHz and a fractional bandwidth of 9.52% with verification via full-wave simulations using HFSS and measurements on manufactured prototypes.**

Keywords*—*Band-pass filters, Chebyshev filters, Mode-matching method, Substrate Integrated Waveguide.

I. Introduction

With the rapid development of microwave and millimeter-wave systems, the performance requirements of passive band-pass filters, as an essential part in these systems, are steadily increasing. Both waveguide and SIW filters are able to satisfy various high-performance requirements, with the waveguide filters offering the advantages of low loss and high power handling capabilities, while the SIW filters have the advantages of low cost and easy integration into planar circuit technology.

The mode-matching method has been developed as a highly accurate and efficient technique to analyze discontinuities in waveguides. Therefore, it also has been extensively applied in designing band-pass waveguide filters realized through irises [1], E-plane metal inserts [2], broadside oriented strip obstacles and multiple quadratic posts [3]. However, because of the limitations of micro-machining processes, for these types of waveguide filter designs, the corners of the various discontinuity features, e.g. between waveguide walls and irises, or for the rectangular holes of an E-plane metal insert, are rounded rather than perfect right angles. The resulting differences between ideal design and realizable geometries do influence the performance of the band-pass filters, especially when they operate at high frequencies [4], [5]. Compared with the above mentioned discontinuities in waveguides, cylindrical posts placed in one cross-section of a rectangular waveguide or circular holes are easier to manufacture. Thus, posts are less prone to machining errors and are promising for realizing band-pass waveguide filters at higher frequencies, e.g. in the mm-wave bands.

Similarly, the mode-matching method has also been utilized to design band-pass filters in SIW technology [6], [7]. However, most of the standard analysis methods to date have been limited to handle square via holes. Some other methods have also been applied to design band-pass SIW filters, including the equivalent circuit method [8] and the finite element method [9], where rows of vias were used to realize irises or E-plane inserts. All these designs require tuning or optimization in full-wave simulation tools (such as HFSS or CST) which are quite time-consuming because of the amount of variables and the quantity of vias, especially considering the requirement on mesh fineness in order to obtain results with sufficient precision. In addition, the requirement of machining accuracy is raised because each via row consists of several vias, and the distance and displacement between adjacent vias are all factors which may affect the performance of the band-pass filters. Therefore, to improve the analysis and reduce processing difficulties, it is advantageous to model the vias as posts instead of approximating them as irises or E-plane inserts.

In this perspective, the designs of band-pass post filters and band-pass SIW via filters as shown in Fig. 1 are handled as a single issue in this paper, since the SIW filters can be regarded as dielectrically loaded waveguide. Meanwhile, combining the method in [10] and Chebyshev band-pass filter principle, a post filter and a SIW filter with a center frequency of 10.5 GHz and a fractional bandwidth of 9.52% are designed and fabricated. For both filters, at least 20 dB insertion loss at 9.5 GHz and 15 dB return loss in pass band are required. The calculated results are firstly verified with full-wave simulations (Ansys HFSS) and secondly with measurements of manufactured prototypes. The satisfying agreement of results demonstrates the validity of the proposed design method. In addition, this paper also investigates the relationship among the *K* factors, the radii of the posts or vias and the distances between posts or vias in Sec. III, and explores the influence of fabrication errors in Sec. V.

II. Design Method

To adopt the same method to design post filters and SIW filters, firstly, the SIW should be transformed into a dielectric-loaded rectangular waveguide. This paper employs the equation introduced in [11], and the equivalent width W_e can be expressed as $W_e = W_i - \frac{d^2}{0.95p}$, where W_i is the physical width of the SIW, d is the via diameter, and p is the interval between two adjacent vias.

For the sake of convenience in the following section, the analysis focuses on the general problem of a dielectric-loaded waveguide with a width of a and a height of b.

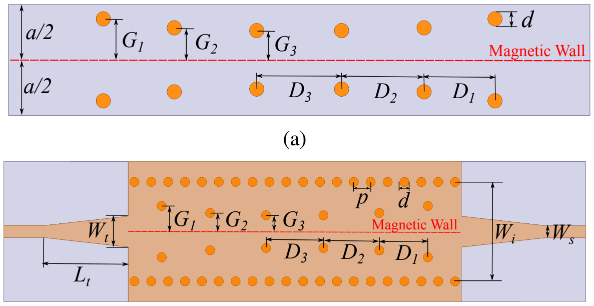


Fig. 1. The realizations of 5-cavity iris band-pass filters: (a) Rectangular waveguide post filter, (b) SIW via filter.

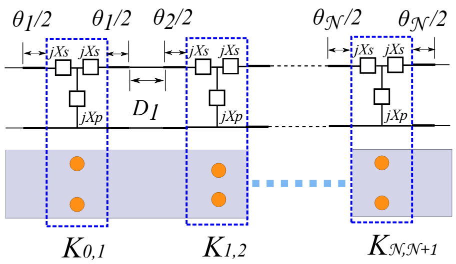


Fig. 2. The K-inverter and LC resonator $\mathcal{N}$-order band-pass filter network.

Theoretically, the scattering matrix of cylindrical posts inserted in the cross-section of a dielectric-loaded rectangular waveguide can be computed by cascading the scattering matrices of a series of rectangular bifurcations. Based on this approximation and adopting the method introduced in [12], an appropriate approach to approximate posts has been provided in [10]. It is noted that, by applying this recommended method to a symmetric structure, a magnetic wall can be placed at the center of the waveguide in order to reduce the computational cost through decreasing the number of coupling matrices.

For an $\mathcal{N}$-order Chebyshev band-pass filter, the network can be transformed into a K-inverter circuit as shown in Fig. 2 where each K factor can be obtained through equations provided in [13].

The K-inverter network can be realized by placing post pairs in a waveguide, since post pairs can behave as K-inverters while half wavelength waveguide cavities can work as LC resonators. The K value of a pair of posts is decided by their diameters d and the distance G to the magnetic wall. Thus, the dimensions can be determined through matching the K values (transformed from the scattering matrices) with the theoretical values. In addition, the lengths of the resonator cavities D_i (index i) can be computed based on the guided wavelength λ_g at the center frequency and the electrical lengths θ_i [1]:

$$D_i = \frac{\lambda_g}{2\pi}\left(\pi - \frac{\theta_i + \theta_{i+1}}{2}\right), \quad \theta_i = -\tan^{-1}(2X_p + X_s) - \tan^{-1}(X_s) \quad (1)$$

where $jX_s = \frac{1+S_{11}-S_{21}}{1-S_{11}+S_{21}}$, $jX_p = \frac{2S_{21}}{(1-S_{11})^2-S_{21}^2}$. Thus, the dimensions d, G, D required to realize band-pass filters can all be determined.

III. K Values Analysis of Posts or Vias

The K factors of post pairs in waveguides depend on the radii R of the posts and distances G to the magnetic wall. Therefore, to match K factors with theoretical values, it is possible to use the following three approaches: (a) fix the radii and adjust the distances, (b) fix the distances and adjust the radii, and (c) adjust both the radii and the distances.

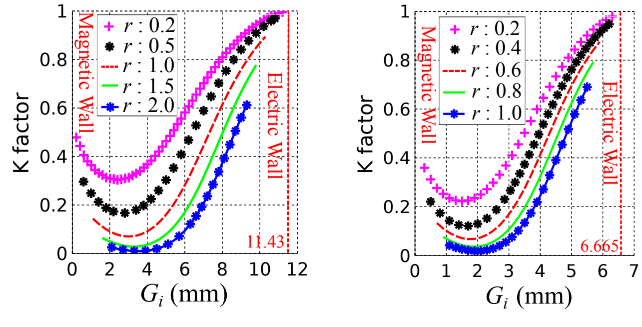


Fig. 3. The relationship among K factors, radii r and distances G_i to the magnetic wall: (a) Rectangular waveguide with a = 22.86 mm and b = 10.16 mm, (b) SIW with W_e = 13.33 mm and b = 0.762 mm.

From a simulation view, the third option should be discarded, since it contains twice the number of variables which increases the complexity of the design. From the fabrication view, it is a better choice to adopt the first option, because it is more convenient to manufacture with the same posts, in particular for the fabrication of SIW filters using rivets with standard sizes. Therefore, approach (a) is selected in the following analysis.

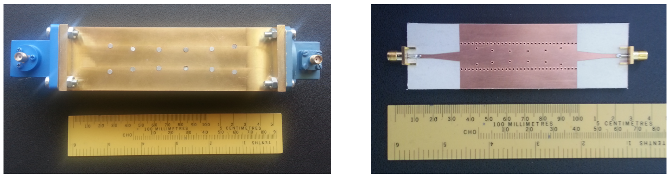
During the design and realization of a band-pass filter based on post pairs with different distances, starting from a blind choice for the post radius may waste time and lead to design failure. Thus, it is important to first ensure that, with the fixed radius, the K factors of the structures can yield all the required theoretical K values. Applying the method presented in [10] to symmetric post pair configurations, the dependence of the K factors on the radii R and the distances G are analyzed in Fig. 3(a) for a rectangular waveguide and in Fig. 3(b) for a SIW implemented in a Rogers 6002 substrate with a thickness of 0.762 mm and a relative permittivity of 2.94.

In general, the K factors for a pair of posts in a rectangular waveguide and a pair of vias in a SIW have similar variation trends. For a fixed radius, when progressively increasing the distance G, the K values drop first and then increase gradually. Besides, lower K values are obtained for thicker posts, when they are moved from the center of the waveguide (magnetic wall) to the electrical side wall. Obviously, from the computed curves as shown in Fig. 3, reasonable post size can be selected conveniently according to the theoretical K values.

IV. Design Examples

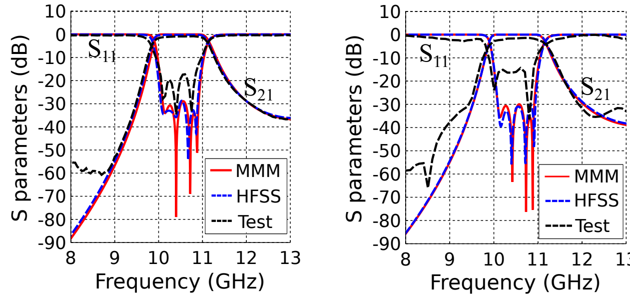
In this section, the presented technique is applied to design a band-pass post filter and a band-pass SIW filter shown in Fig. 4. Both symmetric Chebyshev filters are required to have a center frequency at 10.5 GHz and a fractional band-width of 9.52%. In addition, at least 20 dB insertion loss at 9.5 GHz and 15 dB return loss in pass band are required for both filters.

By utilizing posts with a radius of 1.5 mm and vias with a radius of 0.5 mm, the dimensions of each filter can be obtained within 1 second by a standard computer if 25 modes and 10-step approximation of the post are adopted. The calculated



(a) (b)

Fig. 4. Fabricated band-pass filters: (a) The post band-pass waveguide filter, (b) The SIW band-pass filter.



(a) (b)

Fig. 5. Comparison of S-parameters obtained using mode-matching method (MMM), finite-element method (HFSS) and measurements: (a) Band-pass post waveguide filter, (b) Band-pass SIW filter.

dimensions can be further optimized through space mapping technique or comparing the extracted coupling matrix with the theoretical one [14] in order to have closer frequency responses to ideal ones. However, since the calculated values already give satisfactory results, no optimization is applied in this paper. The obtained values for the geometry variables of Fig. 1(a) and (b) are listed in Table I and Table II respectively. It is noted that, in order to test the second filter, a microstrip-to-SIW transition as shown in Fig. 1(b) is designed by the method introduced in [15].

TABLE I. SIZES OF A BAND-PASS POST FILTER (UNITS: mm)

G_1, G_6	G_2, G_5	G_3, G_4	D_1, D_5	D_2, D_4	D_3
8.42	6.57	6.01	14.64	17.00	17.50

a	b	d
22.86	10.16	3

TABLE II. SIZES OF A BAND-PASS SIW FILTER (UNITS: mm)

G_1, G_6	G_2, G_5	G_3, G_4	D_1, D_5	D_2, D_4	D_3
4.39	3.20	2.79	8.33	9.60	9.87

W_i	W_t	L_t	W_s	d	p	b
13.91	5.29	14.12	2.08	1.00	1.80	0.762

The calculated results for both filters are first verified by finite-element method simulations (performed with Ansys HFSS) as shown in Fig. 5(a) and (b). Obviously, the calculated mode-matching results have a good match with the results of the full-wave simulation. It is noted that both mode-matching calculation and finite-element simulation do not take losses into account.

A second validation of the method is provided with experimental results. For the waveguide post filter, the measured passband agrees well with the calculated results. The measured insertion loss at 10.5 GHz is about 0.87 dB including losses in the two coaxial-to-waveguide adapters, while the return loss in the passband is better than 18 dB. A test of the two adapters in back-to-back configuration shows that in passband the S_{21} is around -0.28 dB and the S_{11} is below -18 dB, hence, the higher S_{11} parameter can be explained through the non-ideal transitions. Besides, unaccounted losses are also caused by the visible surface roughness of the inner waveguide and posts. For the SIW filter, the testing results also match well with the calculated results. The measured insertion loss at 10.5 GHz is about 1.51 dB including losses in the two SMA connectors, while the return loss in the passband is better than 15 dB. Clearly, compared with the waveguide post filter, the SIW filter has relatively high insertion losses since more losses are introduced by the dielectric, the transition structure and the microstrip line. However, the SIW filter is much lighter and easier to integrate into other planar circuits from a practical perspective.

To sum up, the results of both validations for the two filters agree well with the calculation results. Thus, the efficiency and the accuracy of the design approach are successfully validated.

V. TOLERANCE ANALYSIS

The performance of a band-pass post filter or a band-pass SIW filter is affected by manufacture-induced errors on the width a of the waveguide or the equivalent width W_e of the SIW, on the radii R of the posts, on the gaps G from the posts to the magnetic wall, on the lengths D of the resonant cavities as well as by the relative position of the posts. For the SIW filter, the equivalent width W_e also can be influenced by errors on the radius R of the via, on the space W_i between the two via rows and on the pitch p between the two adjacent vias. Owing to the larger number of arbitrary combinations and for the sake of brevity, only the influence of the major sources of errors is described here, i.e. waveguide widths, post radii, gap dimensions and the cavity lengths.

As shown in Fig. 6(a) and (e), by increasing the width or equivalent width with an error from -0.5 mm to +0.5 mm, the center frequencies for both filters shift to lower frequencies. However, the variations of the 3 dB bandwidths change in different ways, i.e. the 3 dB bandwidth of the post filter turns narrower, while that of the SIW filter becomes wider. The offset and variation of the center frequency and the 3 dB bandwidth caused by the other manufacture tolerances have very similar trends in the post filter and SIW filter. Therefore, the comments in the following focus on the SIW filter (Fig. 6(f), (g) and (h)).

Fig. 6(f) shows that by increasing all radii with an error between -0.1 mm and 0.1 mm, the center frequency of the band-pass filter shifts to higher frequencies, while the 3 dB bandwidth becomes narrower. In contrast, Fig. 6(g) shows that by increasing all gaps with errors between -0.5 mm and 0.5 mm, the center frequency moves to lower frequencies, while the 3 dB bandwidth becomes wider. Other than in the previous two cases, the distance errors lead to changes of the centre frequency and bandwidth in the same direction as shown in Fig. 6(h). By increasing the distance with an

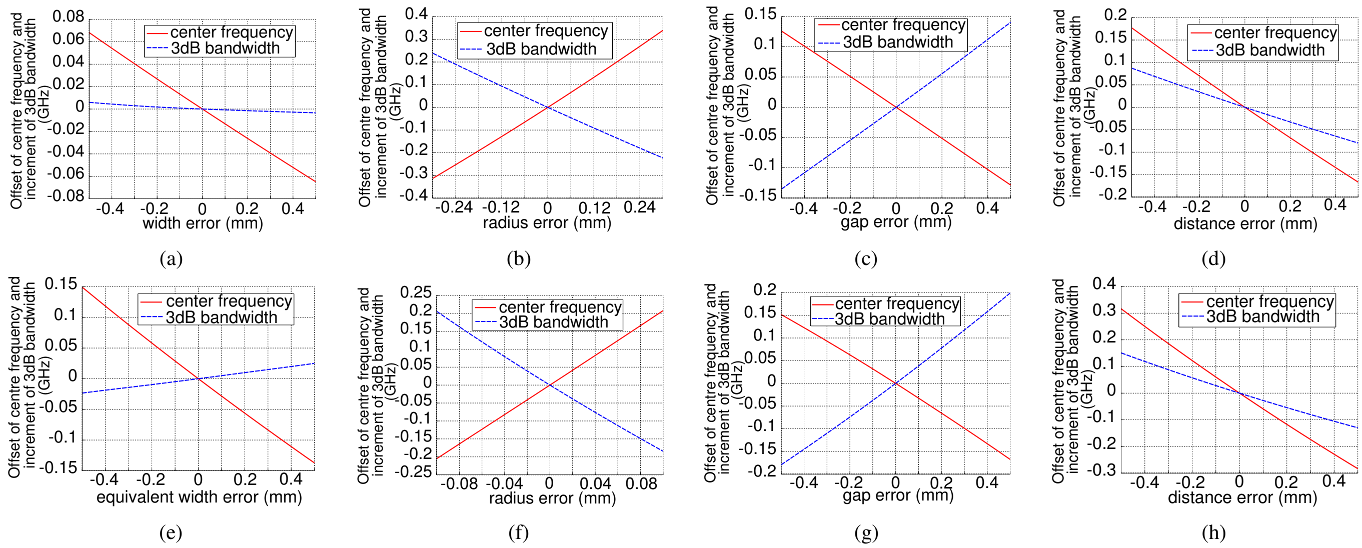


Fig. 6. The offset of center frequency and variation of 3dB bandwidth caused by machining errors: (a) Width errors in the post filter, (b) Radius errors in the post filter, (c) Gap errors in the post filter, (d) Distance errors in the post filter, (e) Equivalent width errors in the SIW filter, (f) Radius errors in the SIW filter, (g) Gap errors in the SIW filter, (h) Distance errors in the SIW filter.

error from -0.5 mm to +0.5 mm, both the center frequency and the 3 dB bandwidth decrease. In addition, for the SIW filter, the offset and variation also can be caused by the error of the relative permittivity, e.g. specified by the manufacturer as ± 0.04. However, tests of this material parameter tolerance indicate that the impact of this error can be neglected.

VI. Conclusion

In this paper, the analysis and design of band-pass waveguide post filters and band-pass SIW filters have been considered. Based on the mode-matching technique, the principle of a common efficient design method has been presented for both types of post filters. Applying this method, the K factors of post or via pairs placed in one cross-section of a rectangular waveguide or SIW have been analyzed, including the influence of manufacture tolerances. Based on the calculated relationship between the K-factors and the structure dimensions, it is convenient to choose reasonable posts or vias for designing band-pass filters, while the tolerance analysis allows to assess the suitability of a machining process with a given precision to fullfil a desired set of specifications. A Chebyshev band-pass post filter and a Chebyshev band-pass SIW filter have been designed and fabricated. The calculation results for both filters match well with the simulation results obtained with HFSS. The experimental data obtained with manufactured prototypes for the two filters also show a good agreement with the calculation results. The presented results demonstrate the viability and validity of the proposed design framework.

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