Analysis and Design of Mass-Producible Cross-Coupled, Folded E-Plane Filters

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***Abstract* — Mass-producible, folded E-plane metal-insert filters with and without finite transmission zeros are introduced for the first time. The metallic inserts and the separating wall between the inserts can be accurately fabricated to +/-1mm tolerances using electroforming techniques. Source-load coupling as well as (negative) coupling between resonators can be realized. The resulting filters are much shorter than traditional E-plane filters and show significantly improved slope selectivity.**

I. Introduction

Filters and duplexers for millimeter-wave applications like LMDS or MVDS etc. must be low-cost, mass-producible and satisfy relatively tight electrical specifications. A class of filters well suited for this purpose are E-plane filters. They can be realized as finline or all-metal insert structure and have been utilized for more than two decades in the frequency range from a few GHz up to 150GHz.

E-plane filters are direct inductively coupled cavity filters and their performance is essentially determined by the metalization pattern of the insert. Since the insert thickness ranges from 50-100μm, it can be fabricated by photolithographic or, for better accuracy and repeatability, electroforming processes. Their relatively simple geometry makes the analysis and design, which is mostly based on the Mode Matching Technique (MMT), (i.e. [1,2]), straightforward.

A well known disadvantage of E-plane filters is the fact that a steep attenuation slope requires a large number of resonators which makes these filters not only quite long but also increases their passband insertion loss.

In this paper we introduce a way to combine the advantages of E-plane filters (i.e. simple design, mass-producible etc.) with that of cross-coupled filters (high slope selectivity) to a new class of E-plane filters. In order to do so, we first introduce folded E-plane filters instead of arranging the resonators and coupling sections in one straight line. This leads to very compact components which are useful when space is a problem. In addition, if the separating wall between the two filter halves is made from a thin metal sheet, preferably the same material from which the metal inserts are fabricated (Figure 1), source-load coupling can be accomplished easily by etching openings into the separating wall. In the same fashion, one can couple various resonators, and also negative coupling can be realized. Introducing finite transmission zeros close to the passband increases the slope selectivity and thus improves the transfer characteristics of E-plane filters significantly.

Since cross-coupling is very sensitive to the dimensions and locations of the coupling holes, these openings must be fabricated with the same precision as the ladder-shaped metal inserts, which is possible due to the small wall thickness. The exact positions and dimensions of the openings are computed accurately with the MMT and 55 higher order modes, therefore eliminating the need for manual fine tuning.

In the following we first introduce the folded E-plane filter and show a comparison with its traditional realization. Secondly, we investigate source-load coupling and again show a comparison with a traditional E-plane filter. For some arrangements, it is necessary to realize negative coupling elements. This is achieved by using higher order resonances and properly shifting the location of the coupling apertures [3]. Using this approach, and source-load coupling, 2 finite transmission zeros are generated using 2 resonators. The resulting filter is then augmented to implement a 4-pole pseudo-elliptic filter with two finite transmission zeros. To our knowledge this is the first time that E-plane filter technology is being utilized in the realization of cross-coupled filters. The advantages are obvious: Low-cost mass-fabrication is possible, no manual fine tuning is required and significantly improved E-plane filter performance is achieved.

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II. THEORY

The geometry of cross-coupled folded E-plane filter is shown in Figure 1. In this example, the structure consists of 4 cavity resonators, directly coupled through evanescent waveguide sections (metal septa). Cross coupling between the 1st and the 4th resonator is realized by introducing an opening in the separating wall. Also the 2nd and the 3rd resonators are coupled through a wall opening. Both openings extend over the full height of the waveguide. This makes the analysis straightforward since only TE_{mo}-modes are excited.

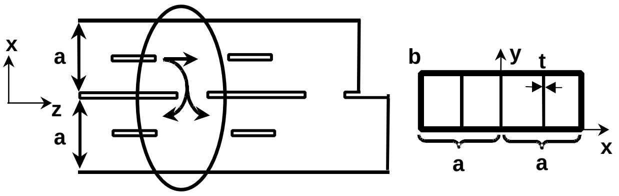


Fig. 1. Cross-coupled folded E-plane single metal insert filter structure.

The individual discontinuities are bifurcations when viewed along the z-axis (Figure 2). Generalized scattering matrices of the waveguide bifurcations are calculated using standard Mode Matching Technique (MMT)[1,2]. For each subregions, the fields are derived from the *x*-component of the magnetic Hertzian potential Π_h which satisfies the vector Helmholtz equation [2]

$$\nabla^2\vec{\Pi}_h + k^2\vec{\Pi}_h = 0 \qquad (1)$$

and the boundary conditions at the metallic surfaces. The field components can be calculated using following equations:

$$\vec{E}^n = -jwm\nabla\times\Pi^n_{hx} \quad \vec{H}^n = \nabla\times\nabla\times\Pi^n_{hx} \qquad (2)$$

By matching the tangential components at the common interfaces and using the appropriate orthogonal functions, three-port scattering matrix of bifurcations, which relate the eigenmode amplitudes in each region to each other, are obtained. For example, S^B matrix of left bifurcation in Figure 2 will be in this form

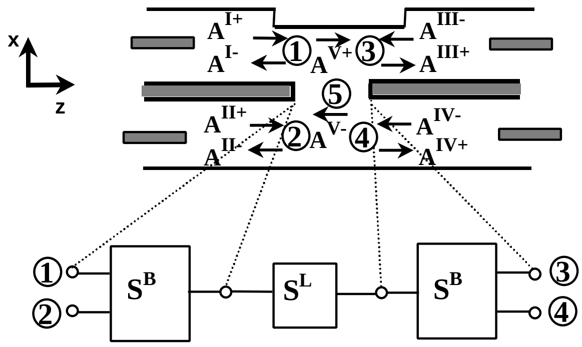


Fig. 2. General key building blocks (Waveguide bifurcation and waveguide of length L).

$$\begin{pmatrix} A^{I-} \\ A^{II-} \\ A^{V+} \end{pmatrix} = \begin{bmatrix} S^B_{11} & S^B_{12} & S^B_{13} \\ S^B_{21} & S^B_{22} & S^B_{23} \\ S^B_{31} & S^B_{32} & S^B_{33} \end{bmatrix} \cdot \begin{pmatrix} A^{I+} \\ A^{II+} \\ A^{V-} \end{pmatrix} \qquad (3)$$

where the elements include the reflection and transmission coefficients related to higher order modes. To find the scattering parameters of the overall structure, generalized scattering matrices of individual discontinuities are cascaded. For example, the structure in Figure 2 has two bifurcations (S^B) and a homogeneous waveguide section (S^L). Thus the overall four-port generalized scattering matrix is as follows:

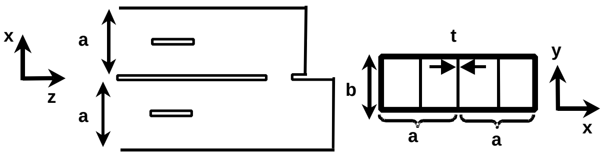
$$\begin{pmatrix} A^{I-} \\ A^{II-} \\ A^{III+} \\ A^{IV+} \end{pmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \cdot \begin{pmatrix} A^{I+} \\ A^{II+} \\ A^{III-} \\ A^{IV-} \end{pmatrix} \qquad (4)$$

Note that no symmetry conditions have been applied since the optimum structure may be asymmetric and thus all modes must be considered.

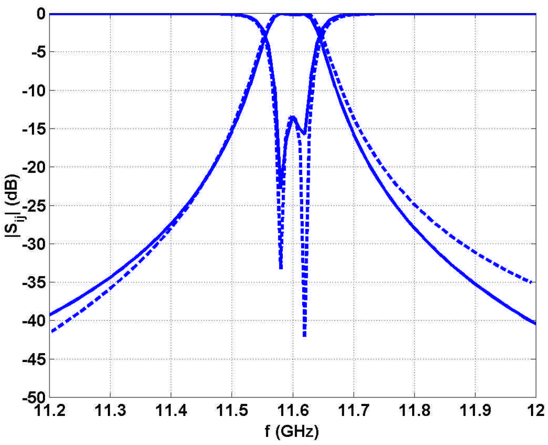
An important issue in cross-coupled filters is the realization of negative coupling using only magnetic coupling. Consider the 4 resonator filter shown in Figure 1. To generate two transmission zeros, the coupling between resonators 1 and 4 must be negative [4]. If only the fundamental resonance (TE_{101}) is used, the cross coupling would be positive thereby placing the transmission zeros on the real axis in the complex s-plane. To get a negative coupling, we use the next resonance, i.e. (TE_{102}), in resonator 3. The coupling slot between resonators 2 and 3 is located in the second half of resonator 3 to force a negative coupling between 1 and 4. This shifting technique is well described in [3]. A synthesis technique of canonical filters with source-load coupling was developed by Bell [5]. Furthermore, the utilization of source-load coupling was also reported by Zaki and co-workers [6] and others [7]. But up to now this technique has never been applied to E-plane filters.

III. Results

In our first example, we investigate a direct coupled 2 resonator filter as shown in Figure 3(a). The synthesis of this filter can be carried out using the standard inverter approach of Cohn [8]. To finalize the design and correct for the dispersion in the coupling between the two resonators, the synthesized filter is optimized. The resulting response is shown in Figure 3(b). The synthesis, optimization and final analysis was performed using M = 55 modes.



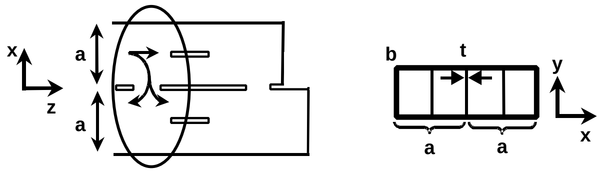
(a)



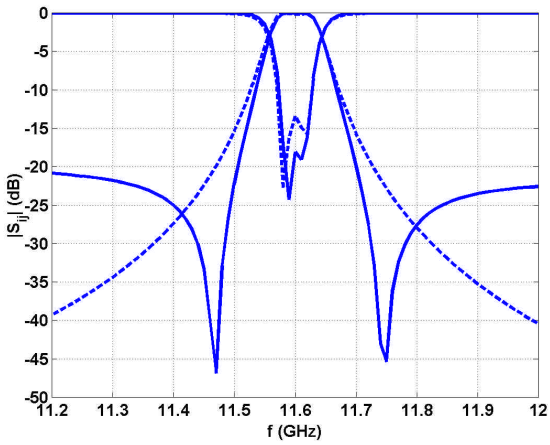
(b)

Fig. 3. (a) Structure of folded E-plane single metal insert filter, (b) response of ordinary folded E-plane single metal insert filter (solid line) and straight E-plane single metal insert filter (dashed line).

The realization of the filter with input-output coupling consists of an additional coupling slot between input and output as shown in Figure 4(a). A similar filter using irises as coupling mechanism was recently proposed in [9]. Unfortunately, the fact that in that solution the irises must be machined with high precision excludes this kind of filters from a mass-production process. The results of the source-load coupled E-plane filter are illustrated in Figure 4(b). The response of the filter is obtained after optimizing 9 dimensional variables. In comparison to a standard E-plane filter with the same number of resonators, the improvement is evident. The presence of the two finite transmission zeros improves the stopband behavior significantly.



(a)



(b)

Fig. 4. (a) Structure of folded E-plane single metal insert filter with source-load coupling, (b) response of folded E-plane single metal insert filter with (solid line) and without source-load coupling (dashed line).

The next example shows a cross-coupled bandpass filter with 4 resonators (Figure 1). Resonator 1 and 4 are coupled with a negative coupling coefficient. The response of the filter is shown in Figure 5 and compared with that of an ordinary E-plane filter with the same number of resonators. Also in this case the improvement is remarkable. Currently several filters are fabricated as prototypes. A preliminary analysis of the optimized filter structures with HFSS and the MMT shows very good agreement (Figure 5).

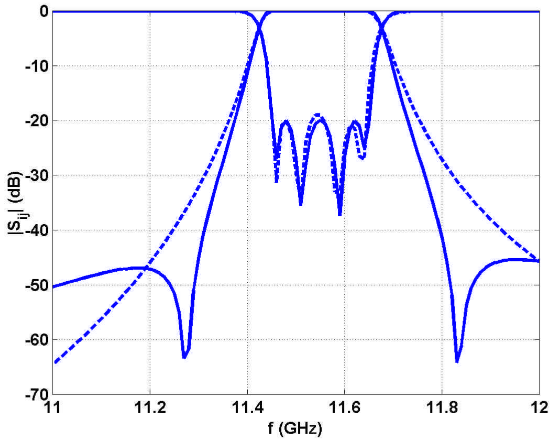


Fig. 5. Response of cross-coupled folded E-plane single metal insert filter (solid line) and straight E-plane single metal insert filter (dashed line) with 4 resonators.

IV. CONCLUSION

For the first time cross-coupled E-plane filters have been developed. Since manual fine tuning can be eliminated with this type of filters, mass production of cross-coupled folded E-plane metal insert filters becomes possible. Analysis and design of these filters is based on the Mode Matching Technique (MMT) in combination with the generalized S-matrix method. Finite transmission zeros are generated either by exploiting source-load coupling and/or standard cross-coupling in the folded structure. Two cross-coupled filters have been designed to show the validity of the approach. In both cases, the filter response was significantly improved compared to the standard E-plane filter performance.

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