A Flexible S-Matrix Algorithm for the Design of Folded Waveguide Filters

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Abstract — **Based on a versatile S-matrix formulation, a flexible design concept for folded waveguide filters is presented. Even- and odd-order filters can be designed with transmission zeros placed arbitrarily. Different configurations are shown to achieve responses, which satisfy a wide range of possible filter requirements. The process is validated by comparison with both commercially available software and measurements.**

I. INTRODUCTION

Folded waveguide topologies are well known in the initial synthesis aspects of elliptic or quasi-elliptic filters. They can be used in combination with subsequent similarity transforms, e.g. [1], as a direct synthesis tool, e.g. [2], or as a simple means of including source-load coupling, e.g. [3]. Earlier designs of folded filters were mainly concerned with phase linearization , e.g., [4], [5].

With the introduction of comb-line filters for size reduction in the lower GHz frequency range and advances in the numerical modeling aspects, the folded concept has been revitalized, e.g. [6] – [8], and recently found applications in standard H-plane filter and diplexer environments, e.g., [9] – [11]. Based on the folded topology, only filters with even numbers of cavities have been used so far. These structures are either symmetric with respect to the center wall between the two folded halves (standard design) or asymmetric in the sense that the two filter halves are slightly shifted in order to obtain the correct signs of the cross couplings, e.g. [8], [9], [12].

Another reason for the rather sparse use of folded filters is the common belief that because of their cross coupling properties, they are more prone to manufacturing tolerances than, e.g., direct-coupled filters. However, this assumption has been contradicted in a recent investigation, which concludes that there is no difference in the passband tolerance behavior between direct- and folded cross-coupled filters [13].

This paper revisits H-plane folded waveguide filters for the purpose of demonstrating their flexibility and adaptability to different filter specifications. A versatile S-matrix algorithm based on mode-matching techniques is set up which is shown to handle even and odd numbers of cavities and a variety of different locations of coupling apertures. The method is verified through computations with µWave Wizard, HFSS and measurements.

II. THEORY

The analysis of folded asymmetric filter components is based on the combination of two-ports and four-ports within the generalized scattering matrix. It is one of the advantages of this approach that contrary to impedance, admittance or coupled-integral-equation approaches, individual section lengths, such as short circuits, can be set to zero without any detriment to the numerical computation of the component. Similarly, irises can be opened to combine individual sections to a single cavity, etc.

Fig. 2 shows the basic concept. The analysis is started at the folded end of the filter, where the two-port generalized scattering matrix representing the two shorts is given by

$$\underline{S}_{short} = \begin{bmatrix} -\mathrm{Diag}\left\{-2k_{zm}^{III} L_1\right\} & \underline{0} \\ \underline{0} & -\mathrm{Diag}\left\{-2k_{zn}^{IV} L_2\right\} \end{bmatrix} \quad (1)$$

In (1), Diag{} denotes a diagonal matrix, $\underline{0}$ a zero matrix, and the k's are the modal propagation constants in the two different waveguides. Note that the scattering matrices of other structures, e.g. irises or cavities, can be connected to that of (1) before a common aperture (four-port) between the two guides is approached.

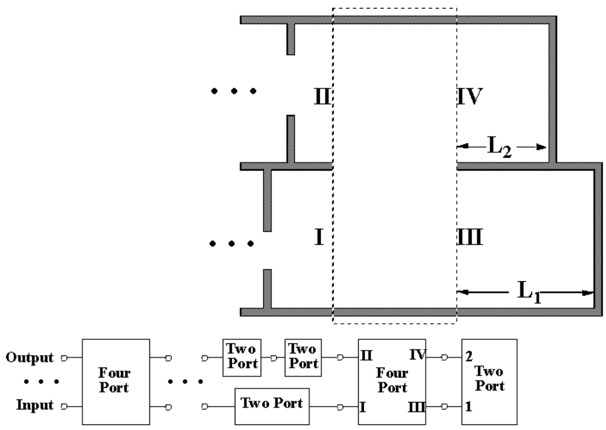


Fig. 1. Top view of the folded-end section and representation as two- and four-port generalized scattering matrices.

The four-port is combined with the two-port on its right (Fig. 1) to form a resulting two-port with ports I and II, e.g. [14]. Different two-port scattering matrices can again be attached to port I or II representing an arbitrary number of irises or cavities, where individual lengths can be set to zero to match the next common aperture (four-port) following to the left. This process is continued until the generalized scattering matrix of the entire folded filter is obtained.

The following examples demonstrate the versatility of the method.

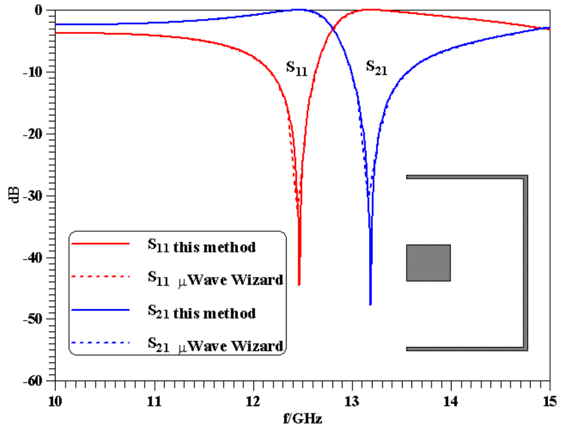


Fig. 2 Performance of a folded waveguide and comparison with results obtained with μWave Wizard.

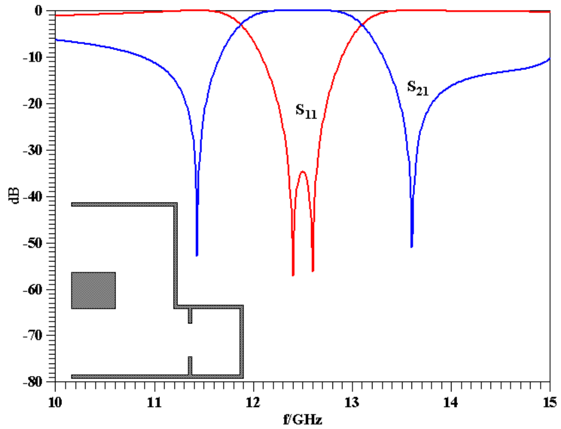


Fig. 3 Performance of folded waveguide with added resonator.

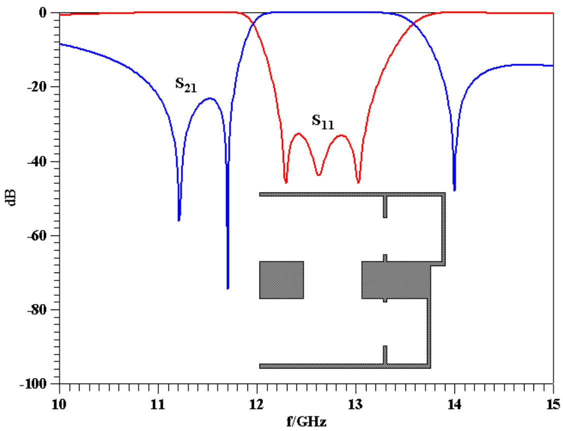


Fig. 4 Performance of folded waveguide with two added resonators.

Fig. 2 shows a waveguide folded in the H-plane. Due to the relatively thick wall between input and output, we achieve a reflection and a transmission zero very close to each other. The performance is validated by the commercial package μWave Wizard.

Figs. 3 and 4 show the folded waveguide with added resonators. Since each of these resonators produce their own reflection and transmission zero (note that they are bypassed by the folded waveguide), Fig. 3 allows for two reflection and two transmission zeros. The second cavity in Fig. 4 adds another pair of reflection and transmission zero.

III. Filter Design

Using the method described above, a specific design of a folded filter is carried out in several steps:

1. Synthesize the coupling matrix for given filter specifications [15].
2. Design a folded Chebychev filter using TE_{101} or TE_{102} cavities, and shift the left and right waveguide parts so that cross-couplings with the appropriate signs can be realized in the following step.
3. Insert cross-coupling apertures by comparing the sizes of the apertures in the Chebychev design with those in the coupling matrix of step 1 and optimize.

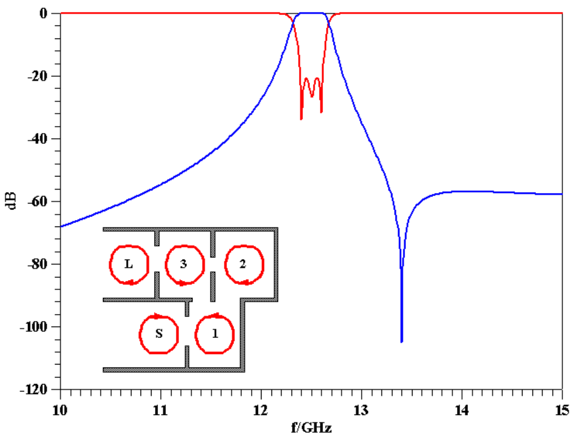
This strategy has been applied to all structure shown below. A number of two-pole designs with source-load coupling have been presented in [12] and will not be repeated here. Instead we will focus first on different possibilities involving folded filters with three cavities. (WR75 waveguide is assumed for this investigation.)

Fig. 5a shows a folded trisection with one transmission zero to the right of the passband. As indicated by the arrows on the circles representing the magnetic field, the 1-3 coupling is negative which is in agreement with the inline trisection arrangement in [16]. In order to move the transmission zero to the other side, the sign of the cross coupling needs to change. This can be accomplished by using a TE_{102} cavity as resonator 1 as shown in Fig. 5b. An additional coupling via the fundamental-mode resonance of the TE_{102} cavity produces the additional transmission zero at 10.55 GHz. It works in favor of the filter specifications and can be used in the filter optimization. Fig. 5c shows a design with two transmission zeros which are realized by a negative cross coupling between resonator 1 and load.

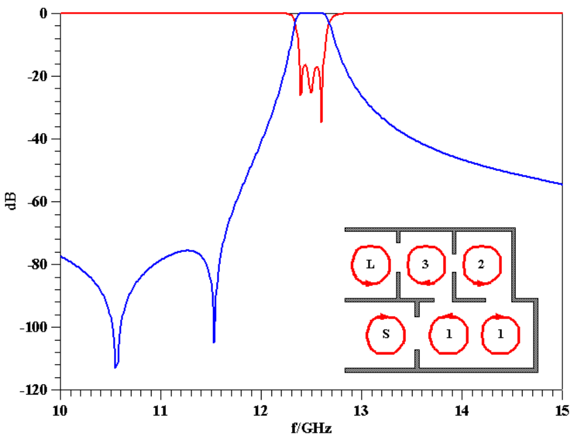
The next example is the four-pole filter shown in the inset of Fig. 6. The coupling matrix dictates source-load and 1-4 coupling to produce four transmission zeros – two on each side of the filter passband. The lower right cavity operates in the TE_{102} mode to produce the correct signs of the cross couplings. Excellent agreement with HFSS is obtained, thus verifying the S-matrix procedure.

Figs. 7 and 8 show design examples with five and six resonators, respectively. Similar to the filters in Figs. 5b and 6, they use at least one TE_{102} cavity to produce the correct cross couplings. Fig. 7 features a 2-5 coupling to create 2 transmission zeros. Additional 1-L coupling (not shown here) can be used for phase linearization. Fig. 8

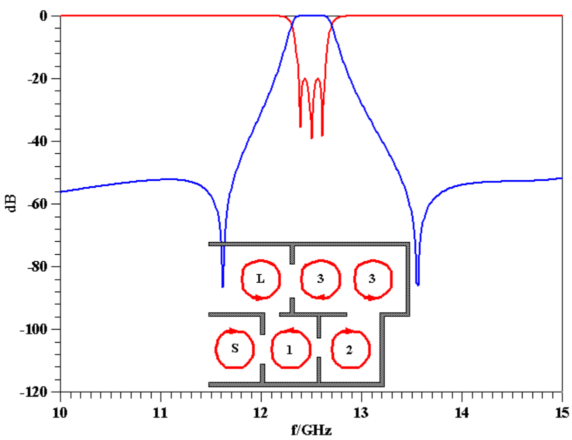
creates the same number of transmission zeros with a 2-5 cross coupling. We believe that these design examples demonstrate the versatility and flexibility of folded H-plane filters as required in the large majority of possible applications.



(a)



(b)



(c)

Fig. 5. Three-pole folded H-plane filters with transmission zeros to the right (a), to the left (b) and on both sides of the passband (c).

In order to verify the code experimentally, measurements of a previously designed Ku-band cross-coupled H-plane filter are compared to the results obtained with our S-matrix mode-matching procedure.

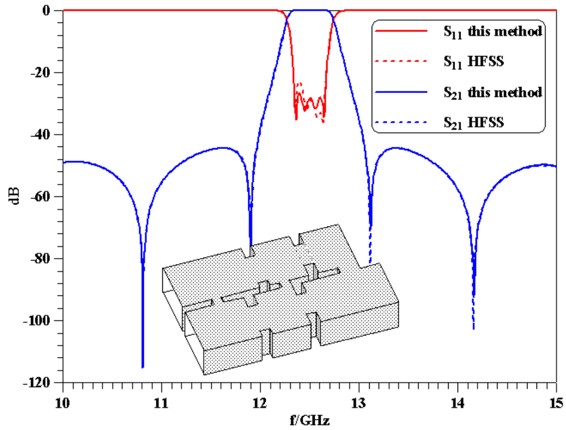


Fig. 6. Four-pole folded filter with four-transmission zeros and performance comparison with HFSS.

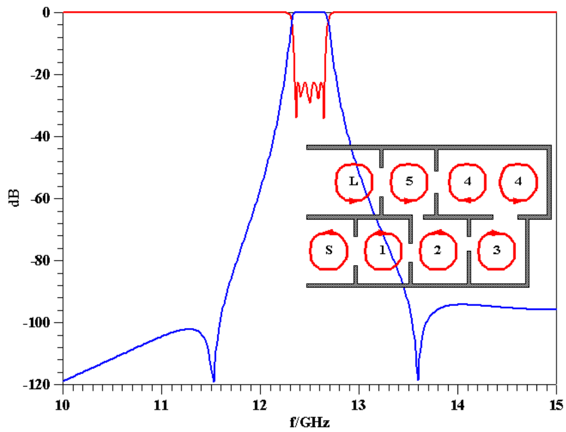


Fig. 7. Five-pole folded H-plane filter with two transmission zeros.

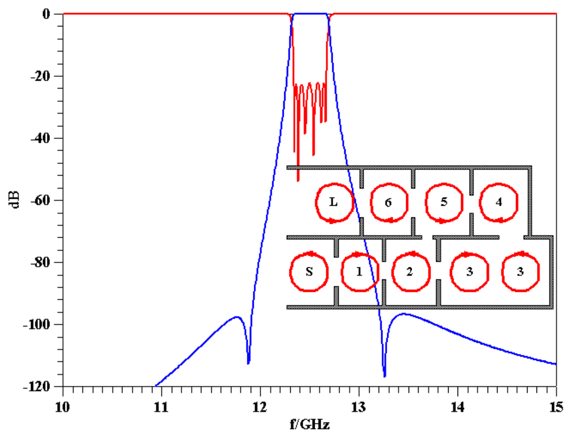
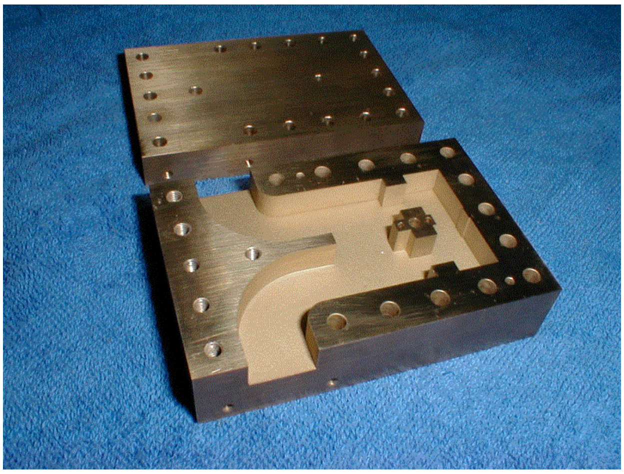
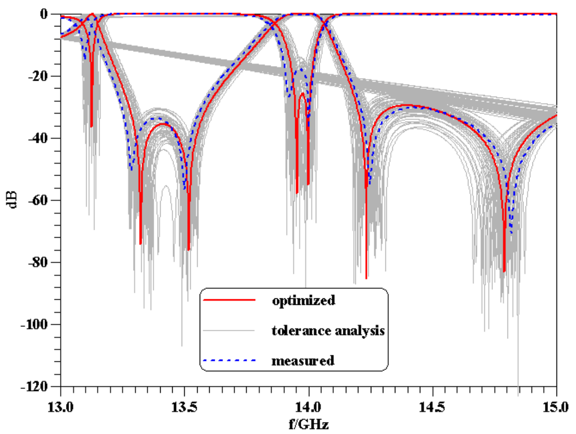


Fig. 8. Six-pole folded H-plane filter with two transmission zeros.

Fig 9a shows a photograph of the prototype. The filter uses overmoding to produce four transmission zeros with two TE_{101} cavities at the expense of another passband around 13.2 GHz (Fig. 9b). Since the dimensions of the fabricated filter differ from the optimized ones by up to 25µm, a tolerance analysis [13] with ±25µm is shown in Fig. 9b as gray lines. (Note that the straight lines in the background are caused by the trace back from the last point of analysis i to the first point of analysis i+1.) Within the tolerance margin, Fig. 9b shows the measured (dotted lines) and computed (solid lines) to be in very good agreement.



(a)



(b)

Fig. 9. a) Photograph of the fabricated Ku-band filter; b) Tolerance analysis and comparison between theory and measurements.

IV. Conclusions

H-plane folded filters present a viable option for versatile filter realizations in waveguide technology. Based on a flexible S-matrix arrangement of the underlying code, the mode-matching routine presented in this paper can handle even and odd numbers of resonators with a variety of cross couplings including that from source to load. Examples demonstrate the applicability of folded filters for different applications. Comparisons with measurements and commercially available software verify the design procedure.

Acknowledgement

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