Novel Coupling Schemes for Microwave Resonator Filters

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Abstract-- **The paper presents novel coupling schemes for microwave resonator filters. Some of these solutions contain more than one main path between the input and output. These paths may be interacting or non-interacting. In other solutions, only some of the direct (main) couplings are zero. It is shown that higher-order filter characteristics can be obtained from lower-order sections, which are connected in parallel between the source and the load, by proper superposition of the individual lower-order responses. Possible applications of these solution to actual design problems are discussed.**

Index Terms—**resonator filters, elliptic filters, band-pass filters, synthesis, N-path filters, design, dual-mode filters.**

I. INTRODUCTION

THE synthesis and design of elliptic and pseudo-elliptic coupled resonator filters is an important part in the design of components for modern communication systems. Filtering structures for these systems are required to provide sharp cutoff slopes, asymmetric responses and equalized group delay. All these features can be successfully achieved by filters with transmission zeros at finite frequencies in the complex plane.

An examination of the synthesis techniques available in the literature shows that elliptic and pseudo-elliptic filters are considered as perturbed versions of the all-pole Chebychev solution for a filter of the same order, center frequency, bandwidth and ripple level. The perturbation, which takes the form of cross or bypass couplings, is responsible for bringing the transmission zeros from infinity to finite positions in the complex plane. In particular, the coupling and routing scheme of these filters always include a main path in which the i^{th} and $(i+1)^{th}$ resonators are directly coupled with relatively strong direct or main couplings. Fig. 1a depicts in principle the conventional coupling scheme for a 4-pole elliptic function filter design. The actual determination of the values of the coupling coefficients can be done using extraction techniques, which may be followed by similarity transformations to eliminate unwanted and un-realizable couplings [1-5], or by optimization [6]-[10].

This paper is written to introduce new solutions to the elliptic and pseudo-elliptic coupled resonator filters where some of the direct (main) couplings are zero. These solutions, which may involve coupling the source and the load to more than one resonator, contain more than one main path (N-path filters) for the signal between the source and the load. These paths may originate at the source and terminate at the load (c.f. schemes of 4-pole filter examples in Fig 1b, 1c) or originate and terminate between internal resonators. There may also be non-interacting, as in parallel realization [11]-[12], or interacting through additional bypass or cross-couplings. Some of these solutions can be used to design dual-mode filters without intra-cavity couplings.

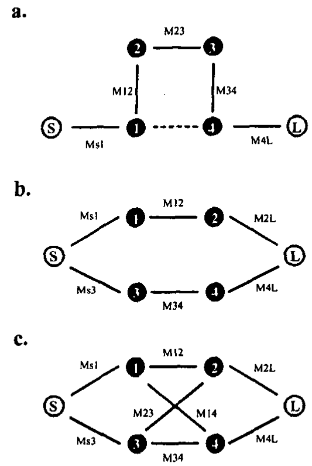

Figure 1. Coupling schemes of 4-pole filters providing elliptic function characteristics. a) conventional with cross coupling b) 2-paths (non-interacting) and c) 2-paths (interacting).

An interesting property of filters consisting of several parallel non-interacting main paths between the source and the load is the fact that the response of the individual paths yield the response of the complete filter by proper superposition. Consequently, these new solutions may facilitate the realization of higher-order filters by breaking them down into separate parallel sections which are designed and tuned separately and then interconnected at the interface ports.

II. SYNTHESIS PROBLEM

The model used for the set of coupled resonators is based on the structure proposed by Atia and Williams with proper extension to include source/load-multi-resonator couplings. The synthesis problem consists in determining the coupling coefficients, which are assumed frequency-independent, and

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the frequency shifts of the resonators such that the response of the structure is identical to a prescribe elliptic or pseudo-elliptic response. To this end, we use the technique presented in [10]. In this technique, the entries of the coupling matrix are used as independent variables in a gradient-based optimization technique where a sufficient cost function is used. The generality of this technique allows the investigation of new topologies for resonator filters. Details and some examples can be found in [10].

The first step in the synthesis is to select a coupling scheme (topology matrix) which is known to generate the required number of finite transmission zeros. This number can be determined using the algorithm in [13] or [14]. The choice of the topology is ultimately dictated by the limitations of the technology used for the implementation. More specifically, we are interested in synthesizing coupled resonator filters where some of the direct couplings are zeros. These topologies can be used to eliminate intra-cavity couplings in dual-mode cavity filters, for example.

Obviously, if the only concern were the elimination of some specific direct couplings the problem would be a trivial exercise. What needs to be achieved is the elimination of selected direct couplings without creating new cross or bypass couplings which may not be realizable due to structural constraints or a given technology. One may still argue that even this goal could be achieved in principle using a series of similarity transformations (rotations). However, there is no known approach to determine such a series or even to establish the existence of one beforehand. Consequently, we apply the technique described in [10] where the desired topology is strictly enforced, in particular the vanishing of specific main couplings.

III. RESULTS

In the following we present a number of examples of elliptic and pseudo-elliptic filters where some of the direct couplings missing. In broad terms these fall into two classes: a) N-path filters where the paths are non-interacting and b) N-path filters where the paths are interacting. Examples from both classes are given below.

A. Two-resonator filter with one transmission zero.

We assume that the normalized position of the transmission zero is Ω = -3.5 and the in-band return loss of the filter is 20dB (c.f. response Fig. 2). Using only 2 resonators, it is not possible to generate any transmission zeros unless the source and the load are coupled to more than one resonator. This can be shown using the algorithm in [14], for example. However, it is possible to generate up to two transmission zeros if the source and the load are coupled to each of the two resonators and possibly to each other [14]. More specifically, a possible conventional coupling and routing scheme providing the desired filter response in is shown in Figure 2a.

The coupling matrix corresponding to this topology is

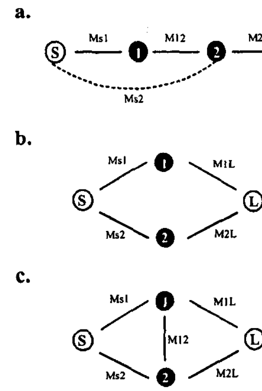

Fig. 2. Coupling schemes for 2-pole filter with one arbitrarily located transmission zero, a) conventional with cross coupling, b) 2-pahts non-interacting and c) all direct couplings present

$$M = \begin{bmatrix} 0 & 1.1178 & -0.5770 & 0 \\ 1.1178 & 0.7941 & 1.3969 & 0 \\ -0.5770 & 1.3969 & -0.6482 & 1.2574 \\ 0 & 0 & 1.2574 & 0 \end{bmatrix} \qquad (1)$$

Another possibility is the topology shown in Figure 2b where there is no direct coupling between resonators 1 and 2. There are two non-interacting paths which both originate at the input and terminate at the load. The coupling matrix for this topology satisfying the same 2-pole response is

$$M = \begin{bmatrix} 0 & 0.6544 & -1.0743 & 0 \\ 0.6544 & 1.6450 & 0 & 0.6544 \\ -1.0743 & 0 & -1.4991 & 1.0743 \\ 0 & 0.6544 & 1.0743 & 0 \end{bmatrix} \qquad (2)$$

Obviously there are more coupling schemes where more coupling coefficients are present leading to denser coupling matrices as in Figure 2c for example.

The response of the coupling matrices, which are obtained from a direct analysis using the expressions for the scattering parameters S_{11} and S_{21} given in [10], are shown in Fig. 3. Also plotted simultaneously, but not visible, is the response of the prototype. The three results agree within plotting accuracy and cannot be distinguished.

Noteworthy for the parallel structure without interaction (Fig. 2b) is the fact that it can be regarded as two separate 1-pole filters connected in parallel-the superposition of the individual responses (c.f. Fig. 4) yield the desired asymmetric 2-pole filter characteristic of Fig. 3.

A possible implementation of this solution in Fig. 2b is the use of a dual-mode cavity where the two resonance modes are not directly coupled. In fact, such a structure was recently presented using TE_{102} and TE_{201} modes in a rectangular waveguide [15] where the coupling mechanism was not investigated.

B. Four-resonator filter with two transmission zeros.

The second example is a 4-resonator elliptic function filter with 2 transmission zeros which are located at ± 4.9

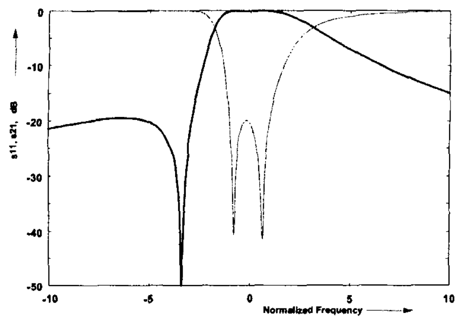

Figure 3. Reflection and transmission coefficients (dB) of the 2-pole filters as obtained from the matrices in equations (1), (2) and prototype. All results agree within plotting accuracy.

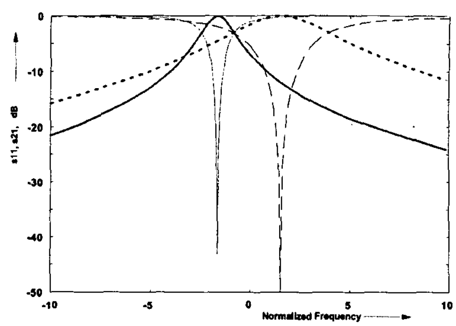

Figure 4. Reflection and transmission coefficients (dB) of separate parallel 1-pole filter sections of structure Fig. 2b (solid line: path 1; dashed line: path 2; according coupling factors of (2)) – superposition yields response of Fig. 3 (normalized frequency according to Fig. 3)

(normalized frequencies) and an in-band return loss of 23 dB. A classical canonical solution to this problem consists in cross-coupling resonators 1 and 4 with a negative coupling coefficient (c.f. Fig. 1a). The respective coupling matrix can be obtained by standard synthesis methods and is not reproduced here due to lack of space. Another solution in which the direct coupling M_{23} is zero is shown in Fig. 1b.

In this solution, there are two non-interacting paths between the source and the load. The coupling matrix corresponding to this configuration (Fig. 1b) is

$$M=\begin{bmatrix} 0 & 0.6185 & 0 & -0.9133 & 0 & 0 \\ 0.6185 & 0 & 1.4156 & 0 & 0 & 0 \\ 0 & 1.4156 & 0 & 0 & 0 & 0.6185 \\ -0.9133 & 0 & 0 & 0 & 0.6941 & 0 \\ 0 & 0 & 0 & 0.6941 & 0 & 0.9133 \\ 0 & 0 & 0.6185 & 0 & 0.9133 & 0 \end{bmatrix} \quad (3)$$

Owing to the two separate main path sections between source and load port, this solution can also be regarded as two 2-pole filters in parallel. The superposition of their different responses (c.f. Fig. 6) yield the 4-pole characteristic of the overall structure, similar as for the respective 2-pole filter design above. However, it should be noted that in the final interconnection the respective phases (coupling signs) of the individual paths have to be considered.

An example for a possible realization of this topology using rectangular waveguide cavities is shown in Fig. 7. It consists of two separate inline filter sections in parallel, each comprising two TE101 mode cavities with irises for the inter-cavity coupling and for the interconnection with the waveguide bifurcations at the waveguide interfaces. It should be noted that the inter-cavity irises of one section are of inductive while those of the other are of capacitive nature to account for the respective signs in the coupling matrix.

Another interesting solution to this problem is shown in Fig. 1c. In this case, there are couplings between the two paths as opposed to the previous one. This structure admits solutions in which the resonators are detuned as well as those in which they are not. Two of these are the following two coupling matrices

$$M=\begin{bmatrix} 0 & 0.8610 & 0 & 0.7612 & 0 & 0 \\ 0.8610 & 0.9011 & 0.5125 & 0 & 0.3712 & 0 \\ 0 & 0.5125 & 0.9011 & -0.3712 & 0 & 0.8610 \\ 0.7612 & 0 & -0.3712 & -1.1527 & -0.2655 & 0 \\ 0 & 0.3712 & 0 & -0.2655 & 1.1527 & -0.7612 \\ 0 & 0 & 0.8610 & 0 & -0.7612 & 0 \end{bmatrix} \quad (4)$$

and

$$M=\begin{bmatrix} 0 & 1.0838 & 0 & -0.2048 & 0 & 0 \\ 1.0838 & 0 & 0.7813 & 0 & 0.3339 & 0 \\ 0 & 0.7813 & 0 & -1.0549 & 0 & -0.1665 \\ -0.2048 & 0 & -1.0549 & 0 & 0.8067 & 0 \\ 0 & 0.3339 & 0 & 0.8067 & 0 & 1.0904 \\ 0 & 0 & -0.1665 & 0 & 1.0904 & 0 \end{bmatrix} \quad (5)$$

Note that whether a direct coupling is present or not in Fig. 1c depends on the numbering of the resonances. For Fig.1c, there is a direct path between the source and the load but the direct coupling coefficient between resonators 2 and 3 is negative.

The response of all the 4-pole filter coupling matrices (3)-(5) is shown in Fig. 5. Although all of them are superimposed, they can no be distinguished which is expected since they are all solutions to the same filter.

C. More Examples

In this section we list several cases which have been examined to highlight some aspects of the new solutions.

Figures 8a-c show coupling schemes for filters of different orders. Figure 8a shows a topology for a 4-resonator filter with one transmission zero. Note that the non-interacting paths do not originate at the source and terminate at the load as in the previous examples. This particular solution, which shows the flexibility of the new approach, can be implemented in dual-mode cavity filter designs, e.g., enhancing the realization of asymmetric responses as will be discussed during the presentation.

The solution in Fig. 8b can be implemented using a dual-mode cavity in which the dual modes are not coupled, and a mono-mode cavity which is connected to the load. Similarly, the solution in Fig. 8c can be implemented using 3 dual-mode cavities in which there are no intra-cavity couplings. Finally, note that higher order filters were also examined and will be

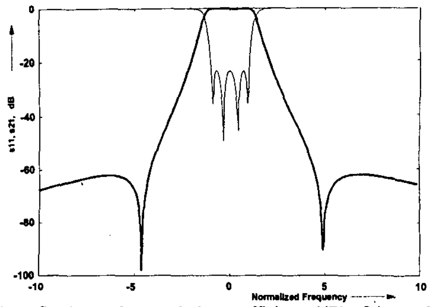

Figure 5. Reflection and transmission coefficients (dB) of 4-pole filters as obtained from the standard synthesis and matrices (3)-(5) corresponding to coupling schemes in Fig 1. All results agree within plotting accuracy.

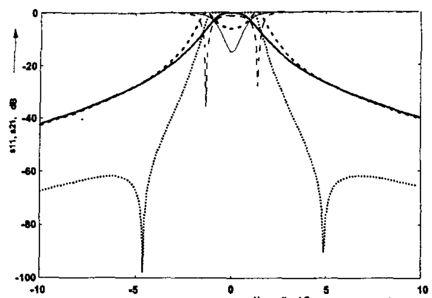

Figure 6. Reflection and transmission coefficients (dB) of the two separate 2-pole filter sections of structure Fig. 1b, solid lines, path 1-2, dashed lines, path 3-4, (coupling factors according (3)), dotted line: resulting s21 4-pole characteristic as Fig. 5

discussed during the presentation.

IV. CONCLUSIONS AND OUTLOOK

Novel solutions to the synthesis problem of coupled resonator elliptic filters were presented. A salient feature of these solutions is the fact that some of their direct (main) couplings are zero. These solutions contain two or more main paths for the signal between the source and load. These paths can be either interacting or non-interacting. . It is shown that higher order filter responses can be obtained by separate parallel connected lower order filter sections between source and load ports due to proper super-position of the different responses of the individual sections.

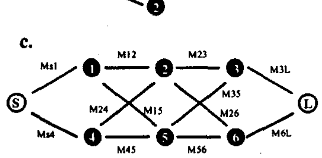

Figure 8. Other cases of new solutions for filter with finite transmission zeros.

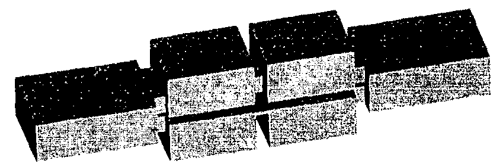

Fig. 7. Possible realization of 4-pole filter structure given in Fig. 1b with 2by2 rectangular waveguide cavity configuration

Owing to the generality of this approach it is not restricted to waveguide cavity filters and, thus, may initiate advanced designs for other microwave filter types as e.g. dielectric/metallic loaded, combline, strip line, etc..

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