A Systematic Search for New Coupling Schemes of Cross-Coupled Resonator Bandpass Filters

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Abstract. *In this paper, a systematic approach to an extensive search for topologies of cross-coupled filters with generalized Chebyshev response is presented. The technique applies graph theory to find unique, nonisomorphic filter configurations, and tests whether a specific frequency response can be realized in a given set of topologies. The results of the search are then stored in a database of possible filter configurations.*

Keywords

Microwave filters, coupling matrix, generalized Chebyshev filters.

1. Introduction

Cross-coupled resonator filters with generalized Chebyshev response are currently one of the most commonly used filtering devices, and can be found in almost all high frequency communications systems. One advantage of this type of filter is the possibility of increasing the selectivity and/or equalizing the group delay response of the filter by introducing transmission zeros. The number and type (purely imaginary or complex pair) of transmission zeros that can be implemented in the design depends on the scheme of couplings between resonators—that is, on the filter topology. For certain types of topologies (e.g. those consisting of groups such as triplets or quadruplets, canonical filters [1], cul-de-sac [2] or extended-box configurations [3]), filtering properties such as type and maximum number of transmission zeros are well known. At the same time, new filter configurations continue to appear in the literature, some showing new resonator arrangements [4]-[14], [23], [24]. In any case, the catalog of filter topologies that can implement a certain type of frequency response is far from being complete, and adding new configurations to this catalog is of interest to filter designers.

In this paper, an approach to a systematic search for new filter topologies is presented. The technique begins with the generation of a set of unique candidate topologies for filters of a given order N. For each candidate topology, an extensive search for realizable responses is then performed. Finally, the topologies that can realize a particular type of generalized Chebyshev filtering response are stored in a database in the form of pairs (topology, type of realizable response). The database can be easily filtered by imposing various criteria on the requested filter topology, such as number of couplings, planarity, presence of source-load coupling. Then for a given electric specification, a database query can be executed to quickly find the topologies that can realize the desired response and a coupling matrix can be synthesized for each of these topologies. The results can also be filtered by additional criteria, like the number of couplings needed to realize the filter. For a filter designer, such a database provides a set of optional configurations, from which the designer can choose one to suit particular requirements in the best possible way, taking into account, for example, resonator arrangement or the number of couplings and the values of the computed coupling coefficients. This also enables one to compare different coupling schemes and select the optimal solution for given technology of filter implementation.

It should be noted that the functionality of the database is much different to (and to a certain extent complementary to) that offered by a package such as Dedale-HF [28]. For a given coupling topology and a given filtering characteristic, Dedale-HF can compute all possible coupling matrices that will realize the prescribed response. However, this can currently only be done for a relatively small set of known topologies. The present approach aims to find topologies with at least one solution, for a given number and position of transmission zeros, in the form of a coupling matrix. Once a new topology has been found, one can apply the techniques of Groebner bases [15] that are used by Dedale-HF to find all alternative solutions.

2. Generation of Candidate Topologies

The first step in constructing the catalog is to prepare the set of candidate topologies. The topology of the Nth-order cross-coupled filter can be presented in the form of a symmetric adjacency matrix P of size $(N+2 \times N+2)$ [26], whose nonzero elements $p_{i,j} \quad (i,j = 2\ldots N+2, i \neq j)$ correspond to nonzero couplings between resonators i and j, and $p_{1,j} = p_{j,1}$, $p_{i,N+2} = p_{N+2,i} \quad (i,j = 2\ldots N+1)$ correspond to one or more couplings between the source/load and resonators. Finally, the element $p_{(1,N+2)} = p_{(N+2,1)}$ corresponds to the direct source-load coupling. It should be noted that different adjacency matrices do not necessarily imply different topologies. For example, let us look at two matrices P_1 and P_2 that define the topology of a third-order filter (only the upper triangular elements are shown):

$$P_1 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ & 0 & 1 & 1 & 0 \\ & & 0 & 1 & 0 \\ & & & 0 & 1 \\ & & & & 0 \end{bmatrix}, P_2 = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ & 0 & 1 & 1 & 0 \\ & & 0 & 1 & 1 \\ & & & 0 & 0 \\ & & & & 0 \end{bmatrix}. \tag{1}$$

Despite the different appearance, both matrices represent the same filter configuration, shown in Fig. 1. The difference comes from the different numbering of the nodes, but from the point of view of filter realization, the structures represent the same device. This observation implies that, in order to create a catalog of filter topologies, one must be able to generate a set of unique adjacency matrices which cannot be transformed into each another by a node renumbering. This problem can be readily solved using graph theory.

Matrix P can be regarded as an adjacency matrix of undirected, nonweighted, connected graph with $Q = N+2$ nodes (with two vertex labels, one for source/load and one for the resonators) and edges representing couplings. The problem of finding a set of unique topology candidates may be expressed in the language of graph theory as finding nonisomorphic graphs[1] with a given number of vertices and edges. The set must be composed of all possible nonisomorphic arrangements of resonators and couplings between them.

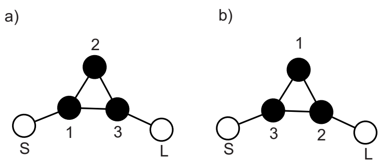


Fig. 1. Two isomorphic filter configurations with different adjacency matrix P.

Q	K
4	6
5	21
6	112
7	853
8	11 117
9	261 080
10	11 716 571

Tab. 1. Number of nonisomorphic connected graphs with $Q = N+2$ unlabeled nodes.

The procedure for selecting unique topology candidates is as follows: At first, the set of K nonisomorphic graphs with $Q = N+2$ nodes is created. This is a problem of a combinatorial nature, and the size of this set grows rapidly as the number of vertices (nodes) increases, as shown in Tab. 2. In Fig. 2a), all six nonisomorphic graphs with 4 nodes ($N = 2$) are presented. Since two nodes must be used as source and load, these 6 configurations form an initial set of second-order filter candidates.

Looking at this set, it can be seen that in the first step the graphs with exactly $N+1$ edges can be removed, as they represent the inline and tree-like topologies which do not have cross-couplings.

At this stage, we can also define which nodes act as the source and the load, and which are regular resonators. This can be done by labeling graph vertices. Vertex labeling increases the number of possible combinations. Note that, for a graph with $N+2$ nodes, one obtains $\frac{(N+2)!}{2(N!)}$ possible combinations of source-load position, and each candidate topology has to be considered for different combinations of load/source location. This gives an augmented set, and the resulting graphs are further processed to remove isomorphic graphs from the set.

To illustrate this, all candidates that can be labeled by the described procedure for second-order filters (4-node graphs) are shown in Fig. 2b. It can be seen that labeling (adding source/load) increases the set of unique topologies from 4 to 10. Tab. 2 gives the total number of unique topologies with source/load for an increasing filter order N.

It can be seen that the count grows very rapidly, and so during the construction phase various additional requirements can be imposed on the set in order to reduce the total number of topology candidates:

- Limiting the number of couplings allowed by restricting the number of graph edges M that control the maximum number of interresonator couplings. Topologies with too many cross-couplings are not interesting from the practical viewpoint;
- Limiting the maximum number of couplings from source/load to resonators;
- Removing all candidates with source (load) connected only to load (source);
- Removing all candidates with direct source-load connection (optional for high-order filters);
- Eliminating nonplanar filter topologies.

These restrictions can be applied by postprocessing the generated topology candidates. In the case of the topology candidates of second order filters shown in Fig. 2b), one topology was removed from the set at this stage – namely, the one that has source (load) connected only to load (source). As a result, for a second-order cross-coupled filter, there are 9 possible resonator and coupling arrangements, as shown in Fig. 2c.

[1]Two graphs are nonisomorphic if they contain the same number of nodes (vertices) and cannot be transformed into each other by renumbering the nodes

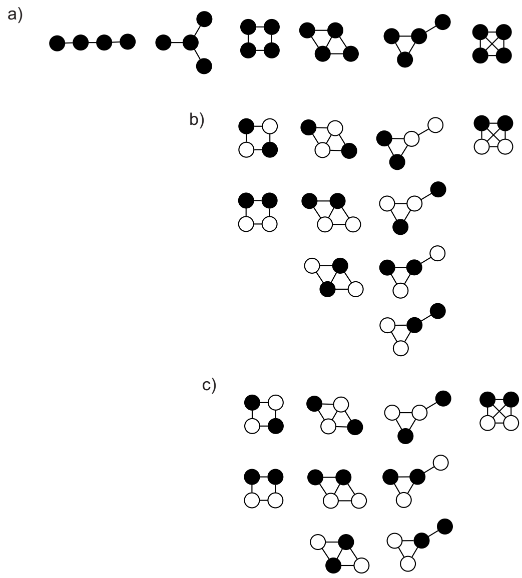


Fig. 2. Example graphs for second-order filter candidate dataset construction: a) initial set of nonisomorphic graphs with 4 nodes, b) basic set of 10 nonisomorphic candidates after adding labels and removing in-line and star topologies, c) final set of 9 nonisomorphic candidates for filter topology (the topology with source(load) connected only to load(source) was removed). White circle: source/load, black circle: resonators.

Q	N	K
4	2	10
5	3	83
6	4	836
7	5	11 144
8	6	230 176

Tab. 2. Number of nonisomorphic topology candidates for Nth order filters (graphs with $Q = N+2$ nodes), labeled without restriction on filter topology

3. Definition of Response Types

The graph-theory methodology presented in the previous section yields a set of topology candidates. The next step is to determine whether the desired frequency response can be realized by any of these candidates. The low-pass prototype response of the generalized Chebyshev coupled-resonator filter is defined by the filter order, return loss level, and the set of transmission zeros (their number; their type, whether real, imaginary, or complex; their symmetry with respect to the center frequency; and their position with respect to passband, whether above or below). For a given filter order and topology, the number and type of realizable transmission zeros is one of the most important features. For instance, as far as the location of TZs with respect to center frequency is concerned, two variants of transmission zeros can be investigated:

- Asymmetric purely imaginary zeros at $s = j\omega_{0i}$ (counted as N^{TZ}_{asym});
- Symmetric pairs of purely imaginary zeros at $s = j\omega_{0i}$ and $s = -j\omega_{0i}$ (counted as N^{TZ}_{sym}).

The total number of transmission zeros is equal to $N^{TZ}_{Total} = N^{TZ}_{asym} + 2N^{TZ}_{sym}$, and for symmetric responses $N^{TZ}_{asym} = 0$. The admittance parameter $y_{21}(s)$ of the Nth-order coupled-resonator filter described by the coupling matrix M, of size $(N+2)\times(N+2)$, can be computed as

$$y_{21}(s) = j\left[-M - \omega W\right]^{-1}_{(N+2,1)} \tag{2}$$

where W is a matrix similar to the identity matrix with w_{11} and $w_{N+2,N+2}$ equal to zero. The zeros of y_{21} can therefore be computed as the eigenvalues λ_i of the generalized eigenproblem in the following form [17], [18]

$$\hat{M}x - \lambda\hat{W}x = 0 \tag{3}$$

where the matrices $\hat{M}$ and $\hat{W}$ are created from the matrices M and W by removing the last row and the first column. The problem is real-valued and asymmetric, and $\hat{W}$ is singular. For a given topology (nonzero pattern of M) the maximum number of finite eigenvalues is constant, and the position of the eigenvalues depends on values of nonzero m_{ij} elements. If a single solution of the coupling-matrix synthesis for a given set of zeros (eigenvalues), positions, and types is found, then it is clear that a continuum of other locations can also be realized due to the continuity of the eigenvalues with respect to the elements m_{ij}. The existence of continuum does not imply that it cover the whole ω axis. There might be up to N disjoint continuous sections. With this observation, it seems sufficient to test a filter configuration for various combinations of discrete transmission zeros.

Let us consider two types of transmission zeros:

- Purely imaginary zeros that can be located above or below the passband;
- Pairs of symmetrically located transmission zeros.

By limiting the number of purely imaginary zeros to 3, up to 5 different transmission characteristics can be obtained, as shown in Tab. 3. Only one characteristic is symmetric with respect to the center frequency. For asymmetric responses, the upper and lower band TZs can also be differentiated.

N^{TZ}_{Total}	N^{TZ}_{asym}	N^{TZ}_{sym}
1	1	0
2	2	0
2	0	1
3	3	0
3	1	1

Tab. 3. Example filter prototypes for filters with up to 3 transmission zeros with different numbers of purely imaginary transmission zeros N^{TZ}.

4. Topology Validation

To test if a candidate filter topology can realize a given type of response, a trial synthesis of the coupling matrix must be performed. If the synthesis succeeds, the topology is accepted. To perform the trial, a robust technique of coupling-matrix synthesis must be applied. Classical techniques based on rotations [1] are not suitable for this purpose, as it would be very difficult, if not impossible, to find the desired rotation sequence for all possible configurations generated by the procedure described in Sec. 2. Another technique for coupling-matrix synthesis based on multivariate polynomial systems [15] involves a polynomial equation that is very expensive to solve numerically. It is therefore not suitable in the case where tens of thousands of (topology, response) pairs are being processed. For this reason, techniques based on fast optimization algorithms are more suitable here. In particular, the author's experience suggests that techniques involving eigenvalue optimization [17], [18], [19] perform remarkably well in terms of speed and convergence, and for this reason they have been chosen for testing. The trial synthesis is first performed using analytical gradients [20], and if the procedure fails to converge within a prescribed number of iterations, an additional global optimization based on a particle swarm algorithm and using a zero-pole goal function [21] is performed.

At this stage, the procedure tries for each candidate topology to synthesize the coupling matrix with different types of response. In our work, responses with up to 6 transmission zeros were investigated. The search is composed of a series of trial coupling-matrix syntheses, starting from the most complex responses (with the highest number of transmission zeros) and progressing to the simplest (one asymmetric TZ). When the coupling-matrix synthesis succeeds for an assumed response (number of TZs), then the candidate is saved for further processing and the search process is restarted for the next candidate.

To speed up the database construction, the number of searches for realizable responses can be limited by incorporating a minimum path rule [2] or by the technique described in [25]. This allows one to estimate the maximum number of realizable transmission zeros for a given topology, thus limiting the number of response types that need to be checked. During synthesis, some of the couplings can be set to zero by the optimization procedure. When this occurs, the topology is discarded and the processing of the next candidate begins.

5. Final Caveats

The goal of the proposed methodology is to look for and create a catalog of the topologies of microwave cross-coupled bandpass filters. Two issues related to the proposed approach must be noted:

- During the trial synthesis, it was assumed that the transmission zeros are located close to the passband. This is a reasonable assumption, it is filters with high selectivity that we are interested in. As described in Section 3, using the continuity of eigenvalues, a certain continuum of other locations of TZs can also be realized. However, the opposite is not true – if the candidate topology does not realize transmission zeros at a given set of test locations ω_{0i}, this does not imply that other zeros locations are not realizable. To the author's knowledge, the problem of whether an arbitrary topology can produce finite TZs of a particular type and at particular locations is still open.
- Despite the fact that a very robust technique was selected for the coupling-matrix synthesis, the convergence of the optimization method cannot be guaranteed. In consequence, there might appear cases in which the topology (which in theory is able to realize a given response) is missed during the search, due to the failure of the optimization technique. To minimize this risk, the optimization is performed a few times using different starting points.

With these remarks, it is noted that the proposed search does not ensure that *all* possible topologies are found, but it does allow the creation of a rather broad catalog of the filter topologies currently available.

6. Results

To date, a set of 27920 topology candidates for filters with orders from 2 to 6 has been processed using the technique outlined in the preceding sections. To create the candidates, the graph tools included in the *nauty* [27] software package were used. Statistical information about the numbers of graphs processed at each stage of this procedure is shown in Tab. 4. For practical reasons, it was assumed that source-load can be coupled to at most 2 resonators, and that direct source-load couplings are allowed. Note, that for $N > 3$, some of the candidate topologies correspond to nonplanar graphs[2]. Such nonplanar graphs are shown in Fig. 3 for fourth-order filters.

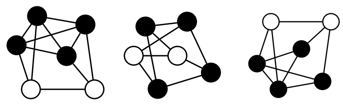


Fig. 3. All possible nonplanar topology candidates processed for fourth-order filters.

In the context of filter design, a nonplanar topology would lead to a device in which at least one coupling is crossed with another – such a crossing is usually difficult to realize when all resonators are in the same plane, but may be possible when the three-dimensional arrangement of resonators is allowed, like in the case of multi-layer LTCC and LCP packaging technology.

Currently, the database contains 7401 unique, nonisomorphic topologies. It took several weeks to generate such a dataset using parallel processing techniques, but once created it can be search in seconds. To give the reader some indication of the database's contents, all the topologies of second and third-order filters found are shown in Tab. 5 and

[2]Nonplanar graphs are those that cannot be drawn in the plane in such a way that no edges cross each other.

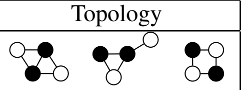
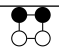
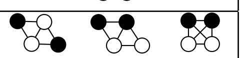
Tab. 6. Additionally in Tab. 7, the count of unique, nonisomorphic topologies found for different filter orders is shown. In Fig. 4, the response of third-order filters with 2 TZs below the passband is shown, along with one selected topology (out of six) found that realizes the response. In this case, the corresponding coupling matrix is:

$$M = \begin{bmatrix} 0 & 0 & 0 & 1.1062 & 0 \\ 0 & 0.7534 & 0.7295 & 0.8544 & 0 \\ 0 & 0.7295 & -0.0337 & -0.8057 & 1.0926 \\ 1.1062 & 0.8544 & -0.8057 & -0.2893 & 0.1733 \\ 0 & 0 & 1.0926 & 0.1733 & 0 \end{bmatrix}. \quad (4)$$

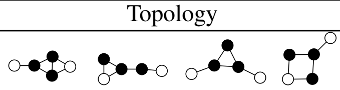
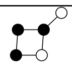
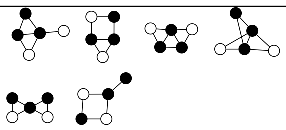
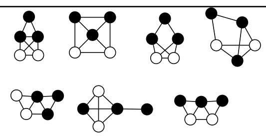
This topology allows two transmission zeros below the passband with a single negative cross-coupling to be realized, with the couplings from source/load to the resonators are all positive. The same response can be realized with the "extended-doublet" coupling scheme [12], which was also found using the technique (shown as the last topology in Tab. 6, in the category of two asymmetric zeros).

Filter order N	Count	Planar	Nonplanar
2	9	9	0
3	45	45	0
4	295	292	3
5	2314	2233	81
6	25257	22202	3055

Tab. 4. Number of topology candidates processed.

Zeros	Topology
One zero	
One pair	
Two zeros	

Tab. 5. Possible topologies of second-order filters found.

Zeros	Topology
One zero	
One zero pair	
Two asym. zeros	
Three asym. zeros	

Tab. 6. Possible topologies of third-order filters with up to 2 couplings from source/load to resonator found.

Filter order N	Count
2	7
3	18
4	106
5	671
6	6599

Tab. 7. Number of nonisomorphic topologies found.

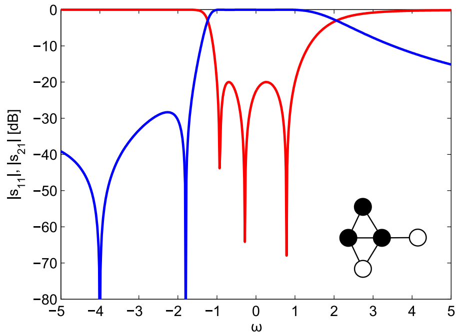


Fig. 4. Frequency response of the third-order filter with 2 purely imaginary TZs at $-j1.8$, $-j4$, and a possible coupling scheme.

Response type	Count
2 pairs	29
1 pair, 2 asym.	4
4 asym.	164
Total	197

Tab. 8. Number of topologies found for fifth-order filters with 4 purely imaginary TZs.

Higher-order filters offer a plethora of topologies. In order to present some early results, we selected a fifth-order filter with 4 asymmetric purely imaginary transmission zeros (see Fig. 5). Over 160 nonisomorphic topologies were found (see Tab. 8). A few possible configurations are shown in Fig. 6. A possible coupling matrix synthesized for the topology from Fig. 6e) and h) are shown in (5) and (6). It should be noted that many of the topologies found would be difficult to realize as physical filters, for example due to the high load of some resonators by a few strong couplings. However, some of them could provide a successful design.

Comparing the results presented here with coupling schemes available in Dedale-HF, it is worth noticing that the latter does not offer any topology that can realize a fifth-order asymmetric response with 4 TZs, while a few such topologies have been shown in this paper. However, the techniques implemented in Dedale-HF [15] could be used to find multiple solutions of the coupling-matrix synthesis problem for topologies found using the approach proposed here.

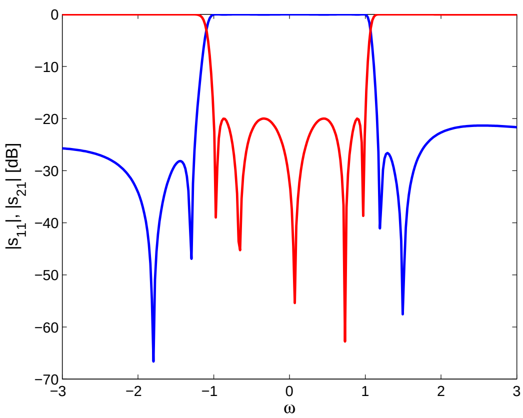


Fig. 5. Frequency response of the fifth-order filter with 4 purely imaginary TZs at $-j1.3$, $-j1.8$, $j1.2$ and $j1.5$.

$$M_1 = \begin{bmatrix} 0 & 0.9957 & 0 & 0 & 0 & 0 & 0 \\ 0.9957 & 0.0005 & -0.0809 & 0.8008 & 0 & 0 & 0.1458 \\ 0 & -0.0809 & 0.0245 & -0.4431 & 0.7416 & 0 & 0.9849 \\ 0 & 0.8008 & -0.4431 & -0.0282 & 0.1837 & 0.5257 & 0 \\ 0 & 0 & 0.7416 & 0.1837 & 0.1326 & 0.8039 & 0 \\ 0 & 0 & 0 & 0.5257 & 0.8039 & -0.2754 & 0 \\ 0 & 0.1458 & 0.9849 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

$$M_2 = \begin{bmatrix} 0 & 0 & 0 & 0.9199 & 0 & 0.3810 & 0 \\ 0 & -0.1483 & 0 & -0.7255 & 0.7255 & 0 & 0 \\ 0 & 0 & 0.8056 & 0 & 0 & 0.6607 & 0 \\ 0.9199 & -0.7255 & 0 & -0.2907 & -0.3850 & 0.3976 & 0 \\ 0 & 0.7255 & 0 & -0.3850 & -0.2907 & 0.3976 & 0.9199 \\ 0.3810 & 0 & 0.6607 & 0.3976 & 0.3976 & -0.2219 & 0.3810 \\ 0 & 0 & 0 & 0 & 0.9199 & 0.3810 & 0 \end{bmatrix} \tag{6}$$

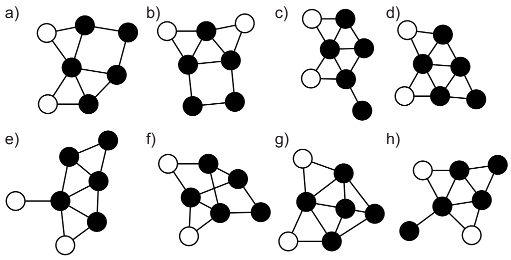


Fig. 6. 8 selected topologies found that can realize the response of Fig. 5.

7. Conclusion

In this paper, a novel systematic approach for exhaustively searching for new cross-coupled resonator filter topologies has been presented. So far, 7401 unique topologies for filters up to order 6 have been found and stored in a searchable database. Further work will be focused on the detailed analysis of the database records with the aim of selecting practically useful coupling schemes and their physical filter realizations.

Acknowledgements

This work was supported by the Polish State Committee for Scientific Research under Contract N N515 245637.

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