Rapid Coupling Matrix Reduction for Longitudinal and Cascaded-Quadruplet Microwave Filters

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***Abstract*—To realize standard microwave filter structures, it is necessary to zero some of the elements in a general even-mode coupling matrix. The zeroing process involves solving a nonlinear set of equations, performed here by using the Newton–Raphson method. Thus, intelligence is added to the numerical iteration procedure, to ensure rapid convergence. The reproduced transmission coefficient S_{21} from the reduced matrix agrees well with the one synthesized.**

***Index Terms*—Cascaded-quadruplet (CQ) topology, coupling matrix, filter synthesis, longitudinal topology.**

I. INTRODUCTION

MICROWAVE filters composed of coupled resonators can generate transmission zeros only by having cross-couplings among nonadjacent resonators. Atia and Williams set out a general theory for cross-coupled resonator bandpass filters in their series of publications [1]–[4], which is still widely used in the synthesis of these types of filters. Once the low-pass transmission coefficient $S_{21}(s)$ has been approximated, their synthesis procedure directly extracts the elements of a full or an even-mode coupling matrix and the external coupling values. However, the resultant coupling matrix generally contains all possible couplings, which makes it unrealizable [4]. Therefore, it is usual to annihilate the unwanted couplings without changing the lossless network characterized by the coupling matrix.

Among the various methods, repeated similarity transformations are applied to minimize the unwanted couplings [1]. However, this method does not always converge for longitudinal (in-line) and cascade quadruplet topologies or can take a very large number of iterations (say, 10^5) to obtain a result. Further, it is often not possible to find a sequence of similarity transformations as presented in [5] or [6] to realize the two topologies commencing from this general full or even-mode coupling matrix.

This paper presents a coupling matrix reduction method commencing from a general even-mode coupling matrix M_e, extracted from the synthesis procedure outlined in [1]–[4]. Physically symmetrical structures are considered for even-order filter realization for longitudinal and cascaded-quadruplet (CQ) topologies. There are three necessary conditions (see Section II) that need to be satisfied by the reduced matrix to preserve the synthesized transmission coefficient of the lossless network. Instead of applying repeated similarity transformations, a system of nonlinear equations is formed for a single orthonormal transformation to find a reduced matrix similar to M_e, with the required topology satisfying the three conditions. The Newton–Raphson (NR) method is used to solve the set of nonlinear equations numerically. Thus, some intelligence is added to the iteration procedure to ensure convergence. The analytical expressions are provided to form the constraints and the Jacobian matrix for the NR procedure. It is shown that this method can be applied for even filter orders 6–12 for longitudinal realization and 8–12 for CQ realization. The validity of the scheme has been verified by synthesizing even-order pseudoelliptic filtering functions. The iteration procedure converges within 40 iterations for all the filter orders considered. The transmission coefficient calculated from the reduced coupling matrix agrees with the synthesized $S_{21}(s)$.

This paper is organized as follows. Section II briefly describes the synthesis procedure to extract M_e and the proposed coupling matrix reduction scheme. The results are discussed in Section III and Section IV presents conclusions.

II. SYNTHESIS OF THE TRANSFER FUNCTION AND COUPLING MATRIX REDUCTION

A. Synthesis of the Transfer Function

The synthesis procedure, which extracts a general even-mode coupling matrix M_e for a given even-order S_{21}, is discussed in [1]–[4]. The synthesis is based on assuming a symmetrical doubly and equally terminated network. The coupling matrix reduction method discussed in this paper commences from the M_e computed from this synthesis procedure.

The even-mode coupling matrix M_e is defined as [2]

$$M_e = -T_e \Lambda_e T_e^t \tag{1}$$

where T_e is an orthonormal matrix and Λ_e is a diagonal matrix. The resultant M_e is an order $N/2$ symmetric real matrix, where N is the filter order.

For a given low-pass S_{21}, the synthesis procedure extracts the first row of T_e, the diagonal matrix Λ_e, and the terminal resistance values R_1 and R_N. The complete T_e may be formed by using the Gram–Schmidt procedure [1].

Matrix M_e, obtained by the synthesis procedure described above, contains all possible couplings. Therefore, it is usual to annihilate the unwanted couplings to result in a more compact structure. The reduced coupling matrix can be expressed as $M_R = T_R \Lambda_e T_R^t$, where T_R is an orthonormal matrix. After annihilation, M_R should satisfy the following three conditions.

1) M_R is real and symmetric.
2) Eigenvalues of M_R should be the same as M_e. i.e., M_R is similar to M_e.

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3) The first row of T_R is identical in magnitude to the first row of T_e.

The first condition retains the symmetric network assumed. The last two conditions preserve the synthesized lossless network. Thus, the reduced matrix can reproduce the same power transmission coefficient $S_{21}(s)$ as synthesized. Even though the similarity transformations satisfy the first two conditions, previous work overlooked the third condition, which also needs to be satisfied.

Section II-B discusses the matrix reduction process, which reduces a general even-mode coupling matrix for longitudinal CQ realizations. This process satisfies the three conditions outlined above.

B. *Matrix Annihilation Using the NR Method*

The general method is to find an orthonormal matrix T_R such that

$$M_R = T_R \Lambda_e T_R^t \tag{2}$$

where M_R gives the required topology and satisfies the three conditions stated above. It is possible to write a system of generalized quadratic equations f to hold orthonormality of T_R and zero elements in M_R in terms of unknown elements in T_R. The resultant quadratic equations can be solved numerically using the NR method, which converges quadratically near a possible solution.

The expression for the quadratic equations f and the linear Jacobian matrix J can be derived as follows.

For an $m \times m$ even-mode coupling matrix, let

$$T1 = T_R T_R^t \tag{3}$$

and

$$M1 = T_R \Lambda_e. \tag{4}$$

Since the first row of T_R is known, the number of unknowns $n = m^2 - m$. The number of constraints to satisfy orthonormality of T_R are $(m^2 + m - 2)/2$ and are given by

$$f_{T1(i,j)} = T1(i,j) - \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases} = 0$$
$$\text{for } i = \begin{cases} 1, & j = i+1, i+2, \ldots, m \\ >1, & j = i, i+1, i+2, \ldots, m. \end{cases} \tag{5}$$

The first derivative of (5) with respect to unknowns $T_R(l, k)$ $l = 2, 3 \ldots, m$ and $k = 1, 2, \ldots, m$ is given by

for $i = 1$ and $j \neq 1$

$$\frac{\partial f_{T1(1,j)}}{\partial T_R(l,k)} = \begin{cases} T_R(1,k), & l = j \\ 0, & l \neq j \end{cases} \tag{6a}$$

for $i > 1$ and $j \neq i$

$$\frac{\partial f_{T1(i,j)}}{\partial T_R(l,k)} = \begin{cases} T_R(j,k), & l = i \\ T_R(i,k), & l = j \\ 0, & \text{else} \end{cases} \tag{6b}$$

for $i > 1$ and $j = i$

$$\frac{\partial f_{T1(i,i)}}{\partial T_R(l,k)} = \begin{cases} 2T_R(i,k), & l = i \\ 0, & l \neq i. \end{cases} \tag{6c}$$

Constraints for the zero elements in the upper triangle of M_R can be given as

$$f_{M_R(i,j)} = M_R(i,j) = 0, \qquad \text{for } i \neq 1 \text{ and } j \neq 1. \tag{7}$$

Since the first row of T_R and Λ_e are fixed, the element $M_R(1,1)$ is a constant. The first derivative of (7) with respect to unknowns $T_R(l,k)$ $l = 2, 3 \ldots, m$ and $k = 1, 2, \ldots, m$ is given by

for $i = 1$ and $j \neq 1$

$$\frac{\partial f_{M_R(1,j)}}{\partial T_R(l,k)} = \begin{cases} M_1(1,k), & l = j \\ 0, & l \neq j \end{cases} \tag{8a}$$

for $i > 1$ and $j \neq i$

$$\frac{\partial f_{M_R(i,j)}}{\partial T_R(l,k)} = \begin{cases} M_1(i,k), & l = j \\ M_1(j,k), & l = i \\ 0, & \text{else} \end{cases} \tag{8b}$$

for $i > 1$ and $j = i$

$$\frac{\partial f_{M_R(i,i)}}{\partial T_R(l,k)} = \begin{cases} 2M_1(i,k), & l = i \\ 0, & l \neq i. \end{cases} \tag{8c}$$

The $n \times 1$, f vector is formed by (5) and (7). Equations (6) and (8) form the Jacobian matrix of order n. The following sections show how the above method can be applied to reduce M_e suitable for longitudinal and CQ topologies.

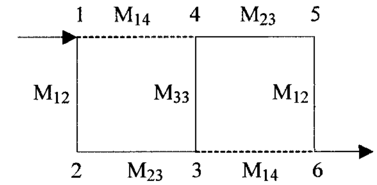
1) Longitudinal Realization: The main disadvantage of a canonical structure is the incidental coupling between the input and output ports [7] since they are adjacent resonators of a single-mode resonator filter or the same cavity of a dual-mode filter. This limits the maximum achievable out-of-band isolation. The longitudinal or in-line structure shown in Fig. 1 avoids this drawback by having its input and output ports located in physically remote resonators. However, this topology is sub-optimum, having less than $N-2$ finite transmission zeros for degrees higher than four. The maximum number of finite transmission zeros (n_1) is given by [6]

$$n_1 = \begin{cases} \dfrac{N}{2}, & \text{for } \dfrac{N}{2} \text{ even} \\ \dfrac{N}{2} - 1, & \text{for } \dfrac{N}{2} \text{odd.} \end{cases} \tag{9}$$

The synthesized S_{21} with finite transmission zeros less than $N-2$ results in no coupling between the first and last resonators, making $M_e(1,1) = 0$.

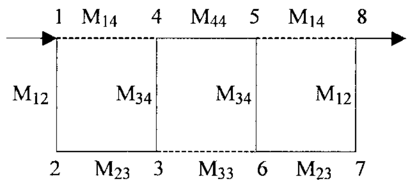
a) Degrees 6 and 8: Fig. 1 depicts the signal flow diagrams [6] for sixth- and eighth-order longitudinal (in-line) realizations with the corresponding even-mode coupling matrix. Table I provides the maximum number of transmission zeros possible for each degree and zero elements in M_R for which the constraint (7) needs to be imposed. From here onwards, the coupling between nodes given in the signal flow graph are marked in terms of the elements of M_R.

The synthesis of a sixth-order pseudoelliptic filtering function S_{21} with two finite transmission zeros results in the general even-mode coupling matrix, from which the first row of T_e and Λ_e are available. The remaining two rows comprising six unknowns can be obtained numerically by the NR procedure explained. The required six constraints can be composed with five



$$M_R = \begin{bmatrix} 0 & M_{12} & M_{14} \\ M_{12} & 0 & M_{23} \\ M_{14} & M_{23} & M_{33} \end{bmatrix}$$

(a)



$$M_R = \begin{bmatrix} 0 & M_{12} & 0 & M_{14} \\ M_{12} & 0 & M_{23} & 0 \\ 0 & M_{23} & M_{33} & M_{34} \\ M_{14} & 0 & M_{34} & M_{44} \end{bmatrix}$$

(b)

Fig. 1. Signal flow graph and the corresponding even-mode coupling matrix. (a) Sixth order. (b) Eighth order. The solid lines show direct couplings, whereas the dotted lines denote cross-couplings.

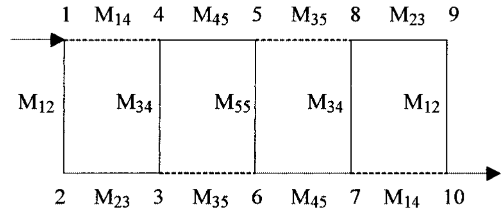
TABLE I
LONGITUDINAL TOPOLOGY: FILTER ORDERS 6 AND 8

Order	max. no. of finite transmission zeros (n_l)	Zero elements in upper triangle of M_R for (7)
6	2	M_{22}
8	4	M_{13}, M_{22}, M_{24}

constraints for orthonormality of T_R using (5) and a zero element $M_{22} = 0$ using (7). A similar procedure can be followed for the eighth-order S_{21} with four finite transmission zeros. The initial values for the variables were randomly chosen to lie between $[0, 1]$.

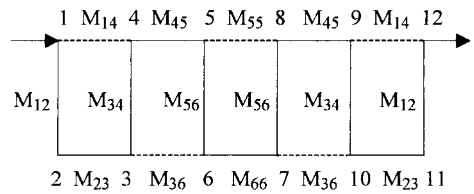
b) Degrees 10 and 12: Fig. 2 illustrates the signal flow diagrams for tenth- and 12th-order longitudinal (in-line) realizations, with the corresponding even-mode coupling matrix. Table II provides the maximum number of transmission zeros possible for each degree, and the zero elements in M_R for which the constraint (7) needs to be imposed.

The filter orders 10 and 12 have one more constraint than degrees of freedom, making the system of equations unsolvable unless one redundancy is found. This leads to an argument that it is possible to find an orthonormal matrix T_R relaxing one constraint. Obviously the constraint to be dropped should be one for a zero element in M_R. The resultant matrix is then expected to contain only one unwanted coupling, still producing the same synthesized S_{21}. We investigated the numerator of S_{21} by direct analysis in terms of nonzero coupling coefficients of the resulting coupling matrix when only one of the constraints for zero elements in M_R is relaxed.



$$M_R = \begin{bmatrix} 0 & M_{12} & 0 & M_{14} & 0 \\ M_{12} & 0 & M_{23} & 0 & 0 \\ 0 & M_{23} & 0 & M_{34} & M_{35} \\ M_{14} & 0 & M_{34} & 0 & M_{45} \\ 0 & 0 & M_{35} & M_{45} & M_{55} \end{bmatrix}$$

(a)



$$M_R = \begin{bmatrix} 0 & M_{12} & 0 & M_{14} & 0 & 0 \\ M_{12} & 0 & M_{23} & 0 & 0 & 0 \\ 0 & M_{23} & 0 & M_{34} & 0 & M_{36} \\ M_{14} & 0 & M_{34} & 0 & M_{45} & 0 \\ 0 & 0 & 0 & M_{45} & M_{55} & M_{56} \\ 0 & 0 & M_{36} & 0 & M_{56} & M_{66} \end{bmatrix}$$

(b)

Fig. 2. Signal flow graph and the corresponding even-mode coupling matrix. (a) Tenth order. (b) 12th order.

TABLE II
LONGITUDINAL TOPOLOGY: FILTER ORDERS 10 AND 12

Order	n_l	Zero elements in upper triangle of M_R for (7)
10	4	$M_{13}, M_{15}, M_{22}, M_{24}, M_{25}, M_{33}, (M_{44})$
12	6	$M_{13}, M_{15}, M_{16}, M_{22}, M_{24}, M_{25}, M_{26}, M_{33}, M_{35}, M_{46}, (M_{44})$

The numerator $p(s)$ for a tenth-order S_{21}, reproduced from M_R when the $M_{44} = 0$ constraint is relaxed, can be written as

$$\begin{aligned} p(s) = &M_{14}^2 M_{44}^2 s^6 \\ &+ \begin{pmatrix} -M_{14}^2 M_{45}^2 M_{55} - 2M_{23}M_{12}M_{35}M_{45}M_{14} \\ +2M_{14}^2 M_{44} M_{35}^2 - 2M_{23}M_{12}M_{34}M_{44}M_{14} \\ +2M_{14}^2 M_{44} M_{23}^2 - 2M_{14}^2 M_{45}M_{35}M_{34} \\ +M_{14}^2 M_{44} M_{55}^2 \end{pmatrix} s^4 \\ &+ (\cdots)s^2 + (\cdots)s^0. \end{aligned} \tag{10}$$

Since the synthesized S_{21} has a fourth-order numerator, either M_{14} or/and M_{44} should be zero. However, it can be seen from (10) that if M_{14} is zero, the order of the numerator drops to two, which cannot happen since the similarity transformation under three conditions stated does not change S_{21}. Therefore, the system of equations should converge to a result, making M_{44}

equal to zero when a solution exists. Thus, it is possible to solve the nonlinear system without a constraint for $M_{44} = 0$, still resulting in the required reduced matrix with $M_{44} = 0$. However, this is not valid for other constraints.

Similarly, for the 12th order, it can be shown that the $M_{44} = 0$ constraint becomes a redundancy when there exists a solution M_R.

2) CQ Realization: The CQ topology is another widely used structure. This consists of cascaded sections of four resonators or nodes, each with one cross-coupling. The filters with this structure are simple to tune since each CQ section is entirely responsible for producing one pair of transmission zeros [8]. The maximum number of finite transmission zeros for the CQ topology is the same as for the longitudinal topology for a given order. This can be verified using the method proposed by Amari [9] to find the maximum number of finite transmission zeros for a given topology matrix.

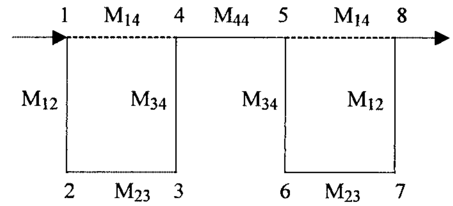
Symmetric CQ structures for eighth, tenth, and 12th orders are discussed in this section. Fig. 3 shows the signal flow graph and the corresponding even-mode coupling matrix for those orders. Table III provides the maximum permissible finite transmission zeros, and lists the zero elements in the upper triangle of M_R that need to be annihilated.

The CQ topology is similar to the longitudinal topology for the orders considered without having some of the couplings. This is reflected by one additional zero element in its even-mode coupling matrix, leading to an additional constraint without increasing the degrees of freedom.

A solution to this problem may be found by exploiting the characteristics of CQ topology and the symmetric nature of the structure. As stated before, each CQ section is entirely responsible for producing one pair of transmission zeros. Further, it is not possible to realize transmission coefficients containing complex transmission zeros in CQ form [10]. Thus, it can be concluded that a symmetric CQ structure should possess at least a pair of second-order transmission zeros for the filter orders considered. This determines the nature of the transmission coefficient that can be realized in a symmetric CQ structure for the above orders.

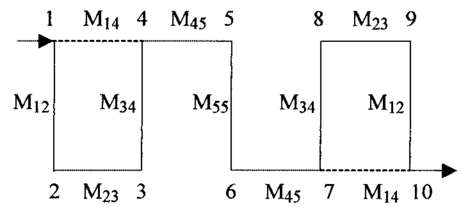
Now the synthesis can be done for S_{21} with a second-order transmission-zero pair. The resultant general even-mode coupling matrix can be converted to the desired form following the same procedure as for the same order longitudinal topology, dropping the constraints for the elements given in brackets for each order in Table III.

However, it is also possible to realize S_{21} with a second-order transmission-zero pair in a longitudinal topology. Thus, the system of equations can converge to two different solutions. One leads to the CQ realization. The longitudinal case has $M_{33} \neq 0$ for the eighth order, $M_{35} \neq 0$ for the tenth order, and $M_{36} \neq 0$ for the 12th order. This can be distinguished very easily and can start the iteration procedure with fresh initial values until it converges to the correct topology.



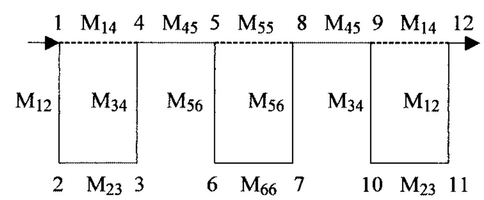
$$M_R = \begin{bmatrix} 0 & M_{12} & 0 & M_{14} \\ M_{12} & 0 & M_{23} & 0 \\ 0 & M_{23} & 0 & M_{34} \\ M_{14} & 0 & M_{34} & M_{44} \end{bmatrix}$$

(a)



$$M_R = \begin{bmatrix} 0 & M_{12} & 0 & M_{14} & 0 \\ M_{12} & 0 & M_{23} & 0 & 0 \\ 0 & M_{23} & 0 & M_{34} & 0 \\ M_{14} & 0 & M_{34} & 0 & M_{45} \\ 0 & 0 & 0 & M_{45} & M_{55} \end{bmatrix}$$

(b)



$$M_R = \begin{bmatrix} 0 & M_{12} & 0 & M_{14} & 0 & 0 \\ M_{12} & 0 & M_{23} & 0 & 0 & 0 \\ 0 & M_{23} & 0 & M_{34} & 0 & 0 \\ M_{14} & 0 & M_{34} & 0 & M_{45} & 0 \\ 0 & 0 & 0 & M_{45} & M_{55} & M_{56} \\ 0 & 0 & 0 & 0 & M_{56} & M_{66} \end{bmatrix}$$

(c)

Fig. 3. Signal flow graph and the corresponding even-mode coupling matrix for CQ topology. (a). Eighth order. (b) Tenth order. (c) 12th order.

TABLE III
CQ TOPOLOGY: FILTER ORDERS 8, 10, AND 12

Order	n_l	Zero elements in upper triangle of M_R for (7)
8	4	$M_{13}, M_{22}, M_{24}, (M_{33})$
10	4	$M_{13}, M_{15}, M_{22}, M_{24}, M_{25}, M_{33}, (M_{36}, M_{44})$
12	6	$M_{13}, M_{15}, M_{16}, M_{22}, M_{24}, M_{25}, M_{26}, M_{33}, M_{35}, M_{46}, (M_{36}, M_{44})$

III. RESULTS

Computer programs have been developed to implement synthesis and matrix reduction procedures. This section demonstrates the results by considering a tenth-order pseudoelliptic function filter with the following specifications: maximum loss in the passband $= 0.05$ dB, and minimum attenuation in the stopband $= 80$ dB. Using the above specifications, finite transmission zeros (z_i) and reflection zeros (r_i) can be computed for the longitudinal realization as $z_1 = j1.6244$, $z_2 = j1.9841$, $r_1 = 0$, $r_2 = j0.4285$, $r_3 = j0.6985$, $r_4 = j0.8900$, $r_5 = j0.9878$, and their complex conjugates. For this case, normalized terminal resistances are $R_1 = R_N = 1.1632$ and the general even-mode coupling matrix M_e is given by

$$M_e = \begin{bmatrix} 0.0000 & -0.5604 & 0.1664 & -0.2268 & 0.6037 \\ -0.5604 & -0.8731 & -0.0813 & 0.1108 & -0.2950 \\ 0.1664 & -0.0813 & 0.4955 & 0.1431 & -0.3809 \\ -0.2268 & 0.1108 & 0.1431 & 0.0129 & -0.5921 \\ 0.6037 & -0.2950 & -0.3809 & -0.5921 & -0.1588 \end{bmatrix}.$$

Following the reduction scheme of Section II, roughly 25 iterations were needed to get to the rapid convergence region. Then the NR quadratic error properties was observed, resulting in only four more iterations for convergence. Convergence was defined as occurring when the maximum change in the T-matrix elements was less than 0.000001. This process gives

$$M_R = \begin{bmatrix} 0.0000 & 0.8588 & 0.0000 & -0.1416 & 0.0000 \\ 0.8588 & 0.0000 & 0.6851 & 0.0000 & 0.0000 \\ 0.0000 & 0.6851 & 0.0000 & 0.5150 & -0.0139 \\ -0.1416 & 0.0000 & 0.5150 & 0.0000 & 0.5165 \\ 0.0000 & 0.0000 & -0.0139 & 0.5165 & -0.5236 \end{bmatrix}. \quad (11)$$

For the CQ realization, the location of the second-order transmission zero is found by averaging the first two transmission zeros of the longitudinal realization in the previous example. The new z_i's and r_i's are $z_1 = j1.80425$, $z_2 = j1.80425$, $r_1 = 0$, $r_2 = j0.4285$, $r_3 = j0.6985$, $r_4 = j0.8900$, $r_5 = j0.9878$, and their complex conjugates. For this case, normalized terminal resistances are $R_1 = R_N = 1.1549$.

$$M_e = \begin{bmatrix} 0.0000 & -0.5555 & 0.1674 & -0.2231 & 0.6045 \\ -0.5555 & -0.8757 & -0.0812 & 0.1082 & -0.2932 \\ 0.1674 & -0.0812 & 0.4921 & 0.1406 & -0.3810 \\ -0.2231 & 0.1082 & 0.1406 & 0.0099 & -0.5914 \\ 0.6045 & -0.2932 & -0.3810 & -0.5914 & -0.1501 \end{bmatrix}.$$

After following the reduction scheme of Section II, with approximately 30 iterations

$$M_R = \begin{bmatrix} 0.0000 & 0.8605 & 0.0000 & 0.1065 & 0.0000 \\ 0.8605 & 0.0000 & -0.6635 & 0.0000 & 0.0000 \\ 0.0000 & -0.6635 & 0.0000 & 0.5253 & 0.0000 \\ 0.1065 & 0.0000 & 0.5253 & 0.0000 & 0.5305 \\ 0.0000 & 0.0000 & 0.0000 & 0.5305 & -0.5237 \end{bmatrix}. \quad (12)$$

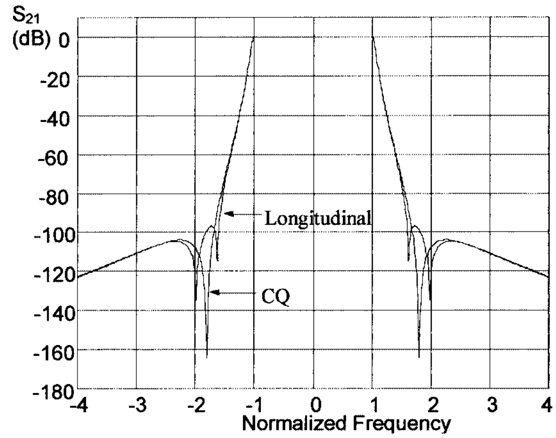


Fig. 4. Transmission coefficients reproduced from the reduced coupling matrices for each case.

A simple scaling procedure described in [6] could be used to make the direct couplings of the same sign and cross-couplings to take arbitrary sign for easy realization.

Fig. 4 depicts the transmission coefficient S_{21} magnitudes, produced by the reduced coupling matrices (11) and (12). Each of them coincides with the synthesized S_{21}. This shows the accuracy of the presented matrix reduction procedure.

IV. Conclusion

Three properties that a reduced even-mode coupling matrix should retain from its initial matrix have been identified. Based on that, a numerical coupling matrix reduction technique has been developed satisfying all three conditions. This scheme numerically finds a reduced coupling matrix suitable for longitudinal and CQ topologies. Adding some intelligence to the iteration procedure ensures rapid convergence of the numerical method. This scheme has been evaluated by synthesizing even-order pseudoelliptic transmission coefficients S_{21} for different filter characteristics. The reproduced S_{21} from the reduced matrix agrees well with the one originally synthesized.

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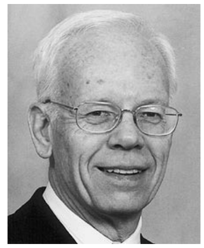

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