Diagnosis and Tuning of Multiple Coupled Resonator Filters

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Abstract-- A robust and efficient tool for extraction of coupling matrix in multiple coupled resonator filters (MCRF) is presented. After collecting frequency samples of the filtering function either from electromagnetic simulations or from measurements, a model based parameter extraction (MBPE) technique is employed to approximate these samples by a rational function using Cauchy method. For lossy filters, the effect of loss is removed from the approximated filtering function by properly shifting its zeros and poles. Finally, lossless models for scattering parameters are obtained in terms of rational functions from which the coupling matrix is extracted through a synthesis and optimization process. The method is employed for diagnosis and tuning of three practical bandpass filters.

Keywords-- Model Based Parameter Extraction (MBPE); Multiple Coupled Resonator Filters (MCRF); Coupling Matrix; Cauchy Method.

I. Introduction

Increasing demand for wireless communication services and systems has put severe constraints on the selectivity of both mobile and fixed wireless transceivers. Consequently, the design of multiple coupled resonator filters (MCRF) with finite transmission zeros has received considerable attention in recent years due to their superior selectivity, small size, and low insertion loss compared with traditional all pole filters. Furthermore, real transmission zeros can be placed at desired frequencies to completely suppress specific interference signals while complex transmission zeros can be synthesized to equalize the group delay. However, tuning and design of these filters is a tedious and time consuming task even for experienced filter designers. The main goal of this paper is to present an efficient and robust diagnosis technique for fast design and tuning of MCRF's.

Diagnosis and tuning of MCRF has been the subject of intensive research in the past three decades. A useful time domain technique was presented by Agilent in a well-known application note [1]. Another method based on fuzzy logic was introduced recently in [2] which tries to eliminate the need for human experience. For frequency domain tuning, an approach based on extraction of group delay was presented in [3]. Another method relying upon frequency response optimization at a number of specific frequencies was outlined in [4] and [5]. In frequency domain tuning methods, extraction of the coupling matrix which contains adjacent and cross couplings and individual resonance frequencies is the main step. The user can make appropriate adjustments in physical dimensions of the filter by comparing the extracted coupling matrix with the desired one so as to achieve an acceptable frequency response. Recently the model based parameter extraction (MBPE) technique has been used as an efficient tool for modelling the scattering parameters of filters with rational functions from which the coupling matrix can be extracted [6]-[7]. The method presented in [6] uses adaptive frequency sampling and is based on rational function modelling of the scattering parameters and is very sensitive to parasitic effects. Moreover, it is only useful for lossless filters or when the losses are very small. A robust diagnosis technique suitable for very low loss filters was described in [7] in which the filtering function was considered instead of the scattering parameters. In this paper, we describe a similar approach; however, we have modified the method for lossy filters.

After taking frequency samples of the filtering function either from measurements (in post fabrication tuning) or from electromagnetic simulations (during the design process), the Cauchy method [8]-[9] is used to fit a rational function to the data. Note that the filtering function only contains the transmission and reflection zeros of the filter. In the case of lossy filters, the effect of loss is removed by properly shifting the zeros and poles of the filtering function so that a lossless model is obtained first. In the next step, using the Feldkeller's equation which is the statement of conservation of energy, the rational functions for scattering parameters are obtained. Finally the coupling matrix is extracted from the polynomials of S-parameters using an eigenvalue based optimization procedure [10].

II. Approximation Of Scattering Parameters

In this section a robust MBPE algorithm is presented to approximate the scattering parameters of the filter by rational functions. In the case of very low loss filters these polynomial functions will be used directly to find the coupling matrix using standard synthesis methods. Otherwise, these rational function models are only used for interpolation and extrapolation of S-parameters in terms of frequency. S_{11} and S_{21} can be approximated by two rational functions with a common denominator [7]-[8]:

$$\begin{cases} S_{11}(s) = \dfrac{F(s)}{E(s)} = \dfrac{\sum_{k=0}^{n} a_k^{(1)} s^k}{\sum_{k=0}^{n} b_k s^k} \\ S_{21}(s) = \dfrac{P(s)}{E(s)} = \dfrac{\sum_{k=0}^{n_z} a_k^{(2)} s^k}{\sum_{k=0}^{n} b_k s^k} \end{cases} \qquad (1)$$

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where n is the order of filter and n_z is the number of finite transition zeros. s is the normalized frequency which is defined by the bandpass to lowpass transformation:

$$s = j\frac{f_0}{BW}\left(\frac{f}{f_0}-\frac{f_0}{f}\right) \qquad (2)$$

In which f_0 and BW are the center frequency and bandwidth of the filter, respectively. If S_{11} and S_{21} are calculated (by electromagnetic simulation) or measured at a reduced number of frequency samples $s_i, i=1,...,N$, then (1) may be written as:

$$\begin{cases}\sum_{k=0}^{n} a_k^{(1)} s_i^k - S_{11}(s_i)\sum_{k=0}^{n} b_k s_i^k = 0 & i=1,2,...,N \\ \sum_{k=0}^{n_z} a_k^{(2)} s_i^k - S_{21}(s_i)\sum_{k=0}^{n} b_k s_i^k = 0 & i=1,2,...,N\end{cases} \qquad (3)$$

After some mathematical manipulations (3) is rewritten as a linear system of equations:

$$\begin{bmatrix} V_n & 0_{N\times(n_z+1)} & -S_{11}V_n \\ 0_{N\times(n+1)} & V_{n_z} & -S_{21}V_n \end{bmatrix}\begin{bmatrix} a^{(1)} \\ a^{(2)} \\ b\end{bmatrix} = X\begin{bmatrix} a^{(1)} \\ a^{(2)} \\ b\end{bmatrix} = 0 \quad (4)$$

Where $a^{(1)} = \left[a_0^{(1)},\cdots,a_n^{(1)}\right]^T$, $a^{(2)} = \left[a_0^{(2)},\cdots,a_{n_z}^{(2)}\right]^T$, $b=\left[b_0,\cdots,b_n\right]^T$, $S_{21} = \mathrm{diag}\left\{S_{21}(s_i)\right\}_{i=1}^N$ $S_{11} = \mathrm{diag}\left\{S_{11}(s_i)\right\}_{i=1}^N$ and V_r is the Vandermond matrix defined by:

$$V_r = \begin{pmatrix} 1 & s_1 & s_1^2 & \cdots & s_1^r \\ 1 & s_2 & s_2^2 & & s_2^r \\ \vdots & & & \ddots & \vdots \\ 1 & s_N & s_N^2 & \cdots & s_N^r \end{pmatrix} \in C^{N\times(r+1)} \qquad (5)$$

After applying singular value decomposition (SVD) to the system matrix X in (4), it can be written as:

$$X\begin{bmatrix} a^{(1)} \\ a^{(2)} \\ b\end{bmatrix} = U\,\Sigma V\begin{bmatrix} a^{(1)} \\ a^{(2)} \\ b\end{bmatrix} = 0 \qquad (6)$$

where Σ is a diagonal matrix containing the singular values and V, U are unitary matrices. The solution to (4) is proportional to the last column of matrix V [7]-[8]:

$$\begin{bmatrix} a^{(1)} \\ a^{(2)} \\ b\end{bmatrix} = \left[V\right]_{n+n_z+2} \qquad (7)$$

After finding the rational functions for S_{11} and S_{21}, the reflection zeros, transmission zeros and poles of the filter can be easily determined. As mentioned before, these rational models are not suitable for coupling matrix extraction in *lossy* filters.

III. Approximation Of Filtering Function

In the case of lossy filters an alternative procedure is proposed here by which an "equivalent" lossless model for the filter is derived first. Standard filter synthesis methods can then be used to extract the coupling matrix. Fig.1 shows the equivalent lumped circuit model of a narrowband lossy MCRF. All resonators are presented by an LC loop and their losses are modeled by series resistors r_i. The coupling coefficient between resonators i and j is denoted by $M_{i,j}$.

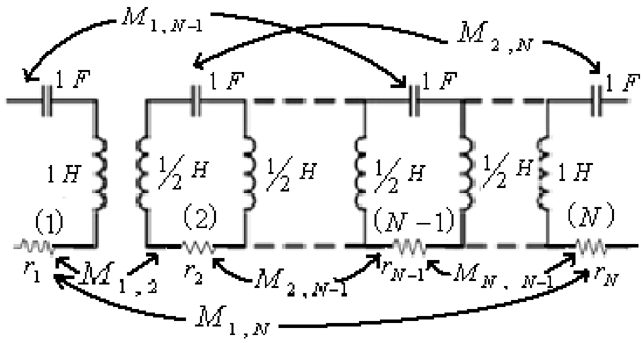


Figure 1. General equivalent circuit for narrowband MCRF filters.

At first step the "*filtering function*" which is the ratio of S_{11} to S_{21} is approximated by a rational model [7],[9]:

$$K(s)\quad \frac{S_{11}}{S_{21}} = \frac{F(s)}{P(s)} = \frac{\sum_{k=0}^{n} a_k^{(1)} s^k}{\sum_{k=0}^{n_z} a_k^{(2)} s^k} \qquad (8)$$

If this filtering function is known at $N \ge n + n_z + 1$ frequency samples, then (8) may be written as:

$$S_{21}(s_i)\sum_{k=0}^{n} a_k^{(1)} s_i^k - S_{11}(s_i)\sum_{k=0}^{n} a_k^{(2)} s_i^k = 0 \quad i=1,2,...,N \quad (9)$$

which can be rewritten as a system of linear equations [9]:

$$\left[S_{21}V_n \; -S_{11}V_{n_z}\right]\begin{bmatrix} a^{(1)} \\ a^{(2)}\end{bmatrix} = X\begin{bmatrix} a^{(1)} \\ a^{(2)}\end{bmatrix} = 0 \qquad (10)$$

$S_{11}, S_{21}, a^{(1)}, a^{(2)}$ were defined following (4) and V_r is the Vandermond matrix defined in (5). Again the system of equations given in (10) is solved via SVD as described by (6) and (7). To improve the accuracy of the extracted filtering function and alleviate the "over ordering" problem that occurs due to parasitic effects, the method described in [7] is employed.

Since the effect of loss shifts the poles and zeros of the filter to the left hand side of the complex plane, in the second step the effect of loss must be removed from the approximated filtering function. For this purpose, it is assumed that the effect of loss on transmission zeros is very small and only the reflection zeros are affected. If the unloaded quality factors Q_u of all resonators are assumed to be the same, then the resistances r_i in Fig.1 will be equal. This means that all reflection zeros are shifted to the left hand side of the complex plane by the same amount. If the reflection zeros of the lossy filtering function are denoted by $Z_i^r = \sigma_i^r + j\omega_i$, then the resistance r may be computed from the following equation [11]:

$$r = \frac{1}{N}\sum_{i=1}^{N}\sigma_i^r \tag{11}$$

Therefore, "lossless" reflection zeros are:

$$Z_i = \sigma_i^r + j\omega_i - r \tag{12}$$

Using the transmission zeros obtained from (8) and the modified reflection zeros given in (12) along with Feldtkeller's equation:

$$F(s)F^*(-s) + P(s)P^*(-s) = E(s)E^*(-s) \tag{13}$$

the lossless scattering parameters are obtained in terms of rational functions. Standard synthesis techniques can now be used to extract the coupling matrix from these "idealized" scattering parameters. First, the analytical method presented in [12] was used to construct the general coupling matrix from scattering parameters. Then, an eigenvalue based optimization procedure described in [10] was used to extract the realized coupling matrix. The external quality factor for the first and last resonator can be computed from the extracted coupling matrix:

$$Q_{EXT,1} = \frac{f_0}{BW \times M_{1,S}^2} \tag{14}$$

$$Q_{EXT,N} = \frac{f_0}{BW \times M_{N,L}^2} \tag{15}$$

The unloaded quality factor of resonators can be obtained approximately from the following equation:

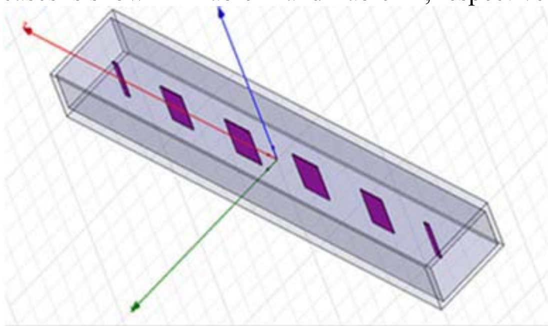
$$Q_u = \frac{f_0}{r \times BW} \tag{16}$$

IV. NUMERICAL RESULTS

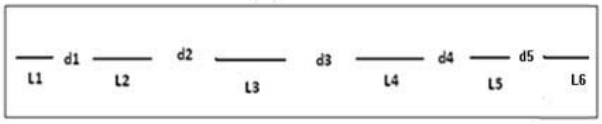
The method outlined above is employed for numerical tuning of two bandpass filters which are simulated with Ansoft HFSS. Furthermore, diagnosis and tuning of a fabricated combline filter will be presented.

A. E-plane Waveguide Filter

An E-plane bandpass filter of order 5 is shown in Fig.2. The desired center frequency and bandwidth of the filter are 29GHz and 500MHz, respectively and the desired return loss is 25dB. Starting values for physical dimensions of the filter given in [7] have been used in this filter and are shown in Table I. We tried to tune these dimensions by extracting the coupling matrix and adjusting the appropriate parameters at each step until an acceptable response was achieved. Only 11 frequency samples within the desired bandwidth were utilized for extracting the rational functions as described in section II. These frequency samples were obtained from Ansoft HFSS. The tuning process of the filter was carried out in 8 steps and the final dimensions of the filter are shown in Table I. The filter responses corresponding to the initial and final steps are plotted in Fig.3 and Fig.4, respectively. The coupling matrix corresponding to these two cases is shown in Table II and Table III, respectively.



(a)



(b)

Figure 2. (a) five poles E-plane waveguide filter (b) top view

TABLE I. PHYSICAL PARAMETERS OF THE WAVEGUIDE FILTER BEFORE AND AFTER TUNING.

(mm)	d1	d2	d3	d4	d5	L1	L2	L3	L4	L5	L6
First step	6.52	6.52	6.52	6.52	6.52	1	1	1	1	1	1
Final step	5.82	5.90	5.90	5.90	5.82	0.66	2.90	3.40	3.40	2.90	0.66

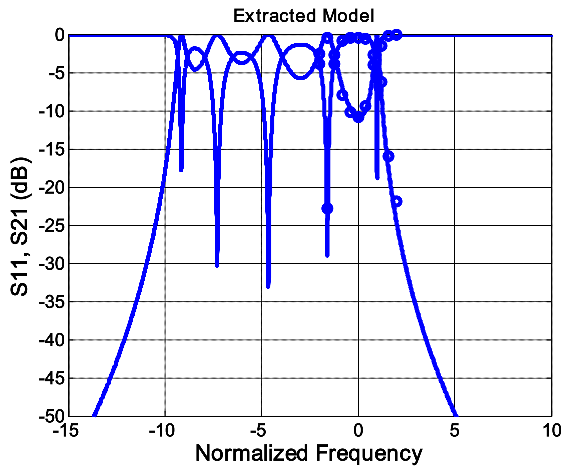


Figure 3. Extracted model for E-plane waveguide filter at initial step of tuning process (solid line) and samples of s-parameters used to extract the model (circles).

B. Multiple Coupled Coaxial Cavity Filter With Single Transmission Zero

The 4-pole coupled resonator coaxial filter is shown in Fig.5. This topology creates a single transmission zero above the pass-band. Desired specifications of this filter are given in Table IV. Only 11 frequency samples were used for extracting the rational model of the filter. The tuning of this filter was completed in 9 steps. The initial and final values of physical dimensions are presented in Table V. In this table R_i denotes the variable length of cylindrical post of i_{th} resonator. Starting values of physical parameters presented in [13] were used to start the procedure. According to [13] the external dimensions of each resonator are $25\times25\times50$ mm and the diameter of all cylindrical posts is $\varnothing 7.2$ mm. The extracted models corresponding to the initial and final steps are plotted in Fig.6 and Fig.7, respectively. The coupling matrices corresponding to these steps are given in Table VI and Table VII, respectively.

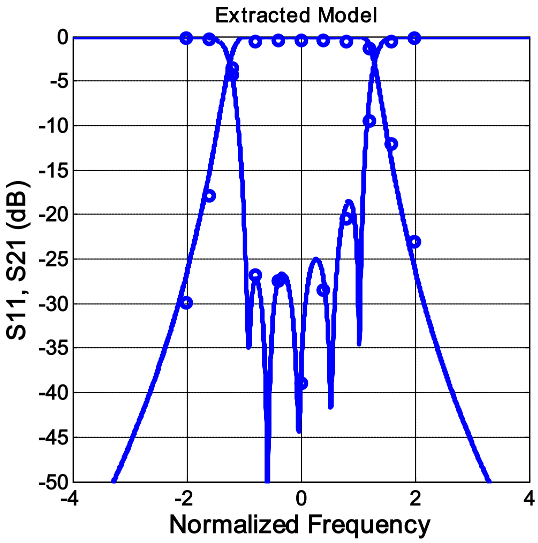


Figure 4. Extracted model for E-plane waveguide filter at final step of tuning process (solid line) and samples of s-parameters used to extract the model (circles).

TABLE II. Extracted Coupling Matrix At Initial Step Of Tuning Process For The Waveguide Filter

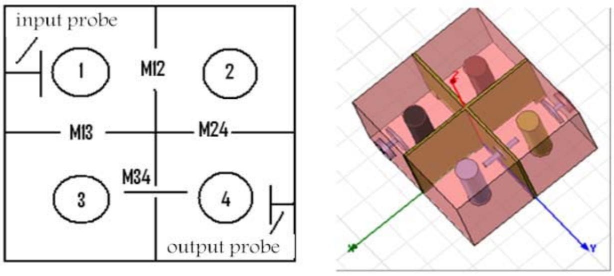
0	0.9916	0	0	0	0	0
0.9916	4.9072	2.8985	0	0	0	0
0	2.8985	3.6705	2.9548	0	0	0
0	0	2.9584	3.9198	2.9737	0	0
0	0	0	2.9737	3.9705	2.8861	0
0	0	0	0	2.8861	4.9072	0.9953
0	0	0	0	0	0.9953	0

TABLE III. Extracted Coupling Matrix At Final Step Of Tuning Process For The Waveguide Filter

0	1.1147	0	0	0	0	0
1.1147	0.0200	0.9639	0	0	0	0
0	0.9639	-0.0149	0.6855	0	0	0
0	0	0.6855	-0.0289	0.6857	0	0
0	0	0	0.6857	-0.0149	0.9626	1.1449
0	0	0	0	0.9626	0.0200	0
0	0	0	0	0	1.1449	

TABLE IV. Desired Specifications For The Coaxial Filter

Center frequency	1842.5MHz
bandwidth	40MHz
Transition zero	1842.5+45MHz
Normalized transition zero	2.17
Return Loss	25dB



(b) (a)

Figure 5. (a) four poles coaxial filter (b) top view

TABLE V. Physical Parameters Of The Coaxial Filter Befor And After Tuning

(mm)	R1	R2	R3	R4	M12	M24	M13	M34	Input probe	Output probe
First step	33.11	35.68	35.08	32.79	7.5	8.08	3.97	6.68	5.4	5.41
Final step	34.9	35.77	35.21	34.72	5.85	6.25	3.13	13.25	3.55	3.51

TABLE VI. Extracted Coupling Matrix At Initial Step Of Tuning Process For The Coaxial Filter

0	2.0268	0	0	0	0
2.0268	-0.4738	1.139	0.8833	0	0
0	1.139	0.9122	0	0.9397	0
0	0.8833	0	-1.767	-0.0969	0
0	0	0.9397	-0.097	-1.6898	2.0271
0	0	0	0	2.02271	0

TABLE VII. Extracted Coupling Matrix At Final Step Of Tuning Process For The Coaxial Filter

0	1.1475	0	0	0	0
1.1475	0.2026	0.8535	0.5837	0	0
0	0.8535	0.7381	0	0.8505	0
0	0.5837	0	-0.7596	-0.5857	0
0	0	0.8502	-0.5857	0.2211	1.1477
0	0	0	0	1.1477	0

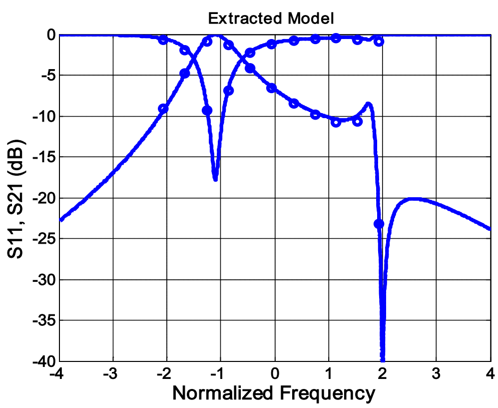


Figure 6. Extracted model for coaxial filter at initial step of tuning process (solid line) and samples of s-parameters used to extract the model (circles).

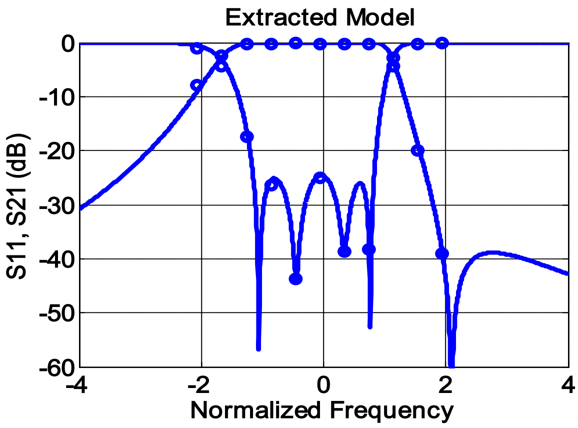


Figure 7. Extracted model for coaxial filter at final step of tuning process. (solid line) and samples of s-parameters used to extract the model (circles).

C. Manufactured Combline Filter

The diagnosis and tuning technique presented in this paper was applied to a fabricated 5-pole Chebyshev combline filter shown in Fig. 8.

The filter was designed for the center frequency of 2.5GHz and bandwidth of 30MHz. The measured response of the filter when it is off tuned is plotted in Fig.9. The extracted rational function model for the lossy filter is also shown in Fig.9 which demonstrates the accuracy of the MBPE procedure. After applying the tuning procedure based on coupling matrix extraction described in section III, the final response of the filter after 3 steps is shown in Fig.10. There are no tuning screws for adjusting the coupling coefficients and only the resonance frequencies can be tuned; therefore, the final response could not be improved further.

Figure 8. A five poles combline filter

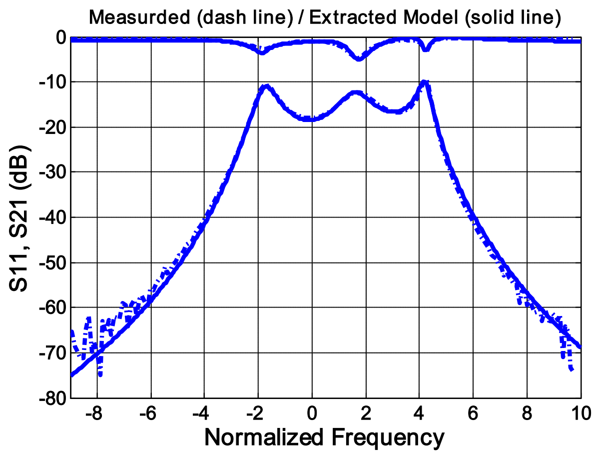


Figure 9. S-parameters obtained from polynomial synthesis (solid lines) and measurement (dash lines) for off-tune combline filter.

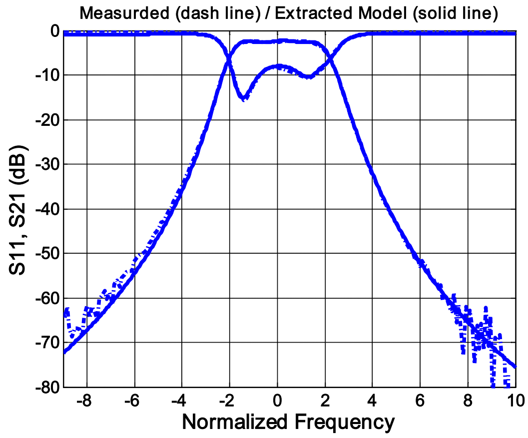


Figure 10. S-parameters obtained from polynomial synthesis (solid lines) and measurement (dash lines) for tuned combline filter.

The extracted coupling matrix from estimated lossless model according to the method described in section III is shown in Table VIII. Unloaded quality factor of the resonators was estimated to be $Q_u = 396.8$. The external quality factors at input and output ports were estimated to be 36 and 37.5, respectively.

TABLE VIII. EXTRACTED COUPLING MATRIX FOR 5-POLE COMBLINE FILTER AFTER TUNING

0	1.4582	0	0	0	0	0
1.4582	-0.2834	2.0552	0	0	0	0
0	2.0552	-0.2167	1.0485	0	0	0
0	0	1.0485	-0.125	1.1713	0	0
0	0	0	1.1713	-0.0443	1.5701	0
0	0	0	0	1.5701	-0.2892	1.4584
0	0	0	0	0	1.4584	0

V. CONCLUSION

An efficient procedure which was presented for extraction of coupling matrix in lossless multiple coupled resonator filters was extended to lossy filters and a robust software package for this purpose was developed. The method was used for tuning and diagnosis of several practical filters demonstrating its robustness and accuracy. The package developed in this research is a valuable tool for filter designers during the design process when repeated EM simulations are used to adjust the filter parameters as well as in post fabrication tuning.

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