Coupling Matrix Extraction of Lossy Cross-coupled Filters Using Exact Pole-Zero Identification

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***Abstract*—This paper proposes a special technique for coupling matrix extraction for both lossy and lossless filters for the first time. Minimum sample points are used to perfectly locate poles and zeros. Proposed optimization offers exact approximation of characteristics polynomial (CP). Losses are introduce by proper scaling of CP. Coupling matrix (CM) is derived from scaled CP for fine tuning. Two different filter configurations are considered for validation of proposed CM extraction method. Finally, a lossy filter tuning case is examined to demonstrate practical applicability of the proposed extraction technique.**

***Index Terms*—Transmission zero (TZ); reflection zero (RZ); coupling matrix (CM); transmission pole (TP); tuning; quality factor (Q_u); optimization.**

I. Introduction

Microwave filter tuning always remain serious challenge to industries. Conventional human experience based tuning approach is not only time consuming but also suffer from inaccuracy. To ease tuning burden, researchers developed computerized automated filter tuning method. Fuzzy or neural network based tuning algorithm is used in [1]–[3]. But these methods are restricted to lossless filters with simple in-line coupling topology. Some researchers apply vector fitting technique [4] to tune uneven Q_u filters. Lossy filter tuning by complex mathematical transformation is discussed in [5]. Recently, lossy filters tuning method is provided in [6]. However, systematic approach for lossy CM extraction hence tuning remain as unsolved issue for microwave filter designers specially for filters having box coupling topology [7]. This work mainly focuses on CM extraction for box topology filters i.e. having multiple lossy and lossless cross-couplings.

Since CM synthesis and CM extraction are transpose operation to each other hence, in case of lossy filters, coupling matrix extraction approach is quite different since the synthesis is unique. This paper imparts a new extraction technique that is applicable to complex coupling matrix for highly lossy as well as conventional lossless filters. Prime achievements of this work are: (i) exact pole-zero approximation from minimum sample points, (ii) lossless, lossy even asymmetric lossy filter can be tuned by proposed method which is illustrated for the first time, (iii) a robust CM extraction technique is proposed unlike previous works, (iv) finally, CM extraction and tuning of box section lossy filter with unequal unloaded quality factor (Q_u) is demonstrated successfully.

II. CM Extraction Method

General scattering matrix of any filter is given by [7]:

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \frac{1}{E(s)} \begin{bmatrix} F_{11}(s) & \hat{P}(s) \\ \hat{P}(s) & F_{22}(s) \end{bmatrix} \tag{1}$$

Where $\hat{P}$ is normalized P by ϵ. This paper presents a unique optimization technique by exact pole-zero approximation followed by CM extraction as discussed in following steps.

Step 1: Sample S-parameter data from measurement or simulation results. Ideally required sample points is sum of TZs and RZs but more data points are preferable. One can pre-processed (smoothing or averaging) raw data for noise cancellation which results better approximation hence perfect CM extraction.

Step 2: Perform bandpass (f) to low pass frequency (Ω) domain transformation and use phase de-embedding method to eliminate phase loading error as discussed in [4].

Step 3: Determine loss factors [μ_p, μ_{11}, μ_{22}] from magnitude response of S_{21}, S_{11}, and S_{22} respectively for lossy filters.

Step 4: Calculate $\Upsilon = \frac{S_{21}}{S_{11}}$ from pre-processed data points for TZ, RZ optimization cycle. During optimization roots of $\hat{P}$ and F_{11} will be evaluated to match previously calculated [Υ].

Step 5: Calculated $\Upsilon^* = \{\Upsilon_1^*, \Upsilon_2^*, \dots, \Upsilon_N^*\}$ at N frequency points $\{\Omega_1, \Omega_2, \dots, \Omega_N\}$ will be used as objective function for TZ, RZ optimization algorithm. Hence optimization problem can be expressed as:

$$\begin{aligned} &\text{minimize } \Delta \\ &\text{such that,} \\ &\sum \|\Upsilon_i(\Omega_K) - \Upsilon_i^*\| \le \Delta \quad i = 1, 2, ..., N \end{aligned} \tag{2}$$

where Δ is error tolerance and $\Upsilon(\Omega_K)$ is evaluated as $\Upsilon = \frac{S_{21}}{S_{11}} = \frac{\hat{P}}{F_{11}}$, and the optimization parameters are the roots of $\hat{P}$ (or TZs), F_{11} (or RZs) and ϵ respectively. The constrained optimization problem (2) is solved in Matlab.

Step 6: Once $\hat{P}$ and F_{11} (or F_{22}) are known then polynomial E can be derived from unitary condition.

Step 7: Scaled E, $\hat{P}$, F_{11}, and F_{22} by corresponding loss factors (μ_p, μ_{11}, μ_{22}) to transform into lossy polynomials. Note that μ_p=μ_{11}=μ_{22}=1 for lossless filters and these factors can be equal (symmetric lossy filter) or unequal (asymmetric lossy filter) with any value depending upon magnitude response.

Step 8: Coupling matrix can be derived from admittance matrix [Y], once all polynomials are obtained as given in [7].

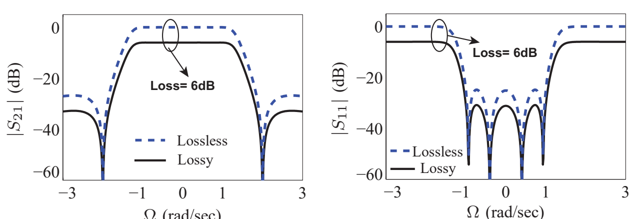
Following these basic steps one can perfectly extract CM for highly lossy as well as lossless filters. Therefore this work proposes more general and robust approach compare to all previously reported works. CM extraction technique for two different lossy filters will be discussed in following Sec. III.

III. CM Extraction Examples

Here we will discuss about two different filters: symmetric 6dB lossy filter and other one is asymmetric lossy case. Since proposed CM extraction technique is primarily on low pass domain (Ω) therefore one need to follow standard transformation as mentioned in [4]. Data sampling and pre-processing will not be discussed here as it is not our main focus and all analysis will be discussed in Ω domain only.

A. Example 1: A Four Pole Symmetric 6 dB Lossy Filter

A lossy 4^{th} order Elliptic filter is considered for CM extraction. Following all extraction steps in, one can derive CP i.e. E, $\hat{P}$, F_{11}, and F_{22}. Since all losses are equal, therefore one need to scale down $\hat{P}$ and F_{11} (or F_{22}) polynomials by common loss factor μ_p=μ_{11}=μ_{22}= 0.5 (i.e. 6 dB loss). This scaling operation transform lossless polynomials into lossy polynomials hence lossy responses as shown in Fig. 1. Table I provides a comparison between ideal and extracted polynomials which points out exact matching between both.



(a) (b)

Fig. 1: Lossless to lossy transformation by scaling μ= 0.5 (Example:1) (a) $|S_{21}|$, and (b) $|S_{11}|$ magnitude response.

TABLE I:
Ideal and extracted characteristics polynomial (Example:1)

Poly	Ideal	Extracted
$E(s)$	$s^4 + 2.57s^3 + 4.34s^2 +$ $4.32s + 2.56$	$s^4 + 2.59s^3 + 4.34s^2 +$ $4.31s + 2.53$
$P(s)$	$s^2 + 4$	$s^2 + 3.994$
$F_{11}(s) = F_{22}(s)$	$s^4 + 1.04s^2 + 4.32s + 0.14$	$s^4 + 1.04s^2 + 4.30s + 0.13$
$Epsilon\ (\epsilon)$	1.5671	1.5659

Then lossy CM is obtained from these derived scaled polynomial and compared in Fig. 2. One can observe most of the elements matches well with minor error in few coupling elements as highlighted in Fig. 2(b). Finally both S-parameter responses are compared and presented in Fig. 3. Both responses replicate each other which imply effectiveness of this technique to extract CM precisely for box coupling topology filters with symmetric losses.

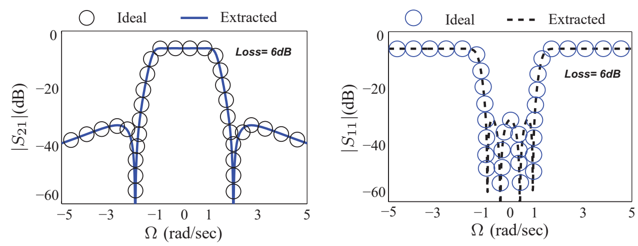
(a)

	S	1	2	3	4	L
S	-0.332i	1.07	0	0	0	0
1	1.07	-0.427i	0.974	0	-0.248	0
2	0	0.974	0	0.854	0	0
3	0	0	0.854	0	0.974	0
4	0	-0.248	0	0.974	-0.427i	1.07
L	0	0	0	0	1.07	-0.332i

(b)

	S	1	2	3	4	L
S	-0.332i	***1.06***	0	0	0	0
1	***1.06***	***-0.430i***	0.974	0	-0.248	0
2	0	0.974	0	0.854	0	0
3	0	0	0.854	0	0.974	0
4	0	-0.248	0	0.974	***-0.430i***	***1.06***
L	0	0	0	0	***1.06***	-0.332i

Fig. 2: Coupling matrix for 4^{th} order 6 dB symmetric lossy filter (Example: 1) (a) ideal CM, and (b) extracted CM.



(a) (b)

Fig. 3: Performance comparison of symmetric lossy filter (Example: 1) (a) $|S_{21}|$, and (b) $|S_{11}|$ response.

B. Example 2: Four Pole Asymmetric Lossy Filter

CM extraction for a more general lossy filter with different losses i.e. S_{21}= 6dB, S_{11}= 3dB and S_{22}= 9dB is considered as last example. Basic steps involved for proper approximation of CP followed by lossy transformation by proper scaling of polynomials i.e. $\hat{P}'$=$\mu_p.\hat{P}$, F'_{11}=$\mu_{11}.F_{11}$ and F'_{22}=$\mu_{22}.F_{22}$ as analyzed in Sec. II. Ideal lossy CM is compared with extracted CM with small errors in few coupling elements as depicted in Fig. 4. Extracted TZs and RZs are co-located with ideal one as plotted in Fig. 5(a). Further exact reproduction of S-parameters as shown in Fig. 5, validates proposed CM extraction approach.

(a)

	S	1	2	3	4	L
S	-0.188i	1.117	0	0	0	0
1	1.117	-0.232i	0.975	0	-0.247	0
2	0	0.975	0	0.852	0	0
3	0	0	0.852	0	0.975	0
4	0	-0.247	0	0.975	-0.605i	0.99
L	0	0	0	0	0.99	-0.471i

(b)

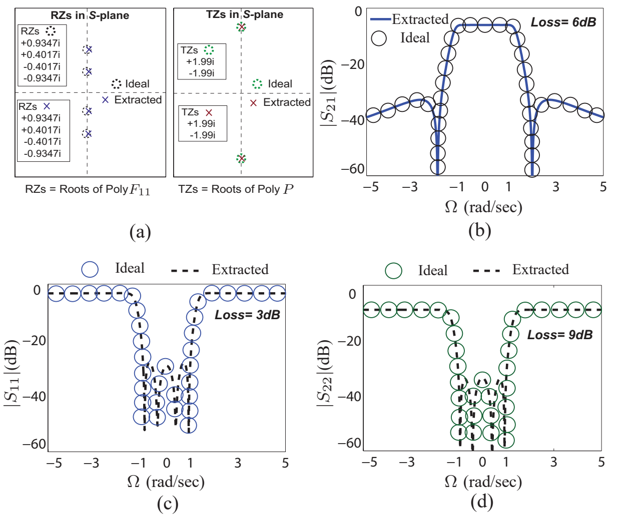
	S	1	2	3	4	L
S	-0.188i	1.117	0	0	0	0
1	1.117	-0.232i	**0.974**	0	-0.247	0
2	0	**0.974**	0	0.852	0	0
3	0	0	0.852	0	0.975	0
4	0	-0.247	0	0.975	-0.605i	**1.01**
L	0	0	0	0	**1.01**	-0.471i

Fig. 4: Coupling matrix comparison for asymmetric lossy case (Example: 2) (a) ideal CM, and (b) extracted CM.

IV. CM Extraction for Fine Tuning

One can use CM extraction technique at intermediate stages for efficient tuning of such filters. As CM carries complete information regarding all couplings as well as resonators, therefore one can extend this technique for coarse and fine tuning of lossy filters. Since the proposed method can extract CM perfectly from measurement or simulation data, so one can apply it for efficient tuning of box topology lossy filters which will be demonstrated by a suitable example.

Consider a 4^{th}-order lossy filter example whose tuned CM along with coupling diagram are shown in Fig. 6(a) and Fig. 6(b) respectively. One direct coupling element m_{23} is



(a) (b) (c) (d)

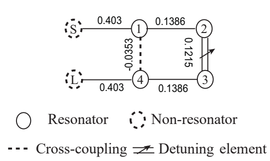
Fig. 5: Response comparison for asymmetric lossy case (Example:2) (a) pole-zero, (b) $|S_{21}|$, (c) $|S_{11}|$, and (d) $|S_{22}|$.

disturbed intentionally (marked in Fig. 6(a)) and as a result filter response changes completely as shown in Fig. 6. Now one needs to identify this perturbed coupling element m_{23} from de-tune responses to tune it properly.

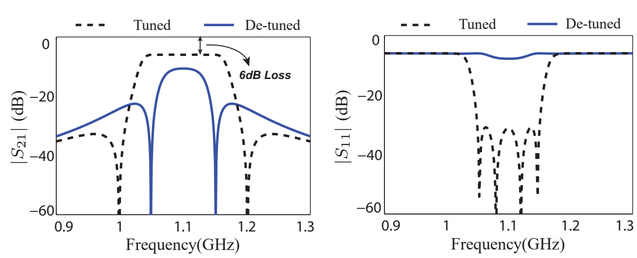
Following all extraction steps, one can derive coupling matrix for this heavily de-tuned filter. Extracted CM for this de-tuned case is shown in Fig. 7(a). Further an error estimator called residue matrix which is nothing but element wise difference between actual de-tuned CM and extracted de-tune CM, is calculated. Note that most of the elements in residue matrix are zero which imply CM extraction was perfect. Residue matrix along with exact matching de-tuned (ideal and extracted) responses are shown in Fig. 7. Since de-tuned coupling element (m_{23}) is identified successfully, therefore one can easily tune it by proper adjustment of respective physical parameters (gap or coupled length) to obtain desired coupling coefficient m_{23} value.

	S	1	2	3	4	L
S	-0.332i	0.403	0	0	0	0
1	0.403	-0.0608i	0.1386	0	-0.0353	0
2	0	0.1386	0	0.1215	0	0
3	0	0	0.1215	0	0.1386	0
4	0	-0.0353	0	0.1386	-0.0608i	0.403
L	0	0	0	0	0.403	-0.332i

(a)



(b)



(c) (d)

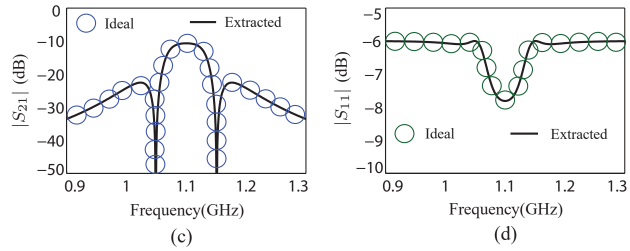
Fig. 6: Tuned and detuned lossy filter response (a) tuned CM, (b) coupling topology, (c) $|S_{21}|$, and (d) $|S_{11}|$.

	S	1	2	3	4	L
S	-0.332i	0.403	0	0	0	0
1	0.403	-0.0608i	0.1386	0	-0.0353	0
2	0	0.1386	0	0.1215	0	0
3	0	0	0.1215	0	0.1386	0
4	0	-0.0353	0	0.1386	-0.0608i	0.403
L	0	0	0	0	0.403	-0.332i

(a)

	S	1	2	3	4	L
S	0	0.001	0	0	0	0
1	0.001	-0.003	-0.002	0	0.0003	0
2	0	-0.002	0	0.001	0	0
3	0	0	0.001	0	0.0005	0
4	0	0.0003	0	0.0005	0.0004	0.001
L	0	0	0	0	0.001	0

(b)



(c) (d)

Fig. 7: Detuned lossy filter responses (a) extracted detuned CM, (b) residue matrix, (c) $|S_{21}|$, and (d) $|S_{11}|$ responses.

V. Conclusion

A robust tuning technique using CM extraction method for lossy filters has been proposed in this paper. Perfect CM extraction has achieved from minimum sample points by exact pole-zero approximation. Proposed extraction method has been verified by examining a symmetric lossy and an asymmetric lossy filter. Finally, a lossy filter tuning example has been demonstrated. Further for future work, a higher order multiple cross-coupled lossy filter can be tuned as an experimental verification of the proposed extraction technique.

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References

[1] V. Miraftab and M. Yu, "Innovative combline rf/microwave filter em synthesis and design using neural networks," in *International Symposium on Signals, Systems and Electronics*, July 2007, pp. 1–4.

[2] V. Miraftab and R. R. Mansour, "Computer-aided tuning of microwave filters using fuzzy logic," in *IEEE MTT-S International Microwave Symposium Digest*, vol. 2, June 2002.

[3] ——, "Fully automated rf/microwave filter tuning by extracting human experience using fuzzy controllers," *IEEE Transactions on Circuits and Systems I*, vol. 55, no. 5, June 2008.

[4] H. Hu and K. L. Wu, "A generalized coupling matrix extraction technique for bandpass filters with uneven-qs," *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 2, pp. 244–251, Feb 2014.

[5] A. G. Lamperez, T. K. Sarkar, and M. S. Palma, "Generation of accurate rational models of lossy systems using the cauchy method," *IEEE Microwave and Wireless Components Letters*, vol. 14, no. 10, Oct 2004.

[6] R. Das, Q. Zhang, A. Kandwal, and H. Liu, "Coupling matrix extraction technique for auto tuning of highly lossy filters," in *2018 IEEE/MTT-S International Microwave Symposium - IMS*, June 2018, pp. 697–700.

[7] R. J. Cameron, "Advanced coupling matrix synthesis techniques for microwave filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 51, no. 1, pp. 1–10, Jan 2003.