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EXTRACTING COUPLING MATRIX AND UNLOAD Q FROM SCATTERING PARAMETERS OF LOSSY FILTERS

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Abstract—This paper presents a method for extracting the coupling matrix and the unloaded Q from the measured (or electromagnetic simulated) S-parameters of a narrow band cross-coupled resonator bandpass filter with losses. The Cauchy method is applied to determine the characteristic polynomials of the S-parameters of a filter in the normalized low-pass frequency domain. A five-parameter optimization method is proposed to obtain the unloaded Q and to remove the phase shift of the measured S-parameters, which is caused by the phase loading and the transmission lines at the input/output ports of a filter. Once the characteristic polynomials of the S-parameters with the phase shift removed have been determined, the coupling matrix of a filter with a given topology can be extracted using well established techniques. Two application examples are given to illustrate the validity of the proposed method.

1. INTRODUCTION

Computer aided diagnosis (CAD) and tuning of a microwave-coupled resonator filter have drawn a great deal of interest in recent years, such as Cauchy methods in [1–5], the sequential tuning method recently reported in [6], analytical methods in [7, 8], and optimization methods in [9–11]. Extraction of the coupling matrix (CM) and the unloaded Q from measurements (or simulations) is very useful in CAD and practical tuning of filters, revealing the differences with the designed one and guaranteeing each step of a tuning in the right direction. CAD

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has a significant impact on the overall filter production cost and project schedules.

The main difficulty of the sequential tuning is that it is not always convenient to segregate each resonator or coupling element in a filter structure such as dielectric resonator filters. Cauchy method has proved to be an effective technique for extracting the characteristic polynomials F, P and E of a filter from the measured S-parameters, where $S_{11} = F/E$, $S_{21} = P/E$ [1–5]. However, the methods in [1–3] can only deal with a lossless or low-loss filter, which restricts its practical uses. In addition, the phase-shift effects of the measured S-parameters, which are caused by the phase loading and the transmission lines at the input/output (I/O) ports of a physical filter, were not discussed in [1–5]. The polynomials F, P and E solved in one step [5] are not suitable for the CM extraction by well-known established technique [12] because of the phase shift, when the raw measured S_{11} and S_{21} are used directly. The polynomials F, P and E solved in two steps [1–4] are only suitable for the CM extraction in the case of the measured S_{11} and S_{21} with the same phase shift, because the same phase shift is removed automatically when F and P are calculated using a ratio of the measured S_{11} to S_{21} at frequency samples (E is then evaluated by solving the Feldkeller's equation). In [7], the phase loading concept is revealed for the first time in CAD. Some techniques have also been proposed for removing the phase-shift effects from the S-parameters [7, 8]. However, the method in [7] requires carefully select frequency samples far below or above the center frequency because of some features of the response such as the presence of spurious passbands and the frequency-dependent coupling, and the measurement noise in the original data acquired from a vector network analyzer need to be removed in advance; The method reported in [8] requires the additional transmission lines at a filter I/O ports, which leads to the inconvenience and difficulties in practical uses.

In this paper, a simple and effective optimization method is proposed to obtain the unloaded Q and to remove the phase shift of the measured S-parameters at the I/O ports of a filter. Different from direct optimization of the CM elements [9–11], the proposed method only includes five optimized parameters, which are independent on the order and the topology of a filter. In our method, the phase shift of the measured S-parameters is derived using the optimized parameters. When removing the phase shift and obtaining the unloaded Q by the proposed five-parameter optimization method, the characteristic polynomials F, P and E are solved in one step by the method in [5]. Finally, the CM is extracted from the polynomials of S-parameters by well-known established technique [12]. Besides [12], a method in [13] for numerically synthesizing the CM of coupled resonator filters was introduced. However, it was only suitable for the canonical quadruplet structure.

Using the presented method, there is no need to deal with the degenerate poles of the admittance parameters and the measurement noise. The proposed method is also suitable for the measured S_{11} and S_{21} with the different phase shift. This method will find many practical applications for the tuning of coupled resonator bandpass filters (as in [14–18]), dual-band resonator bandpass filters (as in [19–22]), and dual-mode bandpass filters (as in [23, 24]), which are designed according to the coupling matrix. It is expected that the proposed CM extraction method can significantly accelerate the tuning of high-order cross-coupled resonator filters to obtain the required filter response and a physical realization. Two examples of the CM extraction are provided to show the validity of the method.

2. THEORY

In a lossless circuit model (see Fig. 1) suitable for the CM synthesis [12], the I/O couplings are represented by a simple inverter without any embedded transmission lines at I/O ports, which shift the reference planes. In a physical model (see Fig. 2), however, three nonideal effects exist: 1) effects of phase shifts due to embedded transmission lines l_{in}, l_{out}; 2) a constant phase loading caused by the higher order modes at the vicinity of I/O coupling structures; and 3) the loss effect associated to each resonator $R_1, R_2, \ldots, R_N$. These three nonideal effects need to be removed from the raw measured data of a physical filter model before the CM extraction.

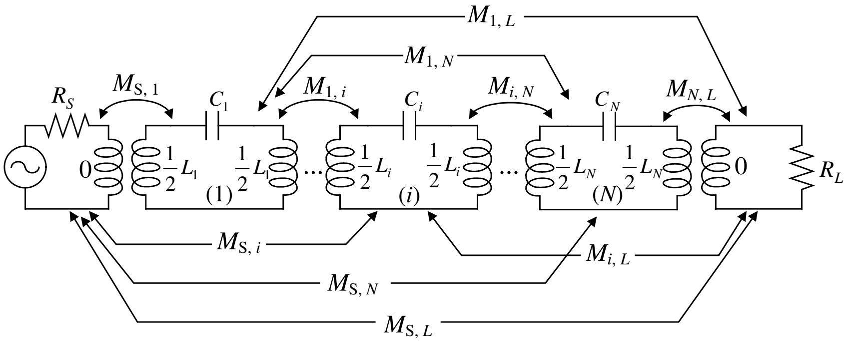

Figure 1. Model of a lossless cross-coupled resonator bandpass filter.

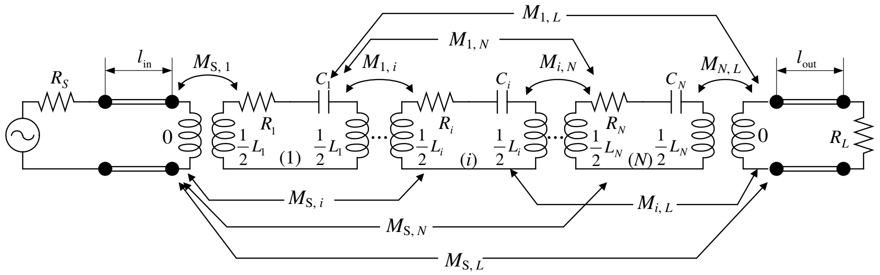

Figure 2. Model of a general coupled resonator bandpass filter. Embedded transmission lines and losses are taken into account by the model.

2.1. Calculation of Characteristic Polynomials

S_{21} and S_{11} can be approximated by three characteristic polynomials F, P and E as [1–5]

$$S_{11}(s') = \frac{F(s')}{E(s')} = \frac{\sum_{k=0}^{N} a_k^{(1)} s'^k}{\sum_{k=0}^{N} b_k s'^k}, \quad S_{21}(s') = \frac{P(s')}{E(s')} = \frac{\sum_{k=0}^{nz} a_k^{(2)} s'^k}{\sum_{k=0}^{N} b_k s'^k}. \tag{1}$$

where, N is the filter order and nz is the number of finite transmission zeros. A modified frequency transformation used for converting the measured S-parameters from the bandpass domain f to the normalized lowpass domain s' is adopted here as [4]

$$s' = \frac{f_0}{BW}\frac{1}{Q_u} + j\frac{f_0}{BW}\left(\frac{f}{f_0} - \frac{f_0}{f}\right). \tag{2}$$

It is usually well verified for a very large class of microwave filters that the unloaded quality factors Q_u of all resonators are nearly the same. So, the approximation here adopted is that Q_u of each resonator is assumed to be the same. BW and f_0 are bandwidth and center frequency of the filter, respectively. In this way the equivalent circuit to be synthesized in the s' domain from the computed polynomials is a lossless circuit [4]. The formulation of the Cauchy method allows the evaluation of the complex coefficients $a_k^{(1)}$, $a_k^{(2)}$ and b_k (and then F, P and E) in one step by solving the following the (over determined) system [5]:

$$\begin{bmatrix} V_N & 0_{Ns\times(nz+1)} & -S_{11}V_N \\ 0_{Ns\times(N+1)} & V_{nz} & -S_{21}V_N \end{bmatrix} \begin{bmatrix} a^{(1)} \\ a^{(2)} \\ b \end{bmatrix} = 0 \tag{3}$$

where $a^{(1)} = [a_0^{(1)}, \ldots, a_N^{(1)}]^T$, $a^{(2)} = [a_0^{(2)}, \ldots, a_{nz}^{(2)}]^T$, $b = [b_0, \ldots, b_N]^T$, $S_{21} = \mathrm{diag}\{S_{21}(s'_i)\}_{i=1,\ldots,Ns}$, $S_{11} = \mathrm{diag}\{S_{11}(s'_i)\}_{i=1,\ldots,Ns}$ and $V_r \in C^{Ns\times(r+1)}$ is a vandermonde matrix with elements $V_{i,k} = (s'_i)^{k-1}, k = 1, \ldots, r+1$. The $S_{21}(s'_i)$ and $S_{11}(s'_i)$ are the measured or simulated S-parameters at frequency points s'_i $(i = 1, 2, \ldots, Ns)$. Ns is the number of frequency points. Frequency points s'_i maps into the physical frequency points f_i. Note that, the measured (or simulated) S_{21} and S_{11} samples in (3) should be chosen around the passband in Cauchy method; in fact it is not convenient to consider frequency points too much distant from the passband because the accuracy of the model may be reduced by second order effects such as the frequency-dependent couplings.

It must be observed that the polynomials F, P and E solved in one step [5] are not suitable for the CM extraction by well-known established technique [12], before the phase shift of the measured S-parameters are removed. Failing to remove the phase shift will leads to an incorrect CM extraction.

2.2. Removal of the Phase Shift and Extraction of Unloaded Q and Coupling Matrix

In a physical filter model, there is always a section of transmission line at I/O ports, which shifts the reference planes. A phase offset φ connected to each port can be very well approximated by the following function in a wide frequency range [7]:

$$\varphi = \varphi_0 + \beta\Delta l \tag{4}$$

Here, the frequency invariant constant term φ_0 is called the phase loading, which is caused by the higher order modes in the vicinity of the I/O coupling elements; β is the propagation constant of the transmission line and Δl is an equivalent length of the transmission line. For a typical transmission line, $\beta\Delta l$ can be expressed as $\beta\Delta l = 2\pi f\Delta l\sqrt{\varepsilon_{eff}\mu}$, where ε_{eff} is the effective dielectric constant of the transmission line. $\beta\Delta l$ can be easily derived as $\beta\Delta l = f\theta_0/f_0$, where θ_0 is the equivalent electrical length of the transmission line at f_0 in radians. The following phase shift caused by the phase loading and the transmission lines should be removed from the measured S_{11} and S_{21}, respectively

$$\begin{aligned} \Delta\phi S_{11} &= -2(\varphi_{01} + f\theta_{01}/f_0), \\ \Delta\phi S_{21} &= -(\varphi_{01} + \varphi_{02} + f\theta_{02}/f_0 + f\theta_{01}/f_0). \end{aligned} \tag{5}$$

where φ_{01} and φ_{02} are the phase loading at I/O ports, respectively. $\theta_{01} = 2\pi f_0 l_{\mathrm{in}}\sqrt{\varepsilon_{eff}\mu}$ and $\theta_{02} = 2\pi f_0 l_{\mathrm{out}}\sqrt{\varepsilon_{eff}\mu}$ are the equivalent electrical length of the transmission line at I/O ports, respectively.

A normalized $N+2$ coupling matrix $[M']$ including losses can be expressed as

$$[M'] = [M] - j[G]. \quad (6)$$

Here, $[M]$ represents the coupling between coupled resonators, and $[G]$ is the diagonal matrix $[G] = \text{diag}[0, G_1, \ldots, G_N, 0]$, which represents the loss of the filter. The loss factor $G_i\,(i = 1, 2, \ldots, N)$ for the ith resonator can be evaluated by $G_i = BW/(f_0 Q_u)$. Once $[M']$ is extracted, the filter response including losses can be obtained via the following equation

$$S_{21} = -2j[A^{-1}]_{N+2,1}, \quad S_{11} = 1 + 2j[A^{-1}]_{1,1}. \quad (7)$$

Here, $A = [\Omega U - jR + M']$, Ω, $[R]$ and $[U]$ can refer to [25]. Equation (7) allows the calculation of a lossy filter response, which is different from that given in [25]. Also, as Q_u approach infinity, $[M']$ degenerates to $[M]$, and Equation (7) is exactly the same as that given in [25], which is suitable for the lossless filter response.

$\varphi_{01}, \theta_{01}, \varphi_{02}, \theta_{02}$ and Q_u are the unknown parameters to be optimized. Once they are known, the phase shift of the measured S-parameters can be removed using (5), and then the characteristic polynomials F, P and E are solved in one step described in Section 2.1; the next step consists of extracting the coupling matrix $[M]$ from the characteristic polynomials by well-known established technique [12] and then $[M']$ according to (6). To show the differences between the designed CM and the extracted CM, a series of the same similarity transformations as the designed one requires to be applied to the extracted $(N+2)$ fully canonical coupling matrix. As the result, the coupling matrix $[M]$ is extracted, which reflects the actual couplings of a given filter response. The extracted S-parameters are obtained using (7). Five unknown parameters φ_{01}, θ_{01}, φ_{02}, θ_{02} and Q_u are obtained by minimize the following objective error function using genetic algorithm:

$$F = \sum_{i=1}^{Ns} [|S_{21}^{\text{ext}}(f_i)| - |S_{21}^{\text{mea}}(f_i)|]^2 + [|S_{11}^{\text{ext}}(f_i)| - |S_{11}^{\text{mea}}(f_i)|]^2. \quad (8)$$

where $S_{21}^{\text{ext}}(f_i)$ and $S_{11}^{\text{ext}}(f_i)$ are the extracted S-parameters, and $S_{21}^{\text{mea}}(f_i)$ and $S_{11}^{\text{mea}}(f_i)$ are the measured S-parameters.

GA can be used to solve the global minimum value of a multivariate function. In this paper, the GA toolbox for Matlab provided by the University of Sheffield [26] is chosen to minimize the error function in (8).

3. EXAMPLES

3.1. Simulated Seventh-order Bandpass Filter (Filter 1)

The technique presented here is first applied to the simulated S-parameters of seventh-order filter with $f_0 = 850\,\text{MHz}$, $nz = 2$ and $BW = 40\,\text{MHz}$ (filter 1), which is designed on a Rogers RO3010 substrate with a relative dielectric constant of 10.2, a thickness of 1.27 mm, and a loss tangent of 0.0023. Physical dimensions of filter 1 are shown in Fig. 3.

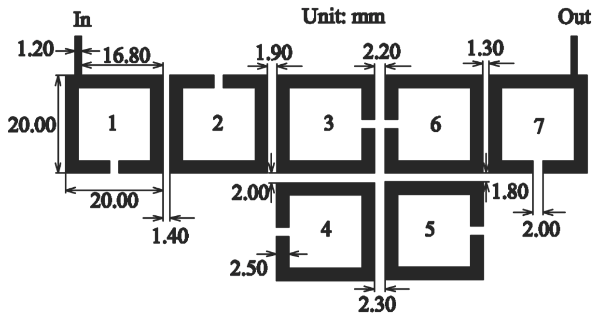

Figure 3. Physical dimensions of filter 1.

The filter has been simulated using a full-wave simulator IE3D. The loss factors (conductor loss and dielectric loss) are included in the simulated response. The proposed algorithm has been applied with $N = 7$, $nz = 2$, $Ns = 71$ (frequency interval 820–890 MHz). $\varphi_{01} = 1.0957$, $\theta_{01} = 0.8684$, $\varphi_{02} = 1.1251$, $\theta_{02} = 0.7725$ and $Q_u = 182.66$ has been obtained by optimization.

The characteristic polynomials F, P and E in the s' domain are obtained as

$$\begin{aligned} P &= [-0.1182 - 0.0050\text{i} \quad -0.0016 + 0.0395\text{i} \quad -0.2215 - 0.0130\text{i}] \\ F &= [1.0 \quad -0.0439 - 0.2466\text{i} \quad 2.0741 + 0.1009\text{i} \\ &\quad -0.0865 - 0.1577\text{i} \quad 1.2909 + 0.1659\text{i} \\ &\quad -0.0220 + 0.1060\text{i} \quad 0.20 + 0.0467\text{i} \quad 0.0102 + 0.0342\text{i}] \\ E &= [1.0041 - 0.0066\text{i} \quad 1.7718 - 0.2560\text{i} \quad 3.6429 - 0.5333\text{i} \\ &\quad 3.8800 - 0.6685\text{i} \quad 3.6914 - 0.6950\text{i} \quad 2.2676 - 0.3544\text{i} \\ &\quad 0.9995 - 0.15557\text{i} \quad 0.2257 - 0.0194\text{i}]. \end{aligned} \tag{9}$$

From these polynomials, the normalized $N + 2$ coupling matrix

$[M]$ has been extracted as

$$M = \begin{bmatrix} 0 & 0.9522 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.9522 & 0.0851 & 0.8048 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.8048 & -0.1139 & 0.5935 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5935 & -0.0842 & 0.5365 & -0.0847 & -0.1717 & 0 & 0 \\ 0 & 0 & 0 & 0.5365 & 0.0701 & 0.07041 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.0874 & 0.7041 & -0.0921 & 0.6139 & 0 & 0 \\ 0 & 0 & 0 & -0.1717 & 0 & 0.6139 & -0.1041 & 0.8127 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.8127 & -0.0117 & 0.9290 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.9290 & 0 \end{bmatrix} \tag{10}$$

Figure 4 shows the original phase responses of the filter 1 obtained by an EM simulation and the one with phase change removed by (5), illustrating the asymptotic behaviour of the S_{11} phase after removing the phase change. The counter-symmetrical asymptotic behaviour of the S_{11} phase outside of the passband has also been reported in [7], which satisfy the phase characteristic of the circuit model in [12].

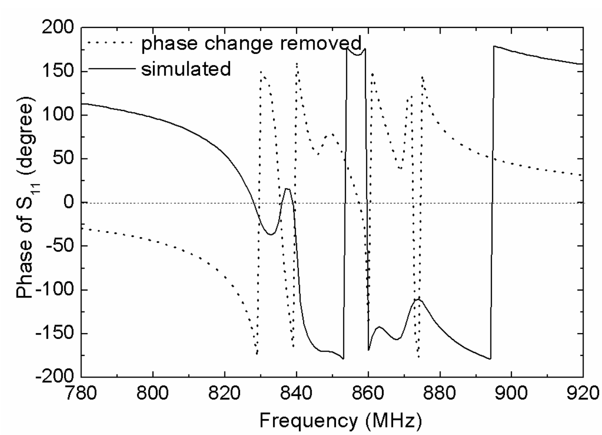

Figure 4. The S_{11} phase of filter 1 with and without removing the phase change.

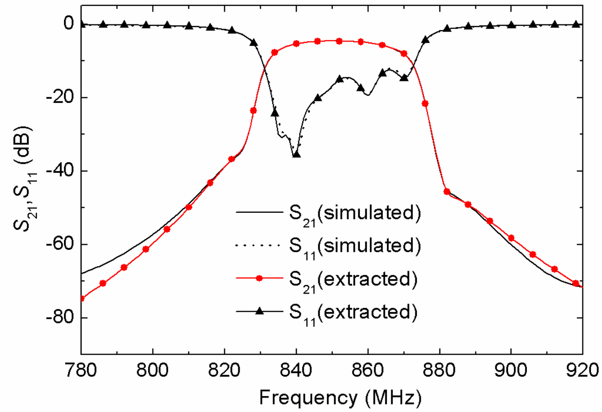

Figure 5. The simulated and the extracted S-parameters of filter 1.

In Fig. 5, the original simulated S-parameters are compared with those calculated by the extracted CM. Very good agreement between the simulated and extracted response can be observed.

3.2. Fabricated Fourth-order Bandpass Filter (Filter 2)

In the second example, the parameter-extraction procedure will be applied in the measured S-parameters of a fourth-order filter with $f_0 = 2.13\,\text{GHz}$, $nz = 2$ and $BW = 60\,\text{MHz}$ (filter 2).

The filter 2 is fabricated on a Rogers RT/duroid 5880 substrate with a relative dielectric constant of 2.2, a thickness of 0.508 mm, and a loss tangent of 0.0009, shown in Fig. 6.

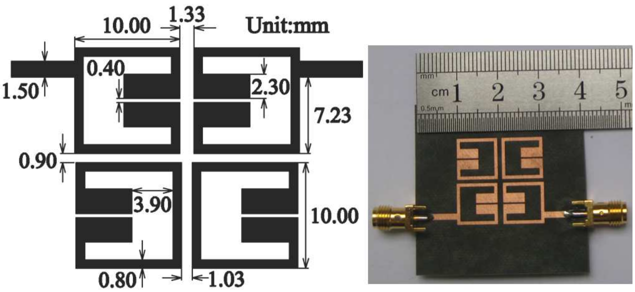

Figure 6. (a) Physical dimensions and (b) photograph of the fabricated filter 2.

The proposed algorithm has been applied with $N = 4$, $nz = 2$, $Ns = 37$ (frequency interval 2.04–2.22 GHz). $\varphi_{01} = 0.8354$, $\theta_{01} = 1.8375$, $\varphi_{02} = 0.6873$, $\theta_{02} = 2.0857$ and $Q_u = 162.75$ has been obtained by optimization. The characteristic polynomials F, P and E in the s' domain are obtained as

$$\begin{aligned} P =& [0.0864 - 0.4428\text{i} \quad 0.0233 + 0.0003\text{i} \quad 0.4878 - 2.4045\text{i}] \\ F =& [1 \quad -0.0058 - 0.8888\text{i} \quad 1.6231 - 0.0131\text{i} \\ & -0.0493 - 0.8369\text{i} \quad 0.5995 + 0.1116\text{i}] \\ E =& [1.0245 - 0.0184\text{i} \quad 2.0384 - 0.9328\text{i} \\ & 3.8275 - 1.5521\text{i} \quad 3.4865 - 2.0288\text{i} \quad 2.2074 - 1.1819\text{i}] \end{aligned} \tag{11}$$

From these polynomials, the normalized $N + 2$ coupling matrix $[M]$ has been extracted as

$$M = \begin{bmatrix} 0 & 1.0177 & 0 & 0 & 0 & 0 \\ 1.0177 & -0.2095 & 1.0183 & 0 & -0.2136 & 0 \\ 0 & 1.0183 & -0.1928 & 0.9107 & 0.1223 & 0 \\ 0 & 0 & 0.9107 & -0.3373 & 1.0297 & 0 \\ 0 & -0.2136 & 0.1223 & 1.0297 & -0.1602 & 1.0061 \\ 0 & 0 & 0 & 0 & 1.0061 & 0 \end{bmatrix} \tag{12}$$

In Fig. 7, the original measured S-parameters are compared with those calculated by the extracted CM. As can be seen, the location of the transmission zeros and the in-band return losses have been accurately modeled. The measured frequency response has somewhat less attenuation at both sides out-of-passband than the extraction one, which is due to second order effects of a physical filter.

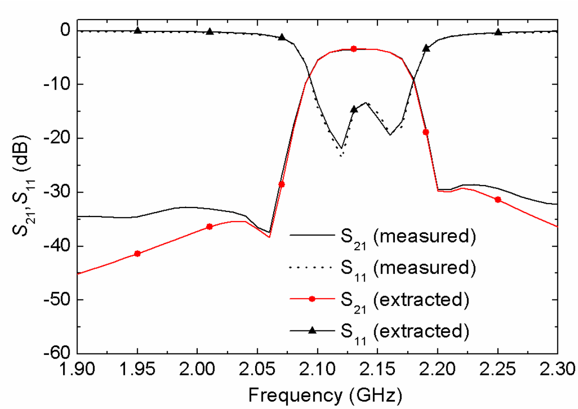

Figure 7. The measured and the extracted S-parameters of fabricated filter 2.

4. CONCLUSION

A technique for the accurate extraction of the CM and the unloaded Q of lossy coupled resonator filters is presented. This technique can be applied to any measured filter response as long as the unloaded Q for each resonator is nearly the same. To make the characteristic polynomials (solved in one step by Cauchy method) to satisfy the circuit model in [12], the phase-shift effects of the measured (or electromagnetic simulated) S-parameters are removed for the first time by optimization, and the unloaded Q is also obtained simultaneously by optimization. To illustrate the validation of the proposed technique, two application examples are provided; one deals with simulated data and the other one uses measured data. The proposed extraction technique is a valuable tool in computer aided tuning of microwave filters.

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