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A HYBRID COMPUTER-AIDED TUNING METHOD FOR MICROWAVE FILTERS

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Abstract—A hybrid tuning method for microwave filters is presented in this paper. This novel tuning technique is based on the combination of the Cauchy method and aggressive space mapping (ASM) technique. Cauchy method is applied to determine the characteristic polynomials of the filter's response, then the parameters (coupling matrix) of the low-pass prototype is extracted from the characteristic polynomials. The aggressive space mapping is used to optimized the fine model to guarantee that each step of a tuning is always in the right direction. The validity is verified by two examples. One deals with the four-resonator cross-coupled filter and the other one is an direct coupled six-resonator filter.

1. INTRODUCTION

Low-cost and High-Q microwave components are key components of many telecommunication systems, and the design method is a mature subject [1–12]. The tuning of microwave filters is the last and important step in filter design procedure and dominates the performance of filters. Since the traditional tuning process is nontrivial, time consuming and very expensive, a great deal of efforts have been made on computer-aided tuning (CAT) on microwave coupled resonator filters in recent years [13–30].

The main approaches in the literature can be concluded as follows:

1) Rational models match the measured admittance parameters [13, 14]: The concept of a constant phase loading was mentioned in [13], but it is not showing how to determine the constant. Furthermore, the analytical diagnosis approach presented in the paper only

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deals with the lossless case. In [14], only the sampled data that is far below or above the center frequency that the phase effect could be obtained. It is not accurate because of spurious pass-bands and the frequency-dependent coupling. And the unknown transmission line needs to be de-embedded in the paper.

2) Analytical models based on the locations of system zeros and poles [15, 16]: These papers provide a method that associates the poles and zeros of a filter system with the CM for cascaded and symmetrically coupled filters. In order to determine the poles and zeros accurately, the phase derivative with respect to frequency is used.

3) Rational models match the measured S-parameters (Cauchy method) [17–20]: In [17–19], it is inconvenient because that the tuning direction and tuning value is not given accurately or suitably. In [20], the polynomial P, F, and E solved in one step are not suitable for extracting the correct coupling matrix because the phase shift is not removed. The phase shift must be removed before the measured S parameter is used to extract the correct coupling matrix.

4) Another diagnosis techniques are based on optimization, such as [21–30]. The optimization procedures are either time consuming (for global optimization) or are sensitive to the initial value and the number of variables. It is easily tripped into a local optimum. The process is very complicated.

One of the difficulties associated with the traditional tuning is that it is not a deterministic process. In other words, there is no guarantee that each step of a tuning is always in the right direction. Such predicament is undesirable in tuning a channel filter for space use as a repeated may wear out the plated silver of tuning screws.

In this paper, in order to rectify the limitation in [17], we present a hybrid tuning method to predict the tuning direction and tuning value accurately. This paper is organized as follows. In Section 2, the basic theory of the hybrid tuning method is discussed in detail. This section consists two parts. The first part is to convert the frequency sampled S-parameters, obtained from the simulation or measurement, into the rational functions given as a ratio of polynomials by using the Cauchy method. Then the parameters of equivalent circuit are extracted from the rational functions. In the second part, the position of the tuning screws are directed by using the ASM technique. Two examples are demonstrated in Section 3. The first tuning example is a four-order cross-coupled filter with two finite transmission zeros; and the second tuning example is a six-pole Chebyshev filter. Both of the examples show the validity of the technique presented in this paper. The comparison between the previous work of the author and the presented method in this work is discussed in Section 4. A conclusion is drawn in Section 5.

2. BASIC THEORY

2.1. Cauchy Method for Parameter Extraction (PE)

The Cauchy method is a mature technique for generating rational polynomial interpolates from measurements (or simulations) of passive devices. Recently, this method has been employed for generating rational models of the low-pass frequency domain, starting from the simulated band-pass response [17–20].

The Cauchy method is well-known in the literature and it will only briefly be recalled here. In case of a two-port lossless network in Figure 1 described by its scattering parameters S_{11} and S_{21}, three characteristic polynomials $F(s)$, $P(s)$ and $E(s)$ completely define a rational model in the normalized low-pass domain s

$$S_{11}(s)=\frac{F(s)}{E(s)}=\frac{\sum\limits_{k=0}^{n}a_{1k}(s)^k}{\sum\limits_{k=0}^{n}b_k(s)^k}\qquad S_{21}(s)=\frac{P(s)}{E(s)}=\frac{\sum\limits_{k=0}^{nz}a_{2k}(s)^k}{\sum\limits_{k=0}^{n}b_k(s)^k}\tag{1}$$

where, n is the order of the filter and nz is the number of finite transmission zeros. Using the matrix notation, (1) can be rewritten as

$$\begin{bmatrix}S_{21}V_n & -S_{11}V_{nz}\end{bmatrix}\begin{bmatrix}a_1\\a_2\end{bmatrix}=0\tag{2}$$

The coefficient is $a_1=[a_{1,0}\ \ldots\ \ldots\ a_{1,n}]^T$, $a_2=[a_{2,0}\ \ldots\ \ldots\ a_{2,nz}]^T$, $S_{k1}=\mathrm{diag}\{S_{k1}(s_i)\}$, $k=1,2.$ and V_m is a increasing-power mth-order Vandermonde matrix whose size is $Ns\times(m+1)$. In order to guarantee the system matrix has solution, Ns must be greater or equal to $n+nz+1$. The coefficients of numerators can be solved with TLS (total least square) method. Once the polynomials $F(s)$ and $P(s)$ have

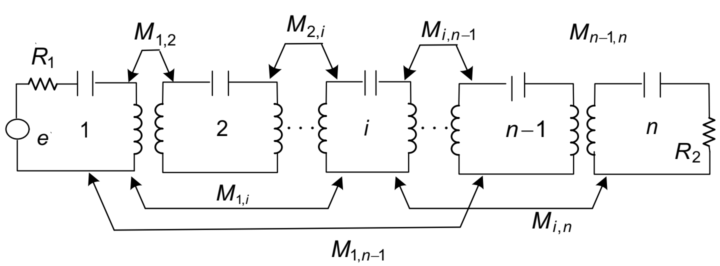


Figure 1. General two-port cross-coupled network.

been computed, The poles (roots of $E(s)$) can be computed using the Feldkeller's equation

$$F(s)F^*(-s) + P(s)P^*(-s) = E(s)E^*(-s) \tag{3}$$

The roots of the LHS side of the above equation are in pairs with opposite real part. Selecting those with negative real part the poles of the filter are obtained. The coefficients $b = [b_1 \quad b_2 \quad \dots \quad b_n]^T$ (which define the polynomial $E(s)$) are finally determined from the poles. So far, the characteristic polynomials $F(s)$, $P(s)$ and $E(s)$ are obtained, and they are suitable for the synthesis of a low-pass prototype network which is shown in Figure 1. That is to say the coupling matrix can be synthesized through the classical method which is presented by Cameron [31].

2.2. ASM Technique

The aggressive space mapping (ASM) is a well known method [32]. In the ASM technique, approximations to the matrix of first-order derivatives are updated by classic Broyden formula.

Here, the coarse model is the equivalent circuit shown in Figure 1, and the fine model is the physical model. We refer to the coarse model parameters as x_c and the fine model parameters as x_f. The optimal coarse model design is denoted as x_c^*. We also denote the responses of the coarse model as $R_c(x_c)$ and that of the fine model as $R_f(x_f)$. First, we measure the filter when the tuning screw in the two different position states, then the coarse model parameters is extracted by the Cauchy method. Second, use the ASM technique to predict the next better positions of the tuning screws. The goal is to find the best position of tuning screw p_i^{ideal}. The recipe is outlined in the following steps.

Step 1) Measure the filter twice with different tuning positions x_{f1}, x_{f2} to obtain the S-parameters, then obtain two groups equivalent circuit parameters x_{c1}, x_{c2} by the Cauchy method. Where, $x_f = [p_1 \quad p_2 \quad \dots \quad p_i \quad \dots]$ is the vector of tuning positions.

Step 2) Calculate the initial Broyden matrix B_0 through the equation $B_0 = \mathrm{diag}(\frac{x_{c2}-x_{c1}}{x_{f2}-x_{f1}})$. Here, the coarse model parameters and fine model parameters have different physical meanings, so the initial Broyden matrix B_0 is not the identity matrix.

Step 3) Evaluate the difference $f^{(1)} = x_c^{(1)} - x_c^*$. Stop if $\|f^{(1)}\| \leq \varepsilon$.

Step 4) Solve $B^{(j)}h^{(j)} = -f^{(j)}$ for the roots $h^{(j)}$. Where $h^{(j)}$ is the increasing value of the tuning screws.

Step 5) Set $x_f^{(j+1)} = x_f^{(j)} + h^{(j)}$.

Step 6) Measure the response $R_f(x_f^{(j+1)})$ when the tuning screws at the position $x_f^{(j+1)}$.

Step 7) Extract $x_c^{(j+1)}$ such that $R_c(x_c^{(j+1)}) \approx R_f(x_f^{(j+1)})$.

Note: The parameter extraction is an important step in the ASM technique. In this step, we extract the parameter of the coarse model by Cauchy method, such that $R_c(x_c^{(j+1)}) \approx R_f(x_f^{(j+1)})$.

Step 8) Evaluate $f^{(j+1)} = x_c^{(j+1)} - x_c^*$. Stop if $\|f^{(j+1)}\| \leq \varepsilon$.

Step 9) Update $B^{(j+1)} = B^{(j)} + \frac{f^{(j+1)} {h^{(j)}}^T}{{h^{(j)}}^T h^{(j)}}$.

Step 10) Set $j = j + 1$; go to step 4.

To illustrate the tuning procedure, a four-resonator band-pass filter with cross coupling between resonator 1–4 and six-resonator Chebyshev band-pass filter are utilized in Section 3.

3. EXPERIMENT RESULTS

3.1. Four-order Cross-coupled Coaxial Filter

The first example is a fourth order cross-coupled filter. The specifications of the filter are listed in the following table.

Table 1. Specifications of the four-resonator cross-coupled filter.

Center frequency f_0	Pass-band	Return loss	Normalized finite transmission zeros	Filter degree
2069.3 MHz	2015 MHz–2125 MHz	20 dB	$-2j$, $2j$	4

The $N + 2$ degree normalized coupling matrix M can be easily obtained through the method in [27]

$$M = \begin{bmatrix} 0 & 1.0236 & 0 & 0 & 0 & 0 \\ 1.0236 & 0 & 0.8706 & 0 & -0.1705 & 0 \\ 0 & 0.8706 & 0 & 0.7673 & 0 & 0 \\ 0 & 0 & 0.7673 & 0 & 0.8706 & 0 \\ 0 & -0.1705 & 0 & 0.8706 & 0 & 1.0236 \\ 0 & 0 & 0 & 0 & 1.0236 & 0 \end{bmatrix} \tag{4}$$

The topology of the filter is shown as Figure 2.

Because coupling matrix of the filter is symmetrical, the tuning screws which are shown in Figure 3 are also symmetrical. The coupling

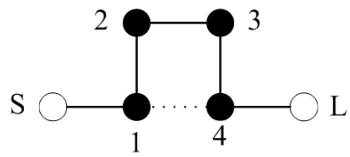


Figure 2. The topology of the fourth-order cross-coupled filter.

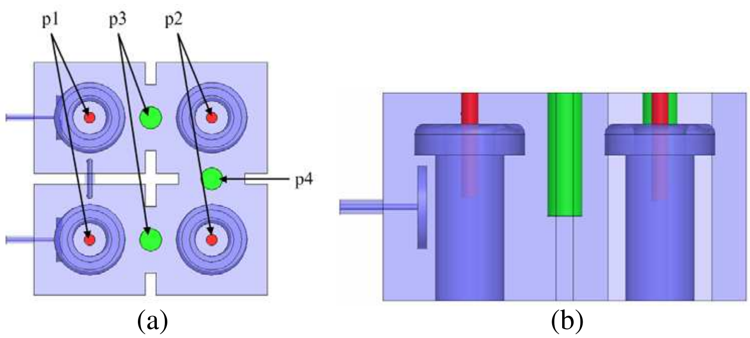


Figure 3. The model of the fourth-order cross-coupled filter. (a) Top view, (b) side view.

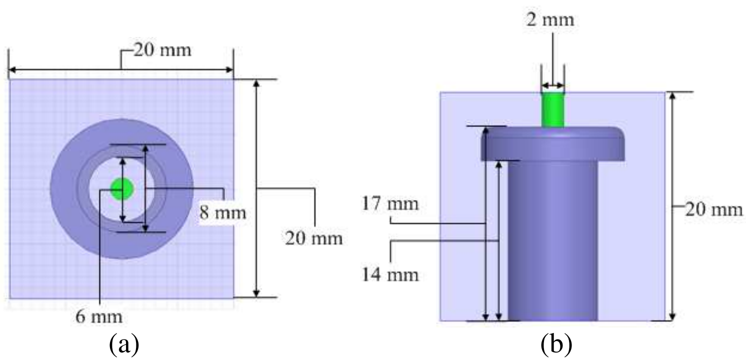


Figure 4. The size of single resonator. (a) Bottom view, (b) side view.

of the source to the first resonator, the load to the last resonator and the cross-coupling are not tunable. In order to help the readers to reproduce the hybrid technique that proposed in this paper, Figure 4 shows the resonating unit of the filter.

The tuning producer is shown as following steps:

Step 1, obtain the optimal coarse model parameters

$$x_c^* = [f_1 \quad f_2 \quad M_{12} \quad M_{23}] = [2.0693 \quad 2.0693 \quad 0.0468 \quad 0.0403] \qquad (5)$$

Step 2, Measure the filter twice with different tuning positions $x_{f\text{int}1}$, $x_{f\text{int}2}$ to obtain the S-parameters, then obtain two groups equivalent circuit parameters $x_{\text{cint}1}$, $x_{\text{cint}2}$. The initial position of tuning screws is

$$x_{f\text{int}1} = [p_1 \quad p_2 \quad p_3 \quad p_4] = [10 \quad 10 \quad 10 \quad 10] \tag{6}$$

then use the Cauchy method to obtain the equivalent circuit parameters

$$x_{\text{cint}1} = [f_1 \quad f_2 \quad M_{12} \quad M_{23}] = [2.0723 \quad 2.0881 \quad 0.0417 \quad 0.0434] \tag{7}$$

the second initial position of the tuning screw is decided by comparing $x_{\text{cint}1}$ and x_c^*.

if $x_{\text{cint}1}(i) > x_c^*(i)$, $i = 1, 2$, $x_{f\text{int}2}(i) = 1.05 * x_{f\text{int}1}(i)$; else $x_{f\text{int}2}(i) = 0.95 * x_{f\text{int}1}(i)$.
if $x_{\text{cint}1}(i) > 1.5 * x_c^*(i)$, $i = 3, 4$, $x_{f\text{int}2}(i) = 0.9 * x_{f\text{int}1}(i)$;
if $1.5 * x_c^*(i) > x_{\text{cint}1}(i) > x_c^*(i)$, $i = 3, 4$, $x_{f\text{int}2}(i) = 0.95 * x_{f\text{int}1}(i)$.
if $x_c^*(i) > 1.5 * x_{\text{cint}1}(i)$, $i = 3, 4$, $x_{f\text{int}2}(i) = 1.1 * x_{f\text{int}1}(i)$;
if $1.5 * x_{\text{cint}1}(i) > x_c^*(i) > x_{\text{cint}1}(i)$, $i = 3, 4$, $x_{f\text{int}2}(i) = 1.05 * x_{f\text{int}1}(i)$;

So the second initial position of the tuning screw is

$$x_{f\text{int}2} = [p_1 \quad p_2 \quad p_3 \quad p_4] = [10.5 \quad 10.5 \quad 10.5 \quad 9.5] \tag{8}$$

then obtain the equivalent circuit parameters

$$x_{\text{cint}2} = [f_1 \quad f_2 \quad M_{12} \quad M_{23}] = [2.0509 \quad 2.0655 \quad 0.0429 \quad 0.0425] \tag{9}$$

And the corresponding response is shown in Figure 5.

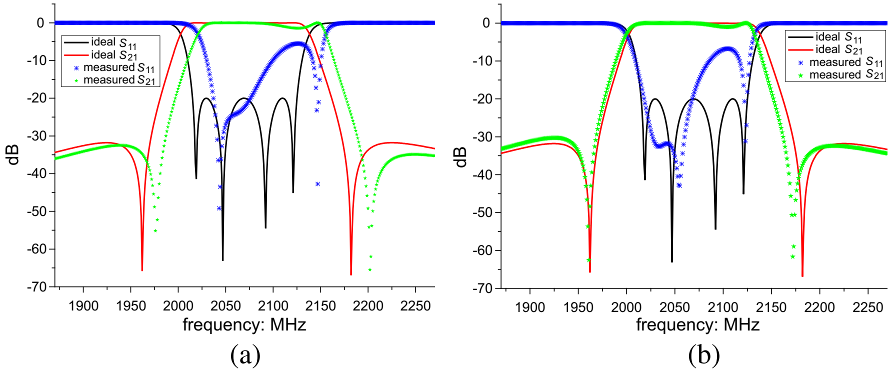


Figure 5. The initial response of the four-order cross-coupled filter. (a) Initial one, (b) initial two.

Step 3, Calculate the initial Broyden matrix B_0 through the equation $B_0 = \mathrm{diag}(\frac{x_{\mathrm{cint2}} - x_{\mathrm{cint1}}}{x_{f\mathrm{int2}} - x_{f\mathrm{int1}}})$.

$$\begin{aligned} B^{(0)} &= \mathrm{diag}\left(\frac{x_{\mathrm{cint2}} - x_{\mathrm{cint1}}}{x_{f\mathrm{int2}} - x_{f\mathrm{int1}}}\right) \\ &= \mathrm{diag}(-0.0427 \quad -0.0452 \quad 0.0025 \quad 0.0018) \end{aligned} \tag{10}$$

Step 4, Start to iterate, Evaluate the difference

$$f^{(1)} = x_c^{(0)} - x_c^* = [-0.0184 \quad -0.0038 \quad -0.0034 \quad 0.0017]^T \tag{11}$$

here $x_c^{(0)} = x_{\mathrm{cint2}}$. Stop if $\|f^{(1)}\| \leq \varepsilon$, where, ε is the convergence precision. Calculate the increased value of the tuning screw

$$H_{\_ite1} = [-0.4309 \quad -0.0834 \quad 1.374 \quad -0.9399] \tag{12}$$

And the position of the tuning screw is

$$\begin{aligned} x_{f\_ite1} &= x_{f\_\mathrm{int2}} + H_{\_ite1} = [p_1 \quad p_2 \quad p_3 \quad p_4] \\ &= [10.0691 \quad 10.4166 \quad 11.8740 \quad 8.5601] \end{aligned} \tag{13}$$

Extract the coarse model parameters

$$x_{c\_ite1} = [f_1 \quad f_2 \quad M_{12} \quad M_{23}] = [2.0668 \quad 2.0687 \quad 0.0463 \quad 0.0398] \tag{14}$$

Update the Broyden matrix $B^{(2)} = B^{(1)} + (f^{(1)} * h^{(1)^T})/(h^{(1)^T} * h^{(1)})$.

Step 5, the second and third iteration are similar as the first iteration. In order to reproduce the tuning methodology, the result of the two iterations are shown in the following

$$H_{\_ite2} = [-0.0501 \quad -0.0112 \quad -0.0153 \quad 0.4714] \tag{15}$$

$$\begin{aligned} x_{f\_ite2} &= x_{f\_ite1} + H_{\_ite2} = [p_1 \quad p_2 \quad p_3 \quad p_4] \\ &= [10.0189 \quad 10.4054 \quad 11.8587 \quad 9.0315] \end{aligned} \tag{16}$$

$$x_{c\_ite2} = [f_1 \quad f_2 \quad M_{12} \quad M_{23}] = [2.0688 \quad 2.0683 \quad 0.0463 \quad 0.0410] \tag{17}$$

$$H_{\_ite3} = [-0.0113 \quad -0.0191 \quad 0.0151 \quad -0.066] \tag{18}$$

$$\begin{aligned} x_{f\_ite3} &= x_{f\_ite2} + H_{\_ite3} = [p_1 \quad p_2 \quad p_3 \quad p_4] \\ &= [10.0077 \quad 10.3863 \quad 11.8737 \quad 8.9655] \end{aligned} \tag{19}$$

After three iterations, we obtain the final response which is required by the specifications. The corresponding responses of the three iterations are shown in Figure 6.

From Figure 6, we can see that the final measured response agrees with the ideal response well. It shows the validity of this method in this paper.

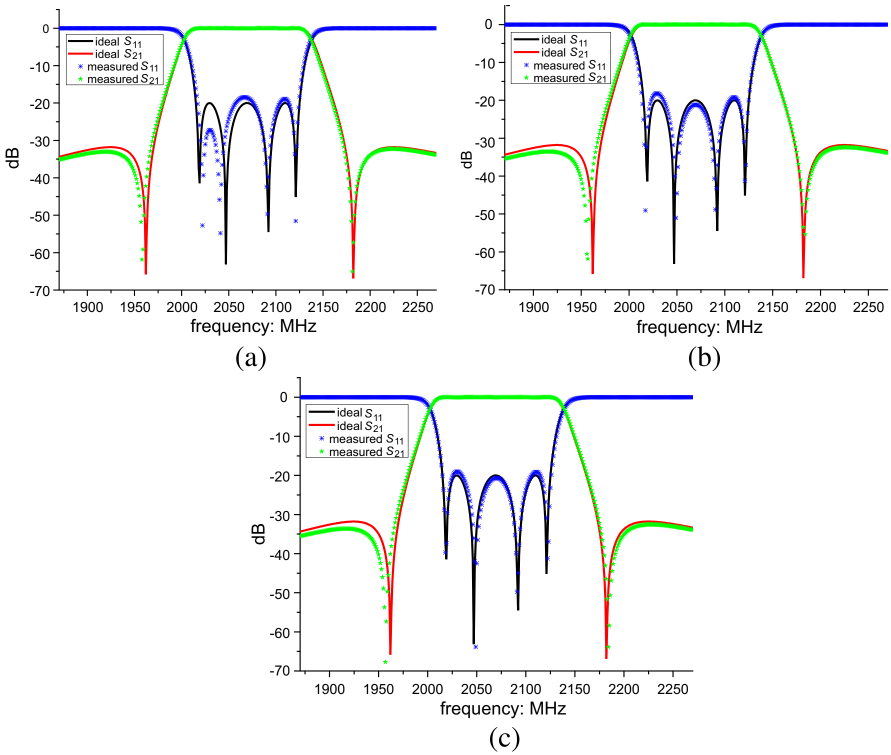


Figure 6. Response of the four-order cross-coupled filter. (a) Iteration one, (b) iteration two, (c) iteration three.

Table 2. Specifications of the six-resonator Chebyshev filter.

Center frequency f_0	Pass-band	Return loss	Filter degree
2069.3 MHz	2015 MHz–2125 MHz	20 dB	6

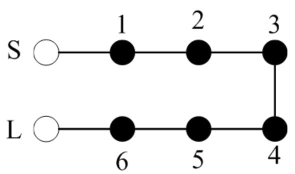
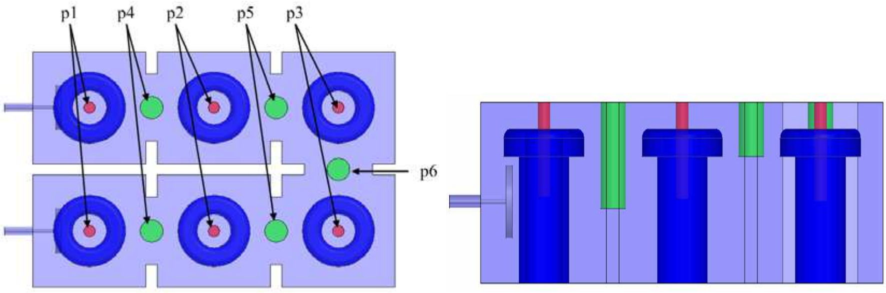


Figure 7. The topology of the six-pole Chebyshev filter.



(a) (b)

Figure 8. The model of six-pole Chebyshev filter. (a) Top view, (b) side view.

3.2. Six-pole Chebyshev Filter

In order to shown this method is validity for higher order filters, now we consider a second example which degree is higher than the previous one, The specification of the filter is shown in Table 2.

The $N+2$ degree normalized coupling matrix M is shown

$$M=\begin{bmatrix} 0 & 1.0021 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.0021 & 0 & 0.8430 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.8430 & 0 & 0.6111 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.6111 & 0 & 0.5834 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5834 & 0 & 0.6111 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.6111 & 0 & 0.8430 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.8430 & 0 & 1.0021 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1.0021 & 0 \end{bmatrix} \tag{20}$$

The topology of the filter is shown as Figure 7.

The filter model is shown as Figure 8. There are six tuning screws for the filter.

The tuning producer is shown as following steps:

Step 1, obtain the optimal coarse model parameters

$$\begin{aligned} x_c^* &= [f_{01} \quad f_{02} \quad f_{03} \quad M_{12} \quad M_{23} \quad M_{34}] \\ &= [2.0693 \quad 2.0693 \quad 2.0693 \quad 0.0448 \quad 0.0325 \quad 0.031] \end{aligned} \tag{21}$$

Step 2, Measure the filter twice with different tuning positions $x_{f\text{int1}}$, $x_{f\text{int2}}$ to obtain the S-parameters, then obtain two groups equivalent circuit parameters $x_{c\text{int1}}$, $x_{c\text{int2}}$. the initial position of tuning screws is

$$x_{f\text{int1}} = [p_1 \quad p_2 \quad p_3 \quad p_4 \quad p_5 \quad p_6] = [10 \quad 10 \quad 10 \quad 10 \quad 10 \quad 10] \tag{22}$$

then use the Cauchy method to obtain the equivalent circuit parameters

$$\begin{aligned} x_{\text{cint1}} &= [\, f_1 \quad f_2 \quad f_3 \quad M_{12} \quad M_{23} \quad M_{34} \,] \\ &= [2.0905 \quad 2.0935 \quad 2.0891 \quad 0.0408 \quad 0.0429 \quad 0.044] \end{aligned} \tag{23}$$

the second initial position of the tuning screw is decided by comparing x_{cint1} and x_c^*.

if $x_{\text{cint1}}(i) > x_c^*(i)$, $i = 1, 2$, $x_{f\text{int2}}(i) = 1.05 * x_{f\text{int1}}(i)$; else $x_{f\text{int2}}(i) = 0.95 * x_{f\text{int1}}(i)$.
if $x_{\text{cint1}}(i) > x_c^*(i)$, $i = 3$, $x_{f\text{int2}}(i) = 1.1 * x_{f\text{int1}}(i)$; else $x_{f\text{int2}}(i) = 0.9 * x_{f\text{int1}}(i)$.
if $x_{\text{cint1}}(i) > 1.5 * x_c^*(i)$, $i = 4$, $x_{f\text{int2}}(i) = 0.9 * x_{f\text{int1}}(i)$;
if $1.5 * x_c^*(i) > x_{\text{cint1}}(i) > x_c^*(i)$, $i = 4$, $x_{f\text{int2}}(i) = 0.95 * x_{f\text{int1}}(i)$.
if $x_c^*(i) > 1.5 * x_{\text{cint1}}(i)$, $i = 4$, $x_{f\text{int2}}(i) = 1.1 * x_{f\text{int1}}(i)$;
if $1.5 * x_{\text{cint1}}(i) > x_c^*(i) > x_{\text{cint1}}(i)$, $i = 4$, $x_{f\text{int2}}(i) = 1.05 * x_{f\text{int1}}(i)$;
if $x_{\text{cint1}}(i) > 1.5 * x_c^*(i)$, $i = 5, 6$, $x_{f\text{int2}}(i) = 0.95 * x_{f\text{int1}}(i)$;
if $1.5 * x_c^*(i) > x_{\text{cint1}}(i) > x_c^*(i)$, $i = 5, 6$, $x_{f\text{int2}}(i) = 0.925 * x_{f\text{int1}}(i)$.
if $x_c^*(i) > 1.5 * x_{\text{cint1}}(i)$, $i = 5, 6$, $x_{f\text{int2}}(i) = 1.05 * x_{f\text{int1}}(i)$;
if $1.5 * x_{\text{cint1}}(i) > x_c^*(i) > x_{\text{cint1}}(i)$, $i = 5, 6$, $x_{f\text{int2}}(i) = 1.025 * x_{f\text{int1}}(i)$;

So the second initial position of the tuning screw is

$$x_{f\text{int2}} = [p_1 \quad p_2 \quad p_3 \quad p_4 \quad p_5 \quad p_6] = [10.5 \quad 10.5 \quad 11 \quad 10.5 \quad 9.25 \quad 9.25] \tag{24}$$

then obtain the equivalent circuit parameters

$$\begin{aligned} x_{\text{cint2}} &= [\, f_1 \quad f_2 \quad f_3 \quad M_{12} \quad M_{23} \quad M_{34} \,] \\ &= [2.0696 \quad 2.0707 \quad 2.0482 \quad 0.0417 \quad 0.0398 \quad 0.0409] \end{aligned} \tag{25}$$

And the corresponding response is shown in Figure 9.

Step 3, Calculate the initial Broyden matrix B_0 through the equation $B_0 = \text{diag}(\frac{x_{\text{cint2}} - x_{\text{cint1}}}{x_{f\text{int2}} - x_{f\text{int1}}})$.

$$\begin{aligned} B_0 &= \text{diag}\left(\frac{x_{\text{cint2}} - x_{\text{cint1}}}{x_{f\text{int2}} - x_{f\text{int1}}}\right) \\ &= \text{diag}(-0.0417 \quad -0.0456 \quad -0.0459 \quad 0.0018 \quad 0.0042 \quad 0.0042) \end{aligned} \tag{26}$$

Step 4, Start to iterate, Evaluate the difference

$$\begin{aligned} f^{(1)} &= x_c^{(0)} - x_c^* \\ &= [0.0003 \quad 0.0014 \quad -0.0211 \quad -0.0031 \quad 0.0073 \quad 0.0099]^T \end{aligned} \tag{27}$$

here $x_c^{(0)} = x_{\text{cint2}}$. Stop if $\left\|f^{(1)}\right\| \leq \varepsilon$, where, ε is the convergence precision. Calculate the increased value of the tuning screw

$$H_{ite1} = [0.0072 \quad 0.0313 \quad -0.5156 \quad 1.6868 \quad -1.7462 \quad -2.3818] \quad (28)$$

And the position of the tuning screw is

$$\begin{aligned} x_{fite1} &= x_{f\_\text{int2}} + H_{\_ite1} = [p_1 \quad p_2 \quad p_3 \quad p_4 \quad p_5 \quad p_6] \\ &= [10.5072 \quad 10.5313 \quad 10.4844 \quad 12.1868 \quad 7.5038 \quad 6.8682] \end{aligned} \quad (29)$$

Extract the coarse model parameters

$$\begin{aligned} x_{cite1} &= [f_1 \quad f_2 \quad f_3 \quad M_{12} \quad M_{23} \quad M_{34}] \\ &= [2.0665 \quad 2.0690 \quad 2.0784 \quad 0.0462 \quad 0.0364 \quad 0.0356] \end{aligned} \quad (30)$$

Update the Broyden matrix $B^{(2)} = B^{(1)} + (f^{(1)} * h^{(1)^T}) / (h^{(1)^T} * h^{(1)})$.

Step 5, the second, third and fourth iteration are similar as the first iteration. In order to reproduce the tuning methodology, the results of the last three iterations are shown in the following

$$H_{ite2} = [-0.0878 \quad -0.0095 \quad 0.2959 \quad -1.0011 \quad -1.2380 \quad -1.4798] \quad (31)$$

$$\begin{aligned} x_{fite2} &= x_{f\_ite1} + H_{\_ite2} = [p_1 \quad p_2 \quad p_3 \quad p_4 \quad p_5 \quad p_6] \\ &= [10.4193 \quad 10.5218 \quad 10.7802 \quad 11.1856 \quad 6.2658 \quad 5.3884] \end{aligned} \quad (32)$$

$$\begin{aligned} x_{cite2} &= [f_1 \quad f_2 \quad f_3 \quad M_{12} \quad M_{23} \quad M_{34}] \\ &= [2.0714 \quad 2.0743 \quad 2.0723 \quad 0.0437 \quad 0.0332 \quad 0.0319] \end{aligned} \quad (33)$$

$$H_{ite3} = [0.0431 \quad 0.1263 \quad 0.1390 \quad 0.5454 \quad -0.4010 \quad -0.5207] \quad (34)$$

$$\begin{aligned} x_{fite3} &= x_{f\_ite2} + H_{\_ite3} = [p_1 \quad p_2 \quad p_3 \quad p_4 \quad p_5 \quad p_6] \\ &= [10.4625 \quad 10.6481 \quad 10.9192 \quad 11.7310 \quad 5.8648 \quad 4.8648] \end{aligned} \quad (35)$$

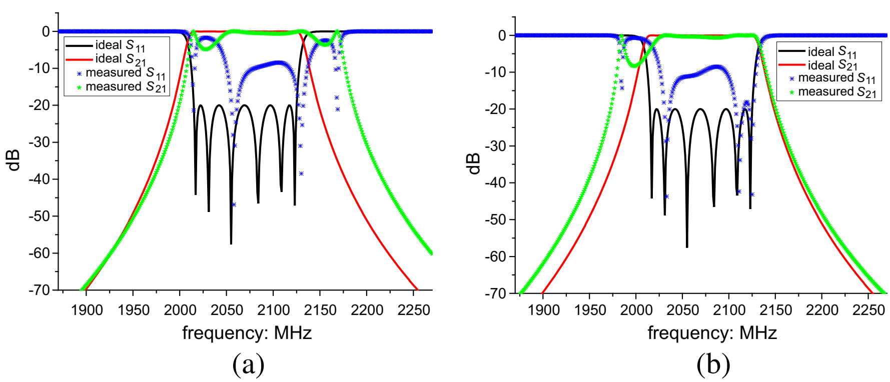


Figure 9. The initial Response of the six-pole Chebyshev filter. (a) Initial one, (b) initial two.

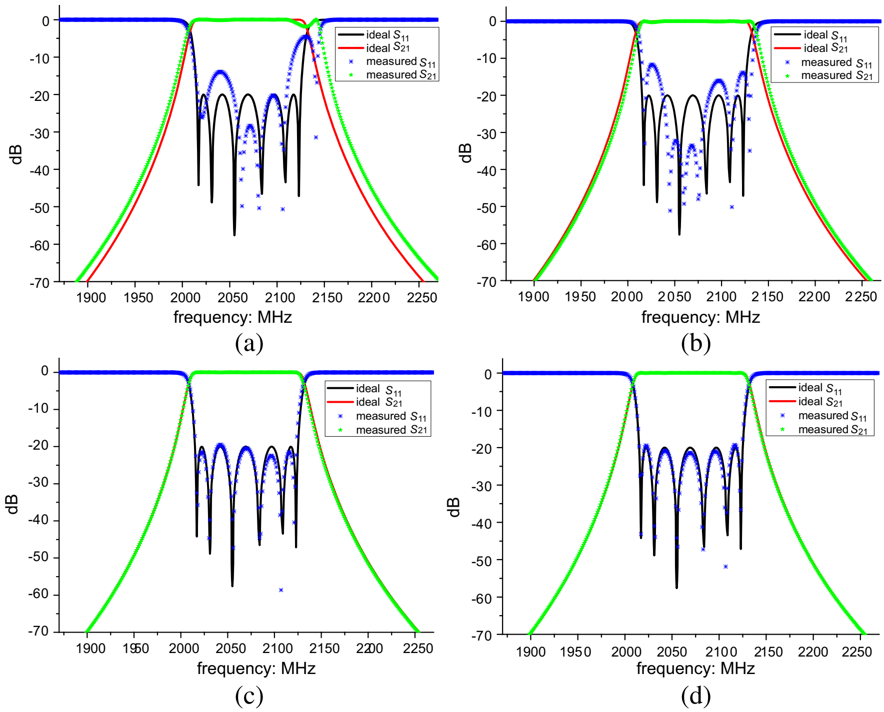


Figure 10. Response of the six-pole Chebyshev filter. (a) Iteration one, (b) iteration two, (c) iteration three, (d) iteration four.

$$\begin{aligned} x_{cite3} &= [\, f_1 \quad f_2 \quad f_3 \quad M_{12} \quad M_{23} \quad M_{34} \,] \\ &= [\, 2.0694 \quad 2.0688 \quad 2.0689 \quad 0.0448 \quad 0.0331 \quad 0.0306 \,] \end{aligned} \tag{36}$$

$$H_{ite4} = [\, 0.0006 \quad -0.0176 \quad -0.0251 \quad -0.0169 \quad 0.1394 \quad 0.1599 \,] \tag{37}$$

$$\begin{aligned} x_{fite4} &= x_{f\_ite3} + H_{\_ite4} = [\, p_1 \quad p_2 \quad p_3 \quad p_4 \quad p_5 \quad p_6 \,] \\ &= [\, 10.4631 \quad 10.6305 \quad 10.8941 \quad 11.7142 \quad 6.0042 \quad 5.0237 \,] \end{aligned} \tag{38}$$

After four iterations, we obtain the final response which is required by the specifications. The corresponding responses of the four iterations are shown in Figure 10.

After four iterations, from Figure 10, we can see that the measured response agree with the required specifications well. It shows the validity of the new tuning technique.

4. COMPARISON AND DISCUSSION

In order to compare the method proposed in [33, 34] with the method proposed in this paper, the summary of the results are shown in Table 3.

Table 3. Performance comparison between the method in [33, 34] and in this paper.

Method	Number of sampled points	Time consuming of each iteration	Speed	complexity
Proposed in [33, 34]	275	About 6.2 seconds	Slow	Yes
Proposed in this paper	96	About 0.2 seconds	Fast	No

In [33], the low degree filters are tuning by the VF-ASM technique. Literature [34] shows the validity of this method for the higher degree filters. Although the method in [33, 34] is time consuming, they suitable for the automated filter tuning. The method proposed in this paper is fast and easy to reproduce. However, the sampled frequency points must be near the passband, and must adjust in the iteration process.

5. CONCLUSION

A novel tuning method based on Cauchy method and ASM technique is presented in this paper. The Cauchy method is applied to extract the equivalent circuit model parameters from the measured S-parameters. And the ASM technique predicts the tuning directions and value of the tuning screws. The filter can be tuned well through less than four iterations. Two examples are used to verify this new method, and the results show the validity of this method.

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