Automated Filter Tuning Using Generalized Low-Pass Prototype Networks and Gradient-Based Parameter Extraction

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***Abstract*—A novel technique for automated filter tuning is introduced. The filter to be tuned is represented by a generalized filter low-pass prototype model rather than a specialized equivalent network. The prototype model is based on the minimum number of characteristic filter parameters to represent the filter transfer function correctly. The parameter values are found from a gradient-based parameter-extraction process using measured S-parameters. Automated filter tuning is performed as a two-step procedure. First, the parameter sensitivities with respect to the tuning elements are determined by a series of S-parameter measurements. Second, the parameter values of the filter are compared to the values of the ideal filter prototype found from a filter synthesis, thus yielding the optimal screw positions. This novel tuning technique has been tested successfully with direct coupled three-resonator and cross-coupled four- and six-resonator filters.**

***Index Terms*—Automated tuning, CAD, gradient methods, parameter estimation, sensitivity analysis, waveguide filter.**

I. Introduction

LOW-COST and high-Q microwave components are key components of many telecommunication systems. Large-volume production and quick turnaround time have become important aspects in the decision as to what kind of filter structures are most suitable to satisfy a range of specifications. In this context, modular filter-design techniques show certain advantages since they allow to pre-design a range of filter modules that can be assembled quickly according to the customer's need in terms of bandwidth, insertion loss, and slope selectivity. A drawback of this approach is, however, that the assembled filters must be fine tuned on the production floor, which, depending on the sensitivity of the filter characteristics, can be a labor-intensive and, thus, an expensive task. Therefore, automatic tuning on the production floor is attractive to speed up turnaround time and lower the costs.

Automatic tuning of filters has been proposed by several authors in the past with varying success. In [1], filter tuning in the time domain is described. However, for this method to work, an optimum filter template is needed and an experienced operator is still required to tune the filter. In [2], the authors propose a diagnosis and tuning method based on model-based parameter estimation and multilevel optimization. With this approach, it is only possible to optimize the locations of the reflection and transmission zeros and not the filter ripple or return loss, respectively. Moreover, diagnosis and tuning of a real (measured) filter has not been investigated in that paper. In [3], an optimization method for the identification of filter network parameters and network sensitivities is proposed. However, in this paper, only the simulated amplitude and delay response of coupled cavity filters is given. Simulated filter structures are optimized in [4]. To accelerate the optimization, the characteristic filter parameters of a fine model (electromagnetic (EM) simulation of a filter) are extracted and mapped onto a coarse model (circuit model). The optimization is then mainly done on the coarse model. There are two obvious drawbacks with this method: first, an intermediate step of finding a valid coarse model is required; second, as this model is only an approximation of the fine model, optimization is not done on the real model, which requires continuous updating of the coarse model during optimization. Moreover, the uniqueness of the coarse model is not guaranteed, and local minima can occur during optimization.

In the present approach [5], there is no need for an equivalent network since all characteristic parameters and sensitivities of measured filters can be directly related to the filter prototype parameters. This is a distinctly different approach to an earlier paper by Harscher *et al.* [6], in which an equivalent network representation of a waveguide filter was mapped onto the measured filter response using gradient optimization. In [6], only magnitudes of S-parameters were used.

The goal of automatic filter tuning is to find the optimum position of tuning elements (e.g., tuning screws) to satisfy given filter specifications. From the filter specifications and based on standard filter synthesis, which provides the ideal filter parameters (resonant frequencies, couplings between resonators, input/ouput couplings), a prototype response can be generated (see Section IV). For a de-tuned filter (basis position), the corresponding characteristic filter parameters can be extracted from S-parameter measurements. This is done by gradient optimization using analytically calculated gradients (see Section V). A comparison between the ideal prototype values and the prototype values of the measured filter response directly shows the difference between the optimum element values and element values represented by the measured filter

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in basis position. The remaining step is then to change the extracted element values to match the ideal prototype element values. For waveguide filters, this is typically done by tuning screws for which the number of turns per unit of tuning element value must be determined. Although tuning screws mainly affect the parameter associated with the screw (e.g., resonant frequency or coupling coefficient), other parameters (e.g., resonant frequency of neighboring resonators) may also be affected. Thus, it is necessary to extract the sensitivity of each tuning screw with respect to the overall prototype model (see Section VI). For this purpose, a series of additional S-parameter measurements is performed with one screw turned at a time. Each time, the prototype parameters are extracted by gradient optimization to give one additional parameter set for each screw. Comparing the parameter set extracted from the filter basis position with those from each screw turn provides the sensitivities of the element values. Knowing the prototype network elements for the de-tuned filter, as well as for the ideal filter response and the sensitivities of the tuning screws, one can extract the optimum set of tuning screw positions.

To summarize, this novel approach offers the following advantages.

- The method is general and can be used for filters with arbitrary topology, number of resonators, and other means of tuning (e.g., varactor diodes and corresponding driving voltages).
- No EM simulator or equivalent network model is needed.
- The effects of all characteristic parameters (input/output coupling, resonant frequencies, resonator losses, and couplings between resonators) including manufacturing tolerances are accounted for. The latter is not if only EM simulation is used.
- The prototype model reproduces the measured S-parameters in the complex plane (not only magnitudes) and, thus, is very accurate.
- The parameter sensitivities of a measured filter are extracted. The so-obtained relationship between changes of network parameters and tuning screw positions allows automatic tuning of filters.
- Analytically calculated gradients of cost functions are used to accelerate the parameter-extraction process, [5].
- The process is very fast, no matrix inversions, matrix rotations, etc., are needed.

The present approach has first been proposed in [5] to tune a direct-coupled three-pole resonator filter. In this paper, the method is extended to filters with a higher number of resonators and cross couplings.

II. Test Setup

The following three different filter topologies are used to test the tuning concept:

- threee-resonator filter, direct coupled [5];
- four-resonator filter, cross coupling between resonators 1–4;
- six-resonator filter, cross coupling between resonators 2–5.

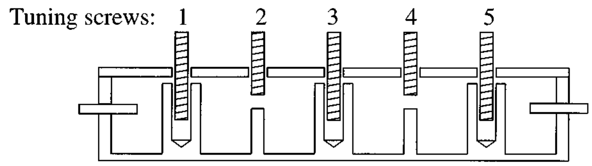


Fig. 1. Three-pole reentrant resonator filter.

Fig. 2. Test setup.

Fig. 1 shows the three-resonator filter, which consists of three reentrant cavities with square diameter. $\lambda/4$ resonators are mounted in each cavity. The structure is capacitively coupled by probes at the input and output. Five tuning screws allow the filter characteristics to be changed. Screws 1, 3, and 5 change the resonant frequency of each resonator. Screws 2 and 4 change the coupling between two adjacent resonators, affecting the bandwidth of the response. The four- and six-resonator filters are folded structures employing the same resonators as the three-resonator filter.

The test setup (Fig. 2) consist of:

- personal computer (PC) with general-purpose interface bus (GPIB) interface;
- vector network analyzer (VNA);
- dc motors with fixture;
- control box for dc motors;
- microwave filter (e.g., three-pole reentrant resonator filter).

The tuning screws are turned by dc motors. They are mounted on the filter by a special test fixture. The S-parameters of the filter are measured with a VNA (HP 8753B) connected to the PC via a GPIB card and controlled by LabView with specialized user interface and interfaces to the dc motors and VNA. The tuning algorithm is programmed in MATLAB, which is also interconnected and controlled by the LabView programming environment.

III. Generalized Low-Pass Prototype Networks

The core of the tuning system is the prototype network shown in Fig. 3. The basic form of this general two-port model has been introduced in [7]. It is applicable for direct-coupled filters, as well as for cross-coupled filters. In this paper, it is extended such that it includes all characteristic parameters of a measured filter such as:

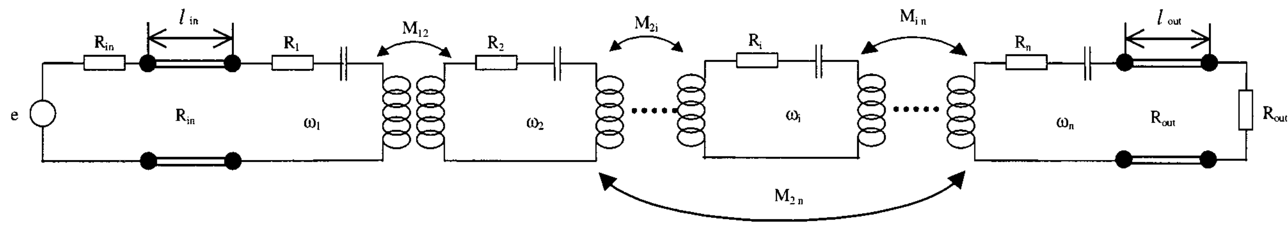


Fig. 3. Model for a general cross-coupled resonator filter.

- operating frequency ω;
- frequency shift of each resonator $\omega_1, \omega_2, \ldots, \omega_n$;
- input/output coupling resistances $R_{\text{in}}, R_{\text{out}}$;
- effects of phase shifts due to input/output coupling probes $l_{\text{in}}, l_{\text{out}}$, [5];
- coupling between resonators M_{ij};
- resonator losses $r_1, r_2, \ldots, r_n$.

A simple analysis shows that the vector current is governed by the following equation (example: four-resonator filter):

$$[A]\{I\} = -j\{e\}. \tag{1}$$

The excitation vector is given by $\{e\}^t = \{1, 0, 0, 0\}$ and matrix A by (2) as shown at the bottom of this page.

It follows for the vector currents $\{I\} = -j[A^{-1}]\{e\}$.

The scattering parameters for the input and output of the prototype network are given by

$$S_{21} = 2\sqrt{R_{\text{in}}R_{\text{out}}}\, I_4 = -2j\sqrt{R_{\text{in}}R_{\text{out}}}\,\left[A^{-1}\right]_{41}$$

and

$$S_{11} = 1 - 2R_{\text{in}}I_1 = 1 + 2jR_{\text{in}}\left[A^{-1}\right]_{11}. \tag{3}$$

S_{12} and S_{22} can be found in the same way. All S-parameters are ratios of polynomials with complex coefficients, e.g.,

$$S_{21} = 2\sqrt{R_{\text{in}}R_{\text{out}}}\,\frac{a_2\omega^2 + a_0}{\omega^4 + b_3\omega^3 + b_2\omega^2 + b_1\omega + b_0}. \tag{4}$$

The coefficients are functions of the unknown parameters (ideal case: $r_i = 0$ and $\omega_i = 0$)

$$\begin{aligned}
a_2 &= jM_{14}\\
a_1 &= 0\\
a_0 &= -jM_{14}M_{23}^2 + jM_{12}M_{23}M_{34}\\
b_4 &= 1\\
b_3 &= -jR_{\text{in}} - jR_{\text{out}}\\
b_2 &= -M_{12}^2 - M_{23}^2 - M_{34}^2 - M_{14}^2 - R_{\text{in}}R_{\text{out}}\\
b_1 &= jR_{\text{in}}\left(M_{23}^2 + M_{34}^2\right) + jR_{\text{out}}\left(M_{12}^2 + M_{23}^2\right)\\
b_0 &= M_{14}^2M_{23}^2 + M_{12}^2M_{34}^2 + M_{23}^2R_{\text{in}}R_{\text{out}}\\
&\quad - 2M_{12}M_{23}M_{34}M_{14}.
\end{aligned}$$

Having so characterized the model, it is now possible to find the unknown filter parameters such that they satisfy the given filter specifications. To do so, a mathematical filter function is derived from the filter specifications. This mathematical model is then used as target function and the network coefficients in (4) are found from gradient optimization. In the following, this process is called "filter synthesis."

IV. Filter Synthesis

In the synthesis procedure, the coupling values and input/output resistances are determined such that the filter specifications (insertion loss , stopband attenuation) are satisfied. Here, we assume the *ideal case* where losses and frequency shifts are zero ($R_i = 0$ and $\omega_i = 0$, $l_{\text{in}} = l_{\text{out}} = 0$). An example of a low-pass prototype filter function obtained using the technique described in [8] is shown in Fig. 4 (solid lines, generalized Chebyshev function, 15-dB return loss, transmission zeros ± 2). The corresponding ratio of polynomials is

$$\left|S_{21}^{\text{mathematical}}\right| = \frac{|0.198653\cdot\omega^2 - 0.794615|}{\left|\begin{matrix}\omega^4 - j\cdot 1.647323\cdot\omega^3 - 2.392735\cdot\omega^2\\ +j\cdot 1.803051\cdot\omega + 0.807485\end{matrix}\right|}$$

$$\left|S_{11}^{\text{mathematical}}\right| = \sqrt{1 - \left|S_{21}^{\text{mathematical}}\right|^2}. \tag{5}$$

To map the prototype function (4) onto the mathematical function (5), the unknown coefficients of (4) must be found. This is done by minimizing (gradient optimization) the following cost function:

$$\begin{aligned}
F = &\left(|a_2| - 0.198653\right)^2 + \left(|a_0| + 0.794615\right)^2\\
&+ (b_3 + j\cdot 1.647\,323)^2 + (b_2 + 2.392735)^2\\
&+ (b_1 - j\cdot 1.803051)^2 + (b_0 - 0.807485)^2.
\end{aligned} \tag{6}$$

This cost function is not very sensitive on parameter start values and convergence of the gradient optimization is guaranteed. The ideal values found from the synthesis are

$$\begin{aligned}
M_{12} &= 0.77797\\
M_{23} &= 0.69950\\
M_{34} &= 0.77797\\
M_{14} &= -0.12059\\
R_{\text{in}} &= R_{\text{out}} = 0.82366.
\end{aligned}$$

The response of the prototype network computed with these parameters is also shown in Fig. 4 (dashed lines). Perfect agree-

$$A = \begin{bmatrix}
\omega + \omega_1 - jr_1 - jR_{\text{in}} & M_{12} & 0 & M_{14}\\
M_{12} & \omega + \omega_2 - jr_2 & M_{23} & 0\\
0 & M_{23} & \omega + \omega_3 - jr_3 & M_{34}\\
M_{14} & & M_{34} & \omega + \omega_3 - jr_4 - jR_{\text{out}}
\end{bmatrix} \tag{2}$$

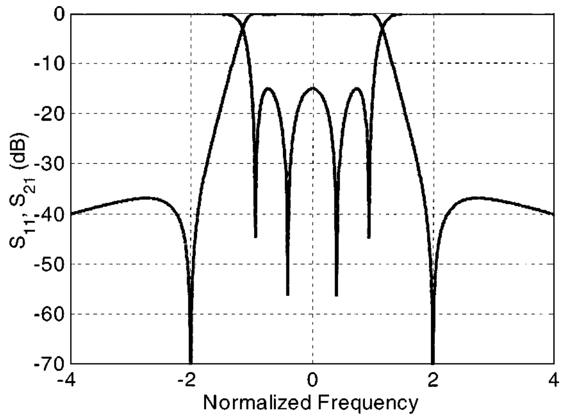


Fig. 4. Prototype response cross-coupled four-resonator filter.

ment with the mathematical function can be observed. The ideal parameter values are later used as target values in the automatic tuning algorithm. These values correspond to those of a tuned filter.

V. Parameter Extraction

For the measured filter (with the nonoptimum response equal to the start values of tuning screws), the filter network model must first be mapped onto the measured filter response. This step produces the coefficients of the network model for the start position of the tuning screws. The coefficients for the ideal case are calculated from the filter specifications, as described in Section IV. The difference between both sets of coefficients gives a direct measure of how to tune the filter. However, before this can be done, the sensitivity of the tuning elements must be determined. Furthermore, it must be considered that individual tuning screws do not only affect the network element they are supposed to tune, but also neighboring elements and, thus, have an impact on the overall network function. Therefore, after establishing the element sensitivities, a final optimization run must be performed to map the network coefficients onto the prototype coefficients.

Parameter Extraction From Measured S-Parameter Data

The roughly pre-tuned filter with a nonoptimum filter response must be characterized first in terms of the prototype model of Fig. 3. For this purpose, the generalized low-pass network is optimized to meet the measured filter response. The following cost function is used in this first step:

$$F=\sum_{\text{freq.}}\sum_{i=1}^{2}\sum_{j=1}^{2}\begin{array}{l}\left[\text{real}\left(S_{ij}^{\text{network}}\right)-\text{real}\left(S_{ij}^{\text{measured}}\right)\right]^2\\+\left[\text{imag}\left(S_{ij}^{\text{network}}\right)-\text{imag}\left(S_{ij}^{\text{measured}}\right)\right]^2.\end{array}\quad(7)$$

S_{ij}^{network} is the response of the prototype network and a function of the unknown parameters. It should be noted that both magnitude and phase or real and imaginary parts, respectively, of the model and measured S-parameters are taken into account. Furthermore, a standard bandpass to low-pass transformation of the measured S-parameters is required since the measured filter shows a bandpass characteristic. The influences of the coupling probes also have to be taken into account (Fig. 1). The main effect of the probes is a phase shift of the S-parameters, which can be modeled by adding transmission lines at the input and output of the filter (Fig. 3). The lengths of the lines are also subject to optimization [5]. Fig. 5 shows the measured and optimized prototype response of the cross-coupled four-resonator filter (1.7-GHz center frequency, 30-MHz bandwidth). Good agreement between the measurement and computed response can be observed, both in the magnitude as well as in the real and imaginary parts. The extracted parameters for the measured response in Fig. 5 (filter was tuned by hand) are

$$\begin{aligned}M_{12}&=0.94978\\M_{23}&=0.77240\\M_{34}&=0.95814\\M_{14}&=-0.09290\\R_{\text{in}}&=1.189200\\R_{\text{out}}&=1.183047\\\omega_1&=0.30011\\\omega_2&=0.31304\\\omega_3&=0.32131\\\omega_4&=0.32935.\end{aligned}$$

A comparison of these parameters with the prototype values for the ideal filter (from the above filter synthesis) clearly shows which coupling coefficients or resonant frequencies must be adjusted. In the above example, all resonant frequencies have a shift in normalized frequency of about 0.3. This is also obvious after inspecting the response in Fig. 5. Fig. 6 illustrates the measured and simulated response of the de-tuned cross-coupled six-resonator filter after parameter extraction. Simulated and measured results also agree very well here.

VI. Sensitivity Analysis

In the previous section, it was shown how prototype parameters of filters under test can be extracted from S-parameter measurements. It was shown that, by extracting the parameters from a de-tuned filter response, it is immediately clear which parameter must be adjusted and how to obtain the ideal filter response. However, these parameters are controlled by tuning screws and, thus, a relationship between tuning screw turns and corresponding units of element values must be established. To do so, the sensitivities of network parameters with respect to tuning screws must be calculated. One parameter set is already extracted from the response of the measured filter in the basis position (de-tuned). Additional parameter sets are obtained if each tuning screw is turned a defined amount and the above procedure repeated.

The sensitivities can then be calculated by finite differences. The sensitivity of one parameter with respect to one screw is the difference of two extracted parameter values divided by the incremental screw turn.

The cross-coupled six-resonator filter for example can be tuned by turning 12 tuning screws (six for changing the resonant frequencies, five for changing the coupling elements, and one for the cross coupling). Since the tuning screws exhibit a mutual dependency (at least in their immediate neighborhood), the optimum screw position is subject to a final optimization run with respect to all screw positions. The mutual dependency

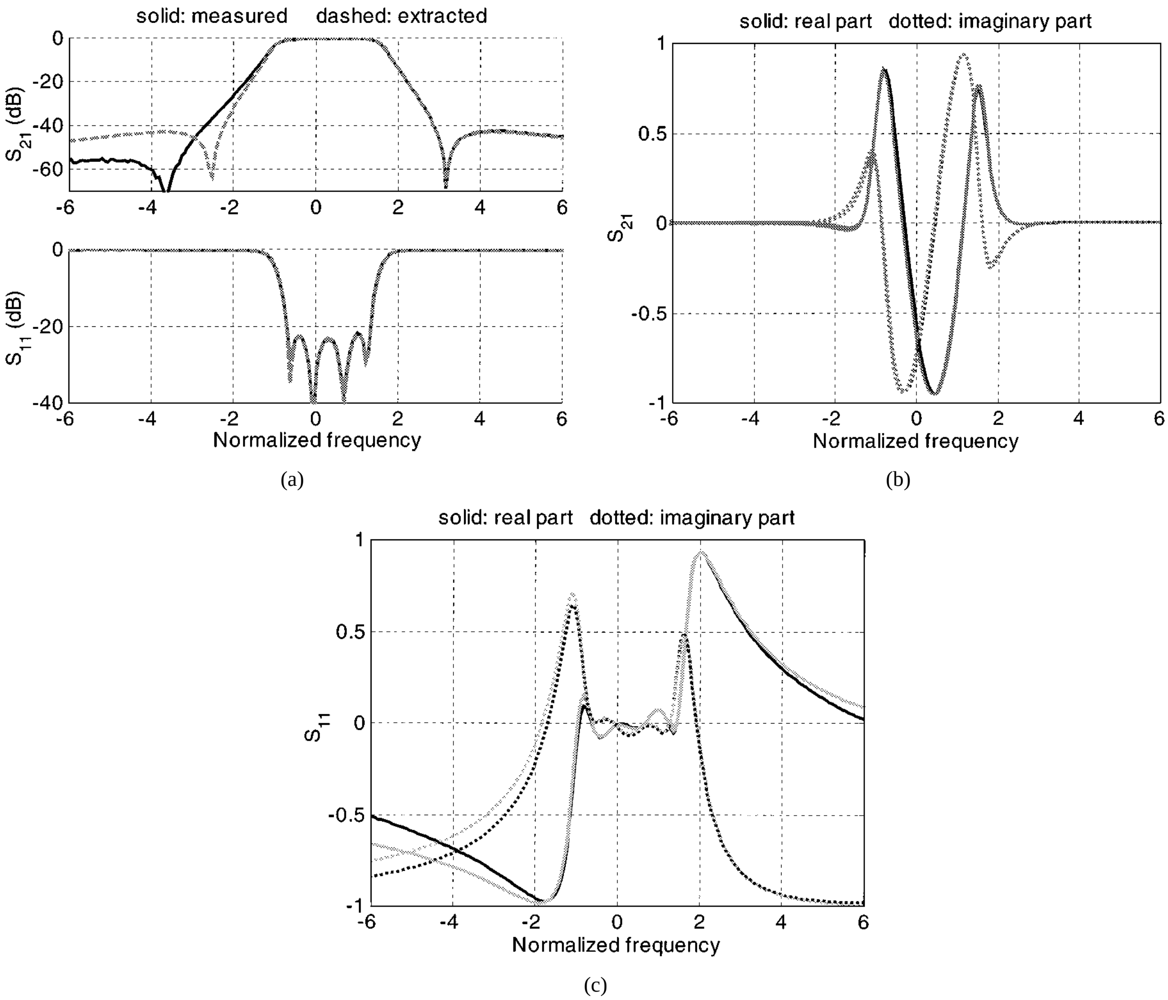


Fig. 5. Measured and prototype response of the cross-coupled four-resonator filter.

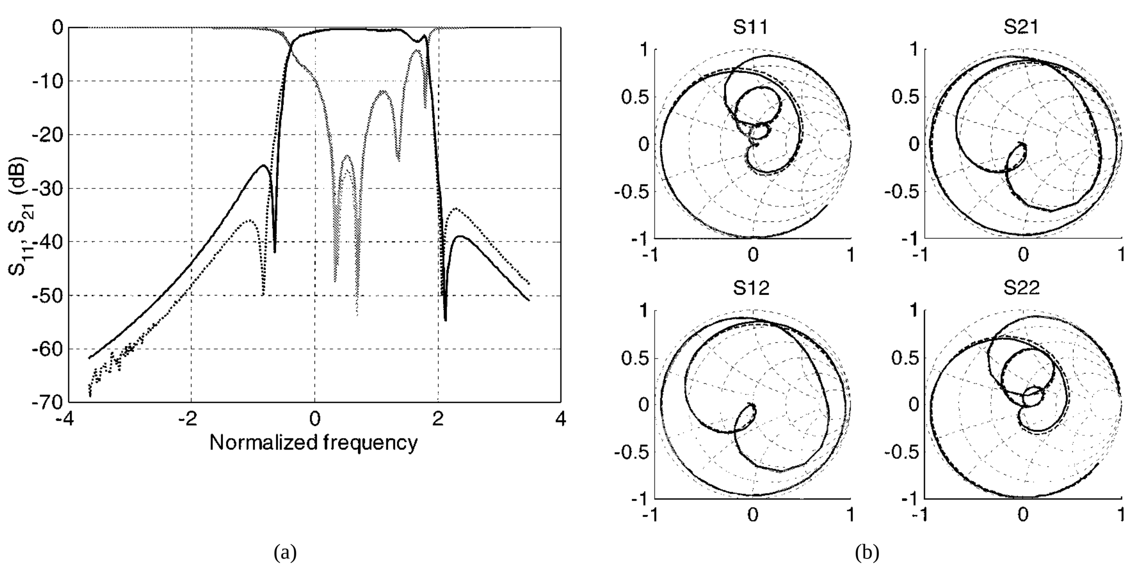
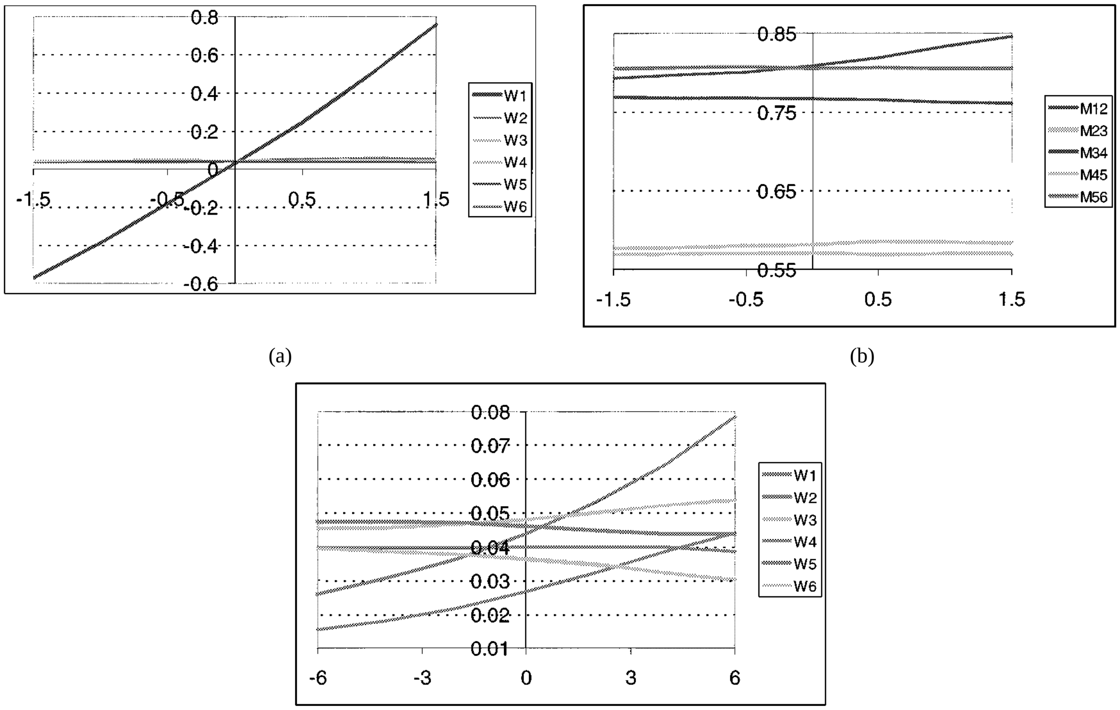


Fig. 6. Measured and prototype response of the cross-coupled six-resonator filter (de-tuned). Dashed: measurement, solid: prototype.

of the screws is illustrated in Fig. 7. Fig. 7(a) shows the influence of screw 1 (resonance frequency of the first resonator) on the frequency shifts of the resonators. Fig. 7(b) shows the parameter changes (coupling coefficients) versus screw turns for screw 1. Screw 1 mainly affects ω_1 [see Fig. 7(a)], but to a lesser extent, also M_{12} [see Fig. 7(b)]. Screw 2 mainly effects M_{12} (not shown here), but to a lesser extent, also ω_1 and ω_2 [see Fig. 7(c)].



(a) (b)

(c)

Fig. 7. Network sensitivities (changes of parameter values (normalized) versus screw turns).

Fig. 7 also shows that the linearity of parameter changes can be assumed in a defined tuning range. This is important for the automatic tuning algorithm presented in Section VII.

VII. Tuning Procedure

To illustrate the tuning procedure, a six-resonator bandpass filter with cross coupling between resonator 2–5 is utilized. The filter is roughly pretuned (basis position) using tuning screws $i = 1, \ldots, n$. The penetration depths of the screws in basis position are d_i^{basis}. The goal is to find d_i^{ideal}. The recipe is outlined in the following steps.

Step 1) Synthesize low-pass prototype $\rightarrow$ ideal parameters M_{ij}^{ideal}, $R_{\text{in}}^{\text{ideal}}$, $R_{\text{out}}^{\text{ideal}}$, ω_i^{ideal}.

Step 2) Measure S-parameters $S_{ij}^{\text{measured}, BP}$ at basis position and map them by standard bandpass to low-pass transformation onto the normalized frequency axis $\rightarrow S_{ij}^{\text{measured}, LP}$.

Step 3) Extract the parameters M_{ij}^{basis}, $R_{\text{in}}^{\text{basis}}$, $R_{\text{out}}^{\text{basis}}$, ω_i^{basis} from the measured filter response $S_{ij}^{\text{measured}, LP}$ at basis position (d_i^{basis}) by minimizing the cost function (7).

Step 4) Turn screw 1 a defined increment Δd_1 and repeat steps 2) and 3) $\rightarrow M_{ij}^1$, R_{in}^1, R_{out}^1, ω_i^1.
Then turn screw back to its basis position.

Step 5) Repeat step 4) for all screws.

Step 6) Calculate all network sensitivities with respect to all screws, e.g.,

$$\omega_1^{\text{sens}}(d_i, i = 1, \ldots, n) = \sum_{i=1}^{n} \frac{\omega_1^i - \omega_1^{\text{basis}}}{\Delta d_i} d_i.$$

Step 7) Compare results of step 3) with step 1) $\rightarrow$ calculate all maladjustments, e.g., $\Delta\omega_1 = \omega_1^{\text{basis}} - \omega_1^{\text{ideal}}$.

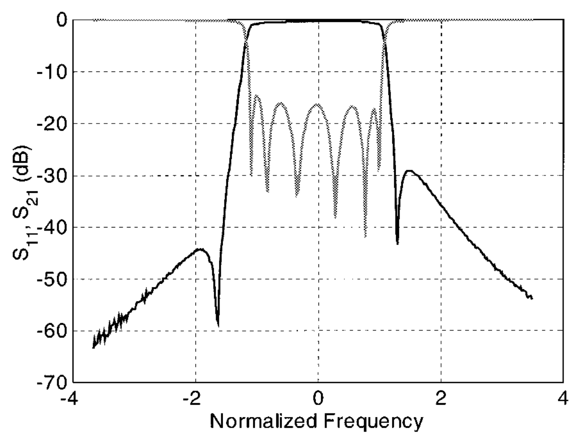


Fig. 8. Measured response of the cross-coupled six-resonator filter (tuned).

Step 8) Determine the optimal screw positions d_i^{ideal} that are necessary to tune the filter from the basis position to the ideal prototype response by minimizing the cost function F_2 subject to screw positions d_i as follows:

$$\begin{aligned} &F_2(d_i, i = 1, \ldots, n) \\ &\quad = \left(\Delta\omega_1 + \omega_1^{\text{sens}}(d_i, i = 1, \ldots, n)\right)^2 + \cdots \\ &\qquad + \left(\Delta M_{12} + M_{12}^{\text{sens}}(d_i, i = 1, \ldots, n)\right)^2 + \cdots. \end{aligned}$$

Result of this gradient optimization: d_i^{ideal}.

Fig. 8 shows the measured response of the six-resonator filter of Fig. 6 after applying the tuning procedure described above. The target parameter values have been synthesized for 15-dB return loss and transmission zeros at ± 1.5 along the normalized frequency axis. For the bandpass to low-pass transformation, the target 1.7-GHz center frequency and 56-MHz bandwidth have been used.

VIII. Conclusion

An automated computer-controlled tuning technique has been introduced. The approach described allows the extraction of all characteristic filter parameters (e.g., frequencies of resonators and couplings between resonators) from a measured filter response. A comparison with element values from an ideal prototype network, in conjunction with a sensitivity analysis of all tuning screws, provides all information necessary to tune the filter. The new method has been tested successfully in a laboratory setup, using a motorized tuning unit for tuning three-, four-, and six-resonator filters. The latter two including one cross coupling.

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