AUTOMATED TEST AND TUNING SYSTEM FOR MICROWAVE FILTERS

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Abstract — **A novel method for computerized diagnosis and automatic tuning of microwave (cavity) filters is introduced. The method is based on equivalent network theory using modified filter synthesis equations, including all characteristic filter parameters like resonant frequency, losses of individual resonators, input-/output couplings and couplings between resonators. Instead of using field simulators to extract filter parameters and associated network sensitivities, a more practical and more accurate parameter extraction process of measured S-parameter data is utilized. Thus automatic tuning becomes a two step process. In the first step the exact parameter values of an untuned filter as well as parameter sensitivities are extracted from a series of S-parameter measurements. In a second step gradient optimization is used on the so corrected model to find the tuning screw positions to give the same parameter set as obtained from the synthesis.**

I. INTRODUCTION

The explosive growth of the telecommunication market has significantly increased the need for low cost and high Q microwave components. Large volume production and quick turn-around 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 which 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 time consuming and thus expensive task.

To eliminate these extra cost, a novel computer-controlled automatic fine tuning technique for microwave filters is introduced. Although currently this technique is only functional for direct coupled filters, it is expected that the approach presented in this paper can also be applied to cross-coupled filters.

The core of this new method is an efficient parameter extraction technique which generates the element values of a theoretical filter model from measured complex S-parameter data. A great advantage of this approach is that the filter model (element values) need not be very accurate as long as the effect of the tuning screws is represented with sufficient accuracy. After the first measurement all characteristic parameters of the real filter (including element values at given screw position) are found from parameter extraction (filter diagnosis). Subsequent measurements (one per tuning screw) provide a reliable prediction in which direction the tuning screws (with corresponding penetration depths) must be turned for increasing or decreasing values of the network elements. This prediction is valid within the tuning range of the filter. In a second step the corrected filter model is then optimized towards the required filter response (i.e. screw position determined) which is known from filter synthesis.

In the past, various tuning techniques have been proposed, but only few are suitable for automatic tuning of microwave filters. In Ref. [1] filter tuning in the time domain is described. This method has two disadvantages. First, an optimum filter template is needed and second an experienced operator is still required to tune the filter. In Ref. [2] the authors propose a diagnosis and tuning method based on model-based parameter estimation and multi-level optimization. Although their general circuit model is similar to our model, a major disadvantage of the approach in [2] is that they approximate the measured S-parameters by a ratio of polynomials with real coefficients. However, S-parameters of filters can only be modeled accurately by polynomials with complex coefficients. Consequently, in the multi-level optimization only the locations of the reflection and transmission zeros are optimized. This approach does not include the optimization of the filter ripple or return loss, respectively. Moreover, diagnosis and tuning of a real (measured) filter has not been investigated in that paper.

In Ref. [3] an optimization method for the identification of filter network parameters and network sensitivities is proposed. But in this paper only the simulated amplitude and delay response of coupled cavity filters is given.

In the automatic tuning system described in [4] only the magnitudes of S_{11}, S_{21} and S_{22} are used. As a consequence the approximate circuit models are valid only in a very confined frequency region which is not the case in our present system.

II. DESCRIPTION OF THE TEST SETUP

A coaxial filter prototype consisting of 3 cavities with **square diameter and is used to prove the concept** (Fig. 1). The filter is coupled capacitively by probes at the input and output. The structure is symmetric. Five tuning screws allow to change the filter characteristics. 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.

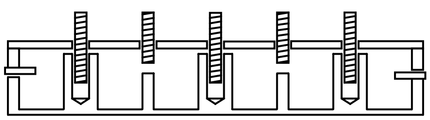

Fig. 1. 3-pole re-entrant resonator filter

The tuning screws are turned by DC-motors which are controlled by a LabView interface.

III. COMPUTER DIAGNOSIS OF FILTER UNDER TEST

A. Theoretical filter model

The method is based on modified filter synthesis equations (including resonator losses and frequency shifts) that include all characteristic filter parameters. A parameter extraction process performed on the measured S-parameters of an initial filter design allows accurate calculation of the individual filter parameters. The method can be easily extended to cross-coupled filters and filters of higher order. The model for the 3-resonator re-entrant cavity filter of Fig. 1 is shown in Fig. 2. The resonators are assumed to be lossy (represented by normalized resistances r_1, r_2, r_3) and are coupled to one another by frequency independent coupling coefficients M_{ij}. ω is the operating frequency and ω_1, ω_2, ω_3 represent the frequency shift of the resonators. This model can easily be extended to represent cross-coupled filter structures.

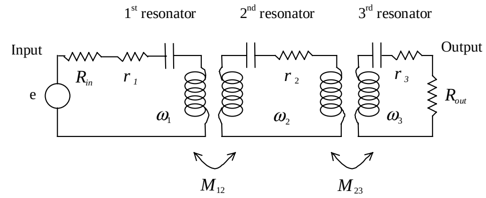

Fig. 2. Circuit model for a 3-resonator filter

A simple analysis shows that the vector current is governed by the following equation [5]:

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

The excitation vector is given by $\{e\}^t=\{1,0,0\}$ and matrix ***A*** by:

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

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

The scattering parameters for the input and output of the filter model are given by:

$$S_{21}=2\sqrt{R_{in}R_{out}}I_3=-2j\sqrt{R_{in}R_{out}}\left[A^{-1}\right]_{31} \text{ and}$$

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

S_{12} and S_{22} can be found in the same way. All S-parameters are ratios of polynomials with complex coefficients. The task is now to find the unknown real filter parameters.

This can be done by using gradient optimization to minimize the following cost function:

$$F=\sum_{freq.}\sum_{i=1}^{2}\sum_{j=1}^{2}\begin{bmatrix}(real(S_{ij}^{computed})-real(S_{ij}^{measured}))^2 \\ +(imag(S_{ij}^{computed})-imag(S_{ij}^{measured}))^2\end{bmatrix}$$

B. Calibration of the theoretical filter model

The theoretical model does not include the effects of the input and output probes (Fig. 1). It is also not possible to calibrate the VNA on the probes. The VNA can only be calibrated with defined standards and the reference planes are always at the end of the coaxial cables used in the measurements. For accurate modeling of a measured filter it is important to take the effects of the probes into account. The reactance of the probes shift the resonant frequencies of the first and last resonator (this effect is included in ω_1 and ω_2). The main effect due to the probe lengths is a phase shift of the S-parameters. This effect can be compensated by multiplying the measured S-parameters by appropriate phase terms (calibration of the theoretical model).

IV. AUTOMATED FILTER TUNING

A. Synthesis of the filter prototype (target)

The goal of the automatic tuning is to tune a filter from a roughly pre-tuned position to a target. The target function is specified in terms of center frequency, bandwidth and passband ripple.

The parameters of the ideal model (prototype) can be found from well known filter synthesis. For a 3-pole Chebychev filter the ideal transfer function is given by:

$$\left|S_{21}^{ideal}\right|^2 = 1 \Big/ 1 + e^2 \cdot \left(4\omega^3 - 3\omega\right)^2$$

e is defined by the ripple (in dB) as: $e = \sqrt{10^{0.1 \cdot ripple} - 1}$

To translate this performance into corresponding element values of the prototype we utilize a gradient optimization with the following cost function:

$$F = \sum_{freq.} \sum_{i=1}^{2} \sum_{j=1}^{2} (abs(S_{ij}^{\text{model}}) - abs(S_{ij}^{ideal}))^2$$

For a 0.3 dB ripple the ideal model parameters are obtained as:

	R_{in}	R_{out}	M_{12}	M_{23}	ω_1	ω_2	ω_3
Target	0.729	0.729	0.800	0.800	0	0	0

Table 1. Parameter values of the ideal model (target)

These values are then used as target values in the automatic tuning. The resonator losses and phase shifts due to in-/output couplings in the ideal case are of course zero.

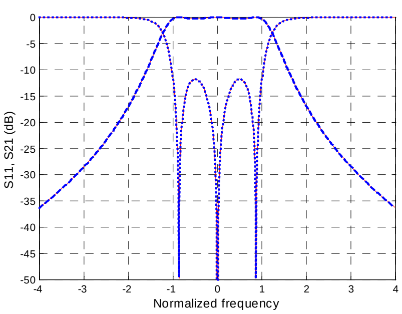

Fig. 3. Ideal and modeled S-parameters

Fig. 3 shows the response of the circuit model (prototype) and the ideal transfer function. Perfect agreement can be observed. The gradient optimization process (routine ´constr´, Matlab™ optimization toolbox) converged after 290 iterations. If the routine is supplied with the analytically calculated gradient of the cost function $\frac{\partial F}{\partial R_{in}}, \frac{\partial F}{\partial R_{out}}, \frac{\partial F}{\partial M_{12}}, \frac{\partial F}{\partial M_{23}}$ the process converges after only 64 iterations (start values for the parameters set to zero). With all start values set to one it converges after only 31 iterations.

B. Extraction of model parameter values from measured filter response

The model described in section III.A is now fitted to measured S-parameter data. As target we choose the above Chebychev bandpass characteristic with ripple 0.3 dB (see Fig. 3), center frequency f_0=1.5GHz and ripple bandwidth BW=50MHz.

To compare the measured and modeled S-parameters, the latter are normalized using standard bandpass to lowpass frequency transformation.

The filter is now roughly pre-tuned by hand (basis position) and the model fitted to this start position. The agreement between measured and modeled filter is very good and shown in Fig.4.

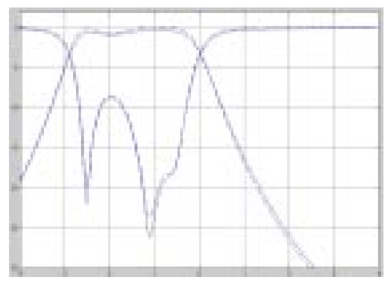

Fig. 4. Measured and modeled S-parameters (basis position) S_{21} and S_{11} (dB) versus normalized frequency

The extracted parameters of the theoretical model for the untuned filter are given in Table 2.

	R_{in}	R_{out}	M_{12}	M_{23}	ω_1	ω_2	ω_3
Basis	0.918	0.915	0.950	0.915	1.45	1.55	1.20

Table 2. Extracted parameters for the basis position

The next step is to utilize the five tuning screws to change the start parameters (Table 2) to the ideal (target) values (Table 1).

For this purpose five additional measurements are necessary, each with one tuning screw turned a defined angle φ_i at a time. For each measurement the model parameters are extracted and thus the effect of the tuning screws determined. Assuming that the model parameters change linearly with screw turns (see Fig.5) (ϕ_i: turns in degree), the model parameters can be found for example as:

$$\omega_1 = \omega_1^{basis} + \sum_{i=1}^{5} \frac{\omega_1^{\varphi i} - \omega_1^{basis}}{\varphi_i} \phi_i$$

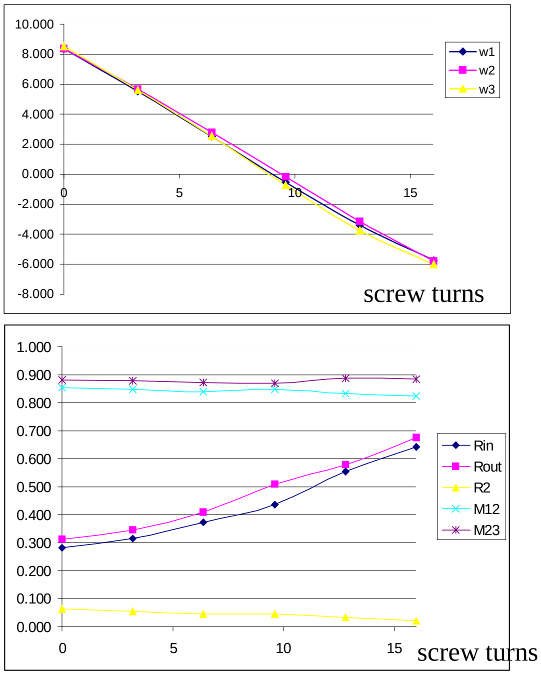

Fig. 5. Extracted parameter values for screws 1, 3, 5

The optimum screw positions can then be calculated by minimizing the following cost function:

$$
\begin{aligned}
F = {} & \left(R_{in}^{basis} + R_{in}\left(screw_1 ... screw_5\right) - R_{in}^{target}\right)^2 + \left(R_{out}^{basis} + R_{out}\left(screw_1 ... screw_5\right) - R_{out}^{target}\right)^2 + \\
& \left(R_2^{basis} + R_2\left(screw_1 ... screw_5\right) - R_2^{target}\right)^2 + \left(M_{12}^{basis} + M_{12}\left(screw_1 ... screw_5\right) - M_{12}^{target}\right)^2 + \\
& \left(M_{23}^{basis} + M_{23}\left(screw_1 ... screw_5\right) - M_{23}^{target}\right)^2 + \left(\omega_1^{basis} + \omega_1\left(screw_1 ... screw_5\right) - \omega_1^{target}\right)^2 + \\
& \left(\omega_2^{basis} + \omega_2\left(screw_1 ... screw_5\right) - \omega_2^{target}\right)^2 + \left(\omega_3^{basis} + \omega_3\left(screw_1 ... screw_5\right) - \omega_3^{target}\right)^2
\end{aligned}
$$

After turning the screws to the optimized screw positions a final test measurement is made. The result is shown in Fig. 6. The automatically tuned filter fits almost perfectly the target function (Fig. 3). The extracted parameter values are given in Table 3 and agree almost perfectly with the those of Table 1. This is also confirmed in Fig. 6 illustrating the Smith chart response.

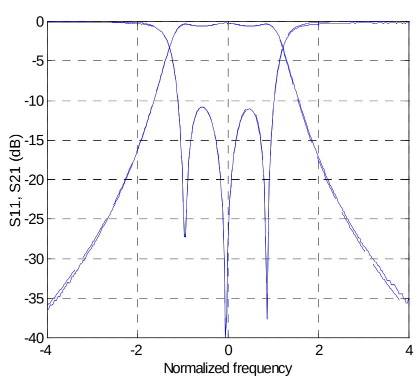

Fig. 6

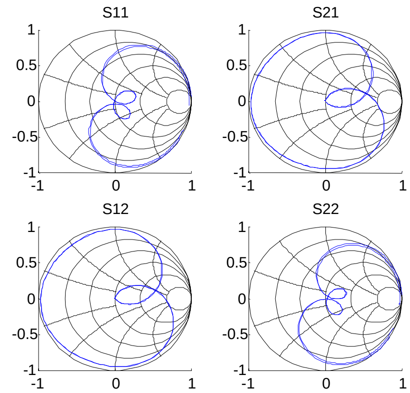

Fig. 6. Result of the automatic tuning

	R_{in}	R_{out}	M_{12}	M_{23}	ω_1	ω_2	ω_3
Target	0.707	0.701	0.804	0.803	0.04	0.04	0.06

Table 3. Parameter values of the automatically tuned filter

V. Conclusion

A novel automatic test and tuning system is introduced. The method is based on a theoretical filter model derived from modified synthesis equations (ratio of polynomials with complex coefficients). The elemental values of the model are found from a parameter extraction process (using gradient optimization) of measured S-parameters. Network sensitivities can be extracted from these measurements as well and are used to find the optimum parameter values from a second gradient optimization run. These element values are then directly translated into screw position. Measured and modeled filter functions are in excellent agreement.

References

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