EM-Simulator Based Parameter Extraction and Optimization Technique for Microwave and Millimeter Wave Filters

P. Harscher, E. Ofli, R. Vahldieck and S. Amari†

Swiss Federal Institute of Technology, IFH, ETH Zentrum, Gloriastrasse 35, CH - 8092 Zürich
† Dept. ECE, Royal Military College of Canada, Kingston, On, K7K 7B4, Canada.

Abstract **— A novel hybrid optimization technique for microwave and millimeter wave filters is presented. The technique is based on a surrogate model represented by a minimum prototype filter network. All characteristic filter parameters like frequency shifts of and couplings between resonators are included. Accurate prototype parameters are extracted from S-parameter computation of the physical filter. In the best case only $n+1$ electromagnetic (EM) field simulations are necessary, where n is the number of geometry parameters. Optimization is performed in the parameter space of the surrogate model with the parameters of the ideal transfer function as target. This approach is very fast and requires only few field simulations.**

I. INTRODUCTION

Full-wave simulation has become an indispensable tool in the design of microwave and millimeter wave circuits. A great variety of EM simulators are commercially available today. Unfortunately, the higher the demand for simulation accuracy the more CPU-time is consumed. This makes it generally impossible to optimize microwave and millimeter wave circuits on the basis of field simulators alone since the resulting computation time becomes excessive.

To eliminate the CPU-time bottleneck and still maintain the accuracy known from EM simulation, this paper introduces an accurate and fast optimization procedure for microwave and millimeter wave filters by combining EM simulations with a surrogate model represented by a minimum prototype filter network. The method is surprisingly simple, does not require the use of individual coarse or fine equivalent networks and is applicable also to more general microwave circuit design problems. The basic idea of the proposed method is to match the response of the surrogate model to the initial (non-optimum) response of the physical filter obtained from EM simulation. This step yields the parameter values for the corresponding surrogate model. The parameter sensitivities as a function of the geometry of the physical filter are also found through EM simulation by varying one geometrical parameter at a time.

Up to this point only $n+1$ EM simulations are necessary (n: number of geometrical parameters) to characterize the surrogate model accurately. The so found parameter set of the surrogate model of the initial filter design is then optimized to meet the ideal parameter set found from standard filter synthesis.

In the following the individual steps of the procedure are illustrated by optimizing a direct coupled 4-resonator E-plane filter as well as a dual-mode filter.

II. PARAMETER EXTRACTION

The concept of using surrogate models to substitute an EM model is not new [1]. Empirical or engineering models are known for many different kinds of microwave structures and are well documented in the literature. However only few of them are accurate enough to represent the real behavior of more complex structures. Most of them provide only a rough estimate of the true response and are only valid within a very small frequency range.

The model proposed in the following is derived from the generalized low-pass filter prototype and can be used for arbitrary filter structures and topologies. It includes the characteristic parameters of a simulated filter: frequency shift of each single resonator with respect to operating frequency ω_1, ω_2,... ω_n, input- and output-coupling and coupling coefficients between resonators M_{ij} (direct and cross couplings). Effects of phase shifts due to input-and output couplings are modeled by transmission lines with lengths l_{in}, l_{out} (Fig. 1.)

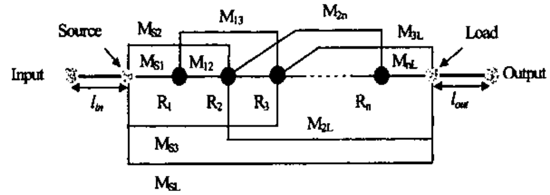

Fig. 1. Coupling and routing scheme of the generalized surrogate model.

The reflection coefficient S_{11} and the transmission coefficient S_{21} of the surrogate model can be found according to [2] as follows:

$$S_{11} = 1 + 2j\left[A^{-1}\right]_{11}, \quad S_{21} = -2j\left[A^{-1}\right]_{(n+2),1} \tag{1}$$

Matrix $[A]$ contains all characteristic parameters of the surrogate model and is given as:

$$A = \begin{bmatrix} -j & M_{S1} & M_{S2} & M_{S3} & \cdots & M_{Sn} & M_{SL} \\ M_{S1} & \omega+\omega_1 & M_{12} & M_{13} & & & \\ M_{S2} & M_{12} & \omega+\omega_2 & M_{23} & & & \\ M_{S3} & M_{13} & M_{23} & \omega+\omega_3 & & & \\ \vdots & & & & \ddots & & \\ M_{Sn} & & & & & \omega+\omega_n & M_{Ln} \\ M_{SL} & & & & & M_{Ln} & -j \end{bmatrix} \tag{2}$$

To take the effects of l_{in}, l_{out} into account the S-parameters (eq. 1) must be multiplied by the phase terms $e^{-j \cdot P11}$ or $e^{-j \cdot P21}$, respectively.

First, the coupling elements and frequency parameters of the surrogate model are determined which correspond to the transfer function of the EM simulated initial filter (non-ideal) design. This is done by minimizing the difference between computed S-parameters of the surrogate model (eq. 1) and the simulated filter response (field solver), both in magnitude and phase [2], [3]:

$$F = \sum_{freq.} \sum_{i=1}^{2} \sum_{j=1}^{2} \begin{matrix} \left[real\left(S_{ij}^{surrogate}\right) - real\left(S_{ij}^{field\ solver}\right)\right]^2 + \\ \left[imag\left(S_{ij}^{surrogate}\right) - imag\left(S_{ij}^{field\ solver}\right)\right]^2 \end{matrix} \tag{3}$$

Matrix $[A]$ must be filled according to the known filter topology. Couplings which are not present are set to zero. Cost F is a function of the matrix elements in matrix $[A]$, p_{11}, and p_{21}.

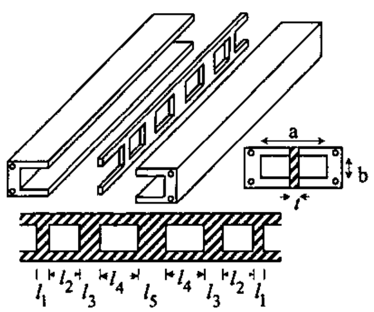

Fig. 2. E-plane single metal insert filter.

To illustrate this approach an E-plane filter was chosen as example because synthesis methods and field simulator-based optimization codes were available for comparison. The initial response is centered at f_0=32GHz with a bandwidth of BW=500MHz, and a return loss of RL=15dB. The field solver was based on the well known Mode Matching Technique (MMT) [4], however any other field solver could be used as well.

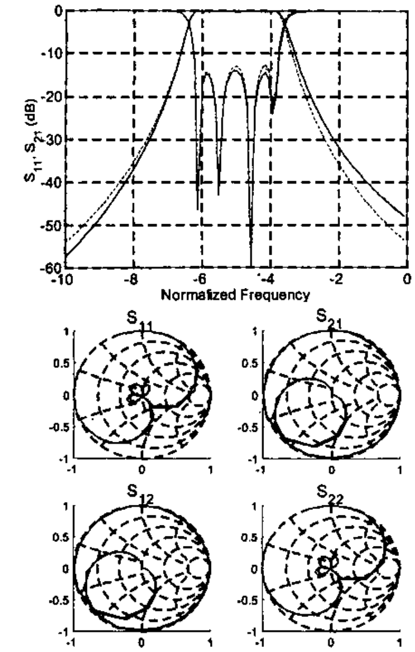

Fig. 3. MMT response (–) and surrogate model response (--) of E-plane filter in basis position.

Fig. 3 shows the filter response calculated with the MMT and the response of the surrogate model calculated with parameter values obtained from the parameter extraction technique (dashed lines). Both agree well in magnitude and phase as shown on the Smith chart. The field simulator response was mapped to the normalized frequency axis with BP-LP transformation using f_0=33GHz; BW=400MHz. The extracted characteristic filter parameters of the surrogate model were found as: M_{S1}=0.950, M_{12}=0.922, M_{23}=0.747, M_{34}=0.922, M_{4L}=0.950, ω_1=5.028, ω_2=5.008, ω_3=5.008, ω_4=5.028. The dimensions of the filter structure in basis position are: l_1=1.541mm, l_2=4.508mm, l_3=4.356mm, l_4=4.520mm, l_5=4.714mm. The target values for the optimization (section IV) are extracted from an ideal Chebychev filter function (RL=20dB): M_{S1}=M_{4L}=1.035, M_{12}=M_{34}=0.911, M_{23}=0.700, ω_1=ω_2=ω_3=ω_4=0. The ideal filter response provides a normalized bandwidth of BW=2. It should be noted, that up to this point only one EM simulator run was necessary. The CPU-time for the parameter extraction is less than one second.

III. PARAMETER SENSITIVITIES

Before the surrogate model can be optimized the sensitivities of the parameters with respect to the geometrical parameters must be determined. This is done in a sensitivity analysis in which the changes of the S-parameters with respect to the geometry are translated into changes of the coupling coefficients and frequency parameters of matrix [A] (eq. 2):

$$\partial S_{ij}^{\text{field solver}}/\partial x_k \rightarrow \partial M_{ij}^{\text{surrogate}}/\partial x_k \text{ and } \partial \omega_i^{\text{surrogate}}/\partial x_k \quad (4)$$

This is done by using finite difference approximation as described in the following four steps:

1) Calculate S-parameters of the filter structure in basis (non-ideal) position using field solver and extract characteristic parameters: $\omega_i^{basis}, M_{ij}^{basis}$
2) Change first geometry parameter $x_1 + \Delta x_1$ and repeat step 1 → $\omega_i^{x1+\Delta x1}, M_{ij}^{x1+\Delta x1}$
3) Repeat step 2 for all other geometry parameters $x_2, x_3, \ldots, x_n$
4) Calculate: (5)

$$\omega_i^{surrogate}(x_1, x_2, x_3, \ldots, x_n) = \omega_i^{basis} + \sum_{k=1}^{n} \underbrace{\frac{\omega_i^k - \omega_i^{basis}}{\Delta x_k}}_{\partial M_{ij}^{\text{surrogate}}/\partial x_k} x_k$$

$$M_{ij}^{surrogate}(x_1, x_2, x_3, \ldots, x_n) = M_{ij}^{basis} + \sum_{k=1}^{n} \underbrace{\frac{M_{ij}^k - M_{ij}^{basis}}{\Delta x_k}}_{\partial \omega_i^{\text{surrogate}}/\partial x_k} x_k$$

IV. PARAMETER OPTIMIZATION

The ideal filter characteristic (the target response) is found from standard filter synthesis. The corresponding model parameters are obtained like the ones for the non-optimum filter (section II eq. 3). The objective of the optimization is now to minimize the difference between the target parameters and the parameters of the non-optimum response, that is the filter optimization is done entirely in the parameter space of the surrogate model:

$$F = \sum_i \left(\omega_i^{surrogate}(x_1, x_2, x_3, \ldots, x_n) - \omega_i^{ideal}\right)^2 + \sum_i \sum_j \left(M_{ij}^{surrogate}(x_1, x_2, x_3, \ldots, x_n) - M_{ij}^{ideal}\right)^2 \quad (6)$$

Since in most cases the parameters of the surrogate model are not a linear function of the geometry parameters, the optimization is done in several steps. The first and sixth optimization steps are illustrated in Fig. 4. After each optimization step the surrogate model is updated. For this, one field simulation with the actual geometry is necessary and one parameter extraction. After only 6 steps the response is very close to the specified target (f_0=33GHz, BW=400MHz, RL=20dB). The optimum dimension were found as: l_1=1.561mm, l_2=4.169mm, l_3=4.659mm, l_4=4.176mm, l_5=5.127mm. Fig. 5 illustrates the parameter changes of the surrogate model. It is obvious, that the

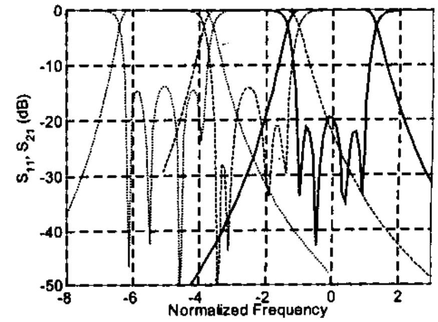

Fig. 4. Filter response (MMT) after different optimization steps (: basis, --step 1, – step 6).

frequency parameters change more than the coupling coefficients since at 32GHz they are further apart from the target value at 33GHz than the coupling coefficients. For the whole optimization procedure only 12 field simulations were necessary: one for the initial response, 5 for the sensitivity analysis and 6 to update the model (after each optimization step one field simulator run). In comparison, a gradient-based direct field simulator optimization would need at least 200-300 optimization steps to achieve the same results. That is, in the above example with five parameters, each optimization step alone would require 6 field simulator runs to find the response of the actual geometry as well as the gradient. For 200 optimization steps gradient-based field simulator would run about 1200 times.

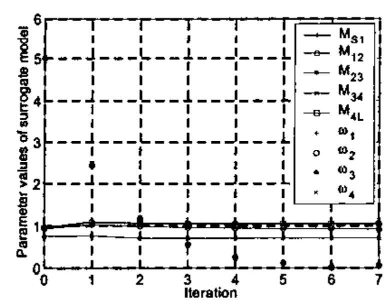

Fig. 5. Parameter changes during optimization.

V. DUAL MODE FILTER

In the previous sections the method was tested for a filter with direct resonator couplings. More complex filter structures like dual-mode filters or filters with cross-couplings can also be optimized with the proposed method, as will be shown next. The filter structure in Fig. 6 was proposed in [5]. It consists of two rectangular waveguide cavities coupled by inductive windows. The cavity on the left side supports two resonant modes, the one on the right side only one.

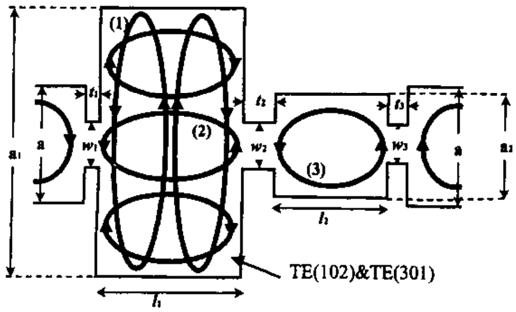

Fig. 6 Dual mode filter [5].

The structure is symmetric. The specifications are f_0=12GHz, BW=500MHz, RL=23dB. It is not possible to synthesize this filter [5]. Therefore a rough guess of the filter dimensions is found (basis position, Fig. 6) and then the structure is optimized. The corresponding non-ideal dimensions are: a_1=43.86mm, a_2=23.78mm, l_1=24.05mm, l_2=12.10mm, w_1=9.05mm, w_2=9.00mm, w_3=7.34mm, t_1=1.50mm, t_2=6.00mm, t_3=0.50mm. It is not obvious from the beginning which coupling coefficients are non-zero. Therefore, the parameter extraction starts with a matrix $[A]$ that includes all coupling coefficients except M_{SL} and M_{12} (both modes in the first cavity are orthogonal and therefore not coupled). As a result, the only non-zero couplings are M_{S1}, M_{S2}, M_{13}, M_{23}, M_{3L}.

Following the procedure described in sections II-IV the filter was optimized in only 2 steps (Fig. 7). After the first step, the sensitivities were updated. Altogether 1 (basis) + 10 (sensitivities) + 1 (step 1) + 10 (additional sensitivities after step 1) + 1 (step 2) = 23 field simulations were necessary. The optimum dimensions are found as a_1=44.01mm, a_2=23.72mm, l_1=23.60mm, l_2=11.56mm, w_1=9.98mm, w_2=9.45mm, w_3=8.35mm, t_1=1.43mm, t_2=6.68mm, t_3=0.63mm. For comparison, using conventional optimization procedures, at least 300 field simulations are necessary to obtain the same result [5].

VI. CONCLUSIONS

A fast filter optimization technique combining an EM simulator with a surrogate model has been described. The method utilizes the EM simulator only to update parameters of the surrogate model and to perform a sensitivity analysis. The optimization is done entirely in

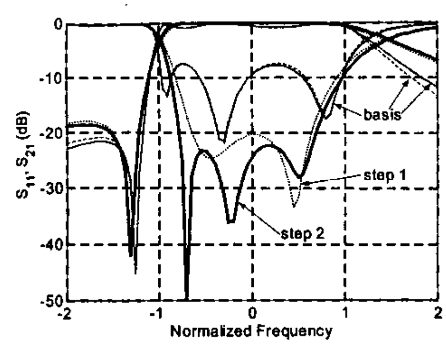

Fig. 7 Optimization of the dual mode filter.

the parameter space of the surrogate model and requires significantly less EM simulator runs than a direct EM simulator-based optimization. The method has been successfully tested with E-plane filters and dual-mode filters.

ACKNOWLEDGMENT

This work was supported by Huber+Suhner AG under a Grant from the Kommission für Technik und Innnovation, (KTI) Government of Switzerland.

REFERENCES

[1] M.H. Bakr, J.W. Bandler, K. Madsen, J.E. Rayas-Sanchez, J. Sondergaard, "Space-mapping optimization of microwave circuits exploiting surrogate models", *IEEE Trans. Microwave Theory Tech.*, vol.48, pp. 2297-2306, Dec. 2000.

[2] S. Amari, "Synthesis of cross-coupled resonator filters using an analytical gradient based optimization technique", *IEEE Trans. Microwave Theory Tech.*, vol.48, pp. 1559-64, Sept. 2000.

[3] P. Harscher, S. Amari and R. Vahldieck, "Automated filter tuning using generalized lowpass prototype networks and gradient-based parameter extraction", *IEEE Trans. Microwave Theory Tech.*, vol.49, pp. 2532-2538, Dec 2001.

[4] R. Vahldieck, J. Bornemann, F. Arndt, and D. Grauerholz, "Optimized waveguide E-plane metal insert filters for millimeter wave applications", *IEEE Trans. Microwave Theory Tech.*, vol. 31, pp. 65-69, Jan. 1983.

[5] M. Guglielmi, O. Roquebrun, P. Jarry, E. Kerherve, M. Capurso, M. Piloni, "Low-cost dual-mode asymmetric filters in rectangular waveguide", *IEEE MTT-S Int. Microwave Symp. Dig.*, vol.3, pp. 1787-90, 2001.