Hybrid EM-Simulator Based Optimization of Microwave and Millimeter Wave Diplexers and Multiplexers

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Abstract — **A hybrid technique for the optimization of microwave diplexers and multiplexers is introduced. The technique is based on a combination of surrogate models with EM simulators. All characteristic model parameters of the initial electromagnetic structure (including the power divider network), as well as their sensitivities, are extracted from an EM-based S-parameter computation of the full structure and are represented by a coupling matrix. The ideal coupling matrix is extracted from the target transfer function representing the multiplexer characteristics. With just $n+1$ electromagnetic field simulations per optimization step new possibilities of design and tuning of multiplexers are given.**

I. Introduction

Diplexers and multiplexers are essential components for channel separation in all communication systems. The demand for compact, low-loss and low-cost multiplexers easy to adapt to various frequencies from the lower microwave band up to the highest millimeter wave frequencies requires a great variety of different filter structures and power dividers. The design of most standard filter structures and their subsequent arrangement to diplexers and multiplexers is typically based on specialized software running very efficiently for the specific configuration they are made for. For non-standard filter and power divider configurations, which may offer much better solutions (fabrication- and performance-wise), general purpose EM simulators are necessary as design tool. Unfortunately, EM simulators are not well suited for optimization of more complex EM structures, because they require significant computational resources just for the analysis of a given structure. In the optimization, hundreds of analysis runs may be necessary leading to excessive computation times.

Several multiplexer synthesis techniques, based on equivalent network representation of the relevant discontinuities, have been presented thus far [1]-[3], [5]. However, once all of the individual parts are connected, they interact and change the transfer characteristics of the individual filters so that an optimization of the overall structure is required.

To avoid direct optimization of the EM structure with an EM simulator this paper introduces a hybrid technique which has been successfully tested in the optimization of stand-alone filters [6]. This method is based on a surrogate model which uses an EM simulator to find the correct values for the model elements. In the following the work in [6] is extended to include several filters and also a power divider network to feed the diplexer/multiplexer.

This approach is new and requires a reformulation of the coupling matrix to include also the power divider network. While the parameters of the surrogate model are

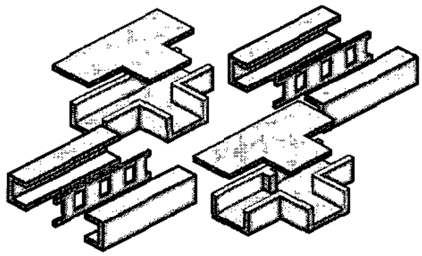

Fig. 1 Millimeter wave diplexer with T-section power divider (with and without compensation nose)

obtained from a single EM simulator run, the sensitivities of the model parameters with respect to geometry parameters are obtained from n additional EM simulator runs, where n denotes the number of geometry elements to be optimized. Thus, to establish an exact model of the EM structure $n+1$ EM simulations are required.

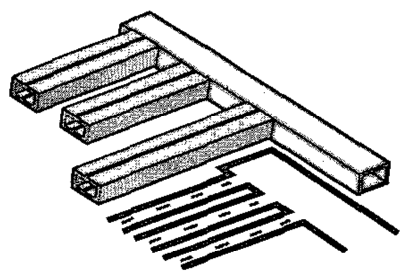

Fig. 2 Millimeter wave triplexer.

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The optimization of the EM structure is then performed in the parameter space of the model which is significantly faster than using the EM simulator directly.

The added difficulty in the optimization of a multiplexer compared to a stand-alone filter stems from the fact that by assembling the individual filters, for example, in a manifold, the mutual interactions between the filters are considerable and must be included in the overall optimization. This requires a formulation of the coupling matrix which is different from that in [6].

In the following a detailed description of this technique will be presented. The standard Mode Matching Technique (MMT) has been utilized as EM simulator but any other EM simulator can be employed as well. In order to proof the concept, the optimization has been performed on two types of E-plane structures illustrated in Fig. 1 and Fig. 2.

II. Parameter Extraction from EM-Simulation

Filter optimization based on an equivalent coupling matrix has been successfully used for tuning and optimization of filters [6]. The model presented in this paper extends the previous work to include also the coupling matrix for multiplexers.

The network topology (Fig. 3) of the diplexer drawn in Fig. 1 consists of an input resonator, with center frequency ω_0, a resistive load R_0 and the two filters represented by the normalized resonances ω_i, coupling coefficients M_{ij} and loads R_j.

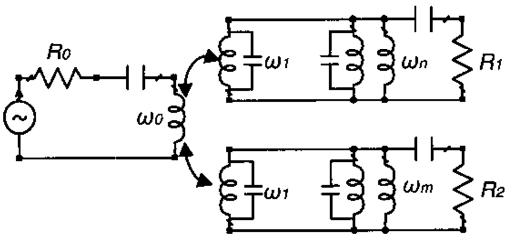

Fig. 3 Network model for the diplexer.

Solving the loop currents of Fig. 3 yields the symbolic coupling matrix $[A]$ in terms of coupling coefficients, resonance frequencies and load impedances of the input and output resonators. The reflection coefficient S_{11} and the transmission coefficient S_{21} and S_{31} can be found:

$$A=\begin{pmatrix} \omega_0-j\cdot R_0 & M_{01} & 0 & \cdots & 0 & M_{0(n+1)} & 0 & \cdots & & 0 \\ M_{01} & \omega_1 & M_{12} & & & 0 & & & & \\ 0 & M_{12} & \omega_2 & & & \vdots & & & & \\ \vdots & & & \ddots & M_{n-1,n} & & & & & \vdots \\ 0 & & & M_{n-1,n} & \omega_n-j\cdot R_1 & 0 & & & & \\ M_{0(n+1)} & & & & & \omega_{n+1} & M_{(n+1)(n+2)} & & & \\ 0 & & & & & M_{(n+1)(n+2)} & \omega_{n+2} & & & 0 \\ \vdots & & & & & & & \ddots & & M_{n+m-1,n+m} \\ 0 & & & \cdots & & & 0 & M_{n+m-1,n+m} & & \omega_{n+m+1}-j\cdot R_2 \end{pmatrix}$$

$$S_{11}=1+2jR_0\left[A^{-1}\right]_{11}$$
$$S_{21}=-2j\sqrt{R_0R_1}\left[A^{-1}\right]_{(n+2),1} \qquad (1)$$
$$S_{31}=-2j\sqrt{R_0R_2}\left[A^{-1}\right]_{(n+m+2),1}$$

For optimum multiplexer performance the filters are positioned at different locations away from the power divider. The resulting phase shift is included in the coupling matrix.

In general, the model parameters for a given EM structure is obtained by minimizing the difference between computed S-parameters of the surrogate model (1) and the simulated filter response using cost function (2):

$$F=\sum_{freq}\sum_{i=1}^{3}\sum_{j=1}^{3}\left[real(S_{ij}^{surrogate})-real(S_{ij}^{simulated})\right]^2-\left[imag(S_{ij}^{surrogate})-imag(S_{ij}^{simulated})\right]^2 \qquad (2)$$

This procedure yields the elements of the coupling matrix of the initial EM structure.

III. Optimization

Before optimizing the model in the parameter space one must calculate the sensitivities of all model parameters with respect to the geometry of the electromagnetic structure.

This is done by changing each geometry parameter an incremental step and repeat procedure (2). Thus, the effects of the geometrical details on all model parameters are properly accounted for. The procedure is as follows:

1. Calculate S-parameters of the filter structure in basis (non-ideal) position using the MMT and extract characteristics parameters: $\omega_i^{basis}, M_{ij}^{basis}, R_i^{basis}$.
2. Change first geometry parameter $x_i+\Delta x_i$ and repeat step 1) $\rightarrow \omega_i^{x_i+\Delta x_i}, M_{ij}^{x_i+\Delta x_i}$
3. Repeat step 2) for all other relevant geometry parameters to obtain $x_1, x_2, \ldots, x_{nr}$ of the structure
4. Calculate:

$$\omega_i^{surrogate}\left(x_1\ldots x_{nr}\right)=\omega_i^{basis}+\sum_{k=1}^{nr}\underbrace{\frac{\omega_i^k-\omega_i^{basis}}{\Delta x^k}}_{\partial\omega_i^{surrogate}/\partial x_k}x_k \qquad (3)$$

$$M_{ij}^{surrogate}\left(x_1\ldots x_{nr}\right)=M_{ij}^{basis}+\sum_{k=1}^{n}\underbrace{\frac{M_{ij}^k-M_{ij}^{basis}}{\Delta x^k}}_{\partial M_{ij}^{surrogate}/\partial x_k}x_k \qquad (4)$$

$$R_i^{surrogate}\left(x_1\ldots x_{nr}\right)=R_i^{basis}+\sum_{k=1}^{nr}\underbrace{\frac{R_i^k-R_i^{basis}}{\Delta x^k}}_{\partial R_i^{surrogate}/\partial x_k}x_k \qquad (5)$$

To optimize the EM structure, a target transfer function must be defined. In order to cast this function into a coupling matrix with realistic (realizable) matrix elements, the target is expressed on the basis of two (diplexer) or m (multiplexer) Chebychev functions with appropriate guard bands. The model parameters for this target function are again obtained from (2) by replacing $realS^{simulated}$ and $imagS^{simulated}$ with the absolute value of the S-parameters from the target model.

The objective of the optimization is to minimize the difference between the target parameters and the parameters of the non-optimum response. This optimization is done entirely in the parameter space of the surrogate model using a new cost function (6):

$$F = \sum_{i=0}^{n+m+1}\left(\omega_i^{surrogate}(x_1 ... x_{nr}) - \omega_i^{ideal}\right)^2 + \sum_{i=0}^{n+m}\sum_{j=0}^{n+m}\left(M_{ij}^{surrogate}(x_1 ... x_{nr}) - M_{ij}^{ideal}\right)^2 + \sum_{i=0}^{2}\left(R_i^{surrogate}(x_1 ... x_{nr}) - R_i^{ideal}\right)^2 \qquad (6)$$

Often the parameters of the surrogate model show a nonlinear behavior with respect to the geometry parameters, requiring that the optimization be done in several steps.

IV. RESULTS

To illustrate this technique, a diplexer with direct-coupled E-plane metal-insert filters and H-plane T-section power divider with and without compensation by a metal slab is used first. The compensation nose is included in the full-wave optimization and helps to improve the isolation between the channels, but leads to a more complicated practical realization.

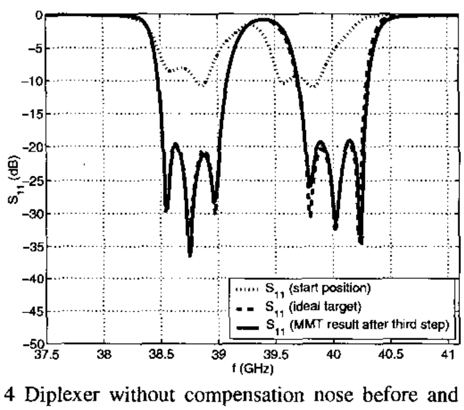

Fig. 4 Diplexer without compensation nose before and after optimization.

The Fig. 4 illustrates the optimization procedure for a Ka-band diplexer with compensation nose. The 3-resonator filters are embedded in Q band waveguide sections for better stopband attenuation. Three optimization steps are required to reach the proposed target of $RL = 20dB$. The number of relevant geometrical parameters is $nr = 16$. A total of 17 field simulations are required per optimization step, which, in comparison to a gradient-based optimizer directly applied to a field simulator, is significantly less. For the diplexer with a compensation nose 3 more geometrical parameters are subject to optimization. In this case the target of $RL = 20dB$ is reached in just 2 optimization steps.

For the initial design in Fig.4 only the return loss needed to be optimized. If the initial design produces also a frequency shift, the optimization procedure performs just as well. This is illustrated in Fig.5 where the initial design of the diplexer with compensation nose was shifted $250MHz$ away from the target response. After only one optimization run (with 20 EM simulations), the return loss is better than $15dB$ and both filter responses are within the target frequency window.

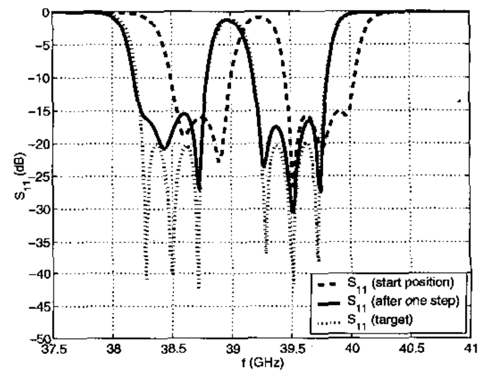

Fig. 5 Diplexer with compensation nose and frequency shift of $250MHz$ before and after one step of optimization.

The optimization procedure can easily be extended to triplexer and multiplexer applications. This is illustrated by using the example of a manifold structure and (Fig.2.) three direct-coupled E-plane filters. All three filters are initially designed separately and then connected to the manifold structure. The resulting interaction between the filters makes a re-optimization necessary, which follows the same procedure as for the diplexer, but with an accordingly expanded model coupling matrix.

The target function for the triplexer (Fig. 6) is specified as follows:

$$f_1 = 36.775GHz, f_2 = 37.775GHz, f_3 = 38.775GHz,$$
$$BW = 500MHz \; and \; RL = 20dB$$

The MMT technique used for the field simulations of the sensitivity analysis takes in account 50 modes and describes accurately the behavior of the manifold multiplexer [4].

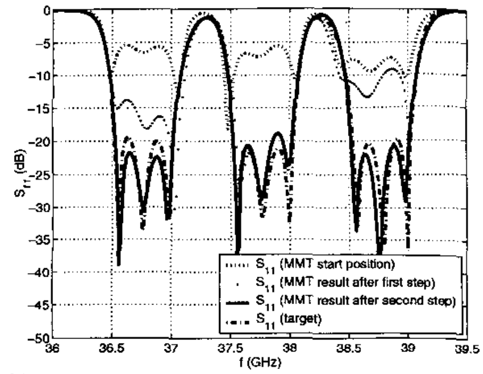

Fig. 6 Triplexer with the manifold structure of Fig.2 before and after optimization.

For every optimization step 27 field simulations are necessary to extract the sensitivities of the relevant geometrical parameters. Fig. 6 and Fig. 7 show that only 2 optimization steps are needed to match the target function. Fig. 7 shows the insertion loss of the triplexer for the initial design and after two optimization steps.

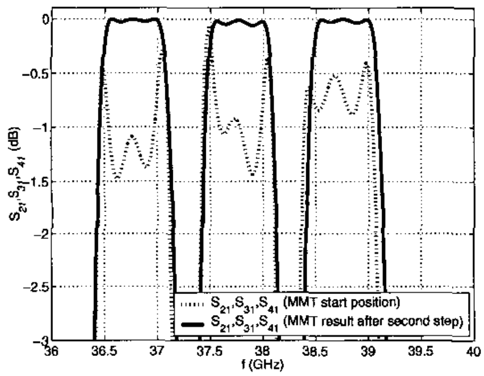

Fig. 7 S_{21}, S_{31}, S_{41} of the optimized triplexer.

The ability to adjust the frequency shift of the initial design after combining the separate filters, as well as the capability of optimizing to a different central frequency without redesigning the filters individually, is shown in the Fig. 8. With just 2 optimization steps the target return loss and a $250MHz-500MHz$ shift of the central frequencies was compensated.

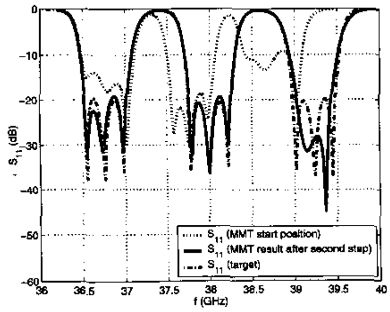

Fig. 8 Shifting capability optimizing the triplexer.

V. CONCLUSIONS

A fast hybrid optimization technique based on a combination of EM simulators with surrogate models has been presented. The method has been tested successfully in the design of diplexers and multiplexers. The EM simulator is only used to determine the model sensitivities and to update the model parameters after optimization in the parameter space of the surrogate model. This reduces the number of EM simulator runs significantly and makes the new approach very attractive for the optimization of complex electromagnetic structures.

ACKNOWLEDGMENT

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