MINIMAX MICROSTRIP FILTER DESIGN USING DIRECT EM FIELD SIMULATION

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ABSTRACT

For the first time we present minimax filter design with electromagnetic simulations driven directly by a gradient based optimizer. Challenges of efficiency, discretization of geometrical dimensions, and continuity of optimization variables are reconciled by a three stage attack: (1) efficient response interpolation, (2) smooth gradient estimation, and (3) dynamic data base updating. Design optimization of two microstrip filters illustrates our technique.

INTRODUCTION

We present results of microwave filter design with accurate electromagnetic simulations (EM) driven by a minimax gradient based optimizer. We exploit recent advances [1-5] in EM simulation which give the designer the opportunity to accurately simulate passive circuit components, in particular microstrip structures [2]. However, we go far beyond the prevailing use of stand alone EM simulators, namely, validation of designs obtained through less accurate techniques.

EM simulators, though computationally intensive, are regarded as accurate at microwave frequencies, extending the validity of models to higher frequencies, including millimeter-wave frequencies, and cover wider parameter ranges [2]. The EM simulators, whether stand-alone or incorporated into software frameworks, will not realize their full potential to the designer (whose task is to come up with the best parameter values satisfying design specifications) unless they are optimizer-driven to automatically adjust designable parameters.

Design optimization tools are widely available (e.g., [6]), typically in conjunction with analytical, heuristic models of microstrip structures developed in recent years. Consequently, designers, using such tools, try to generate designs in the form of either equivalent circuits, or physical parameters based on approximate models [7]. Using an EM simulator, designers currently validate and improve their designs by manual adjustments. The need for direct design optimization with accurate field simulation is clear.

The feasibility of optimizing passive structures using EM simulation has already been shown by Jansen *et al.* [3,4]. Our paper addresses several challenges arising when EM simulations are to be put directly into the optimization loop. We consider the advantages of on-line EM simulations (performed on request) as opposed to up-front simulations, as in Jansen's look-up table approach. The requirement of circuit responses for continuously varying optimization variables must be reconciled with inherent discretization of geometrical parameters present in EM simulation. Finally, the requirement of providing the optimizer with smooth and accurate gradient information must be given serious attention. We effectively deal with all these problems, contributing a new dimension to this subject.

Design of two microstrip filters illustrates our technique.

MINIMAX DESIGN OPTIMIZATION

Frequency domain design of microwave filters involves design specifications the responses (S parameters, return loss, insertion loss, etc.). In order to formulate an objective function for design optimization the filter is simulated at a given point (vector) of designable (optimization) variables $\boldsymbol{\phi}$ and at the same frequency points at which the upper (S_{uj}) and/or lower ($S_{\ell j}$) specifications are selected. The corresponding responses, denoted by $R_j(\boldsymbol{\phi})$, determine the error vector $\boldsymbol{e}(\boldsymbol{\phi})$ as

$$\boldsymbol{e}(\boldsymbol{\phi}) = [e_1(\boldsymbol{\phi}) \;\; e_2(\boldsymbol{\phi}) \; \ldots \; e_M(\boldsymbol{\phi})]^T \tag{1}$$

where the individual errors $e_j(\boldsymbol{\phi})$ are of the form

$$e_j(\boldsymbol{\phi}) = R_j(\boldsymbol{\phi}) - S_{uj} \quad \text{or} \quad e_j(\boldsymbol{\phi}) = S_{\ell j} - R_j(\boldsymbol{\phi}) \tag{2}$$

and M is the total number of errors. A negative error value indicates that the corresponding specification is satisfied. For positive error values the corresponding specifications are violated. All the errors $e_j(\boldsymbol{\phi})$ are combined into a single objective function to be minimized. Minimax design optimization is defined as

$$\underset{\boldsymbol{\phi}}{\text{minimize}} \; \{ \max_{j} \; (e_j(\boldsymbol{\phi})) \} \tag{3}$$

Effective minimax optimization requires a dedicated optimizer, such as [8], and accurate gradients of individual errors w.r.t. the optimization variables $\boldsymbol{\phi}$.

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GEOMETRICAL INTERPOLATION

The vector $\boldsymbol{\psi}$ of all geometrical parameters (structure lengths, widths, spacings, etc.) can be written as

$$\boldsymbol{\psi} = [\boldsymbol{\psi}_{opt}^T(\boldsymbol{\phi}) \quad \boldsymbol{\psi}_{fix}^T]^T \tag{4}$$

where the vector $\boldsymbol{\psi}_{opt}(\boldsymbol{\phi})$ contains designable geometrical parameters which are either directly the optimization variables or are functions of the optimization variables $\boldsymbol{\phi}$, and the vector $\boldsymbol{\psi}_{fix}$ contains fixed geometrical parameters. It is important to realize that each component of $\boldsymbol{\psi}$ belongs to one of the three physical orientations (x, y, or z) and, therefore, the vector $\boldsymbol{\psi}$ can be rearranged as

$$\boldsymbol{\psi} = [\boldsymbol{\psi}^{xT} \quad \boldsymbol{\psi}^{yT} \quad \boldsymbol{\psi}^{zT}]^T \tag{5}$$

Numerical EM simulation is performed for discretized values of geometrical parameters $\boldsymbol{\psi}$. Let the discretization matrix $\boldsymbol{\delta}$ be defined by the grid sizes Δx_i, Δy_i and Δz_i as

$$\boldsymbol{\delta} = \mathrm{diag}\{\delta_i\} = \mathrm{diag}\{\Delta x_1, \Delta x_2, ..., \Delta y_1, \Delta y_2, ..., \Delta z_1, \Delta z_2, ...\} \tag{6}$$

A specific EM simulator may allow only one grid size for each orientation while others may provide the flexibility of independent Δx_i, Δy_i and Δz_i for different parameters of the same x, y, or z orientation. For uniform discretization in each direction $\Delta x_i = \Delta x$, $\Delta y_i = \Delta y$ and $\Delta z_i = \Delta z$.

If the point is off-the-grid we use interpolation to determine each response $R(\boldsymbol{\psi})$. A set of grid points in the space of geometrical parameters is chosen as the *interpolation base* $\boldsymbol{B}$. It is defined by the *centre base point* $\boldsymbol{\psi}^c$ and a *relative interpolation base* $\boldsymbol{B}^\eta$ which is a set of selected integer vectors. While the centre point may move during optimization the relative interpolation base is fixed. The relative deviation of $\boldsymbol{\psi}$ from the centre base point, $\boldsymbol{\theta}$, is defined by the equation $\boldsymbol{\psi} = \boldsymbol{\psi}^c + \boldsymbol{\delta\theta}$. The interpolation base is used as the set of *base points* $\boldsymbol{\psi}^c$ and $\boldsymbol{\psi}^{bj}$ at which EM simulation is invoked to evaluate the corresponding responses.

The interpolating function is devised such that it passes through the exact response values at the base points and can be evaluated as

$$R(\boldsymbol{\psi}) = R_{EM}(\boldsymbol{\psi}^c) + \boldsymbol{f}^T(\boldsymbol{\delta\theta})\, \boldsymbol{F}^{-1}(\boldsymbol{S\delta}, \boldsymbol{B}^\eta)\, \Delta \boldsymbol{R}_{EM}(\boldsymbol{B}) \tag{7}$$

where $\boldsymbol{f}(\boldsymbol{\delta\theta})$ is the vector of *fundamental interpolating functions* and $\Delta \boldsymbol{R}_{EM}(\boldsymbol{B})$ is the matrix of response deviations at the base points: $\Delta R_{EM}(\boldsymbol{\psi}^{bj}) = R_{EM}(\boldsymbol{\psi}^{bj}) - R_{EM}(\boldsymbol{\psi}^c)$. The matrix $\boldsymbol{F}^{-1}(\boldsymbol{S\delta}, \boldsymbol{B}^\eta)$ depends only on the selection of the fundamental interpolating functions and the relative interpolation base $\boldsymbol{B}^\eta$ and can be determined prior to all calculations. $\boldsymbol{S}$ is the symmetry matrix accounting for double grid size increments for parameters whose dimensions are modified by extending or contracting both ends simultaneously.

GRADIENT ESTIMATION

To facilitate the use of an efficient and robust dedicated gradient minimax optimizer we need to provide the gradients of the errors (2), or the gradients of $R_j(\boldsymbol{\phi})$. From (4) we determine

$$\nabla_{\boldsymbol{\phi}} R_j(\boldsymbol{\phi}) = \nabla_{\boldsymbol{\phi}} \boldsymbol{\psi}^T(\boldsymbol{\phi})\, \nabla_{\boldsymbol{\psi}} R(\boldsymbol{\psi}) \tag{8}$$

The first factor on the right hand side of (8) is readily available since the mapping (4), as an integral part of the problem formulation, is known. The second factor on the right hand side of (8) must be determined using EM simulations.

During optimization it is very likely that the gradient will be requested at off-the-grid points. As discussed in the preceding section the responses at off-the-grid points are determined by interpolation. It is, therefore, most appropriate from the optimizer's point of view to provide the gradient of the interpolating function, i.e., the function that is actually returned to the optimizer. This is fortunate since that gradient can be analytically derived from the fundamental interpolating functions. From (7) we get

$$\nabla_{\boldsymbol{\psi}} R(\boldsymbol{\psi}) = \nabla_{\boldsymbol{\delta\theta}} \boldsymbol{f}^T(\boldsymbol{\delta\theta})\, \boldsymbol{F}^{-1}(\boldsymbol{S\delta}, \boldsymbol{B}^\eta)\, \Delta \boldsymbol{R}(\boldsymbol{B}) \tag{9}$$

Equation (9) gives accurate gradient information for the optimizer in a simple, straightforward and efficient manner. Note that $\boldsymbol{F}^{-1}(\boldsymbol{S\delta}, \boldsymbol{B}^\eta)$ and $\Delta \boldsymbol{R}(\boldsymbol{B})$ are already available from response interpolation.

UPDATING DATA BASE OF SIMULATED RESULTS

EM field simulation, though more and more practical, is still quite expensive. In order to efficiently utilize the results of EM simulations and to reduce their number we have considered two levels of control. First, interpolation is invoked only when necessary, i.e., if a specific θ_i is zero we exclude the corresponding base point from the interpolation base. To be able to implement such a scheme the fundamental interpolating functions must be appropriately devised. Secondly, a data base D of base points and the corresponding responses obtained from exact EM simulations is stored and accessed when necessary (see Fig. 1). Each time EM simulation is requested the corresponding interpolation base B is generated and checked against the existing data base. Actual EM simulation is invoked only for the base points not present in the data base (B - D). Results for the base points already present in the data base ($B \cap D$) are simply retrieved from D and used for interpolation.

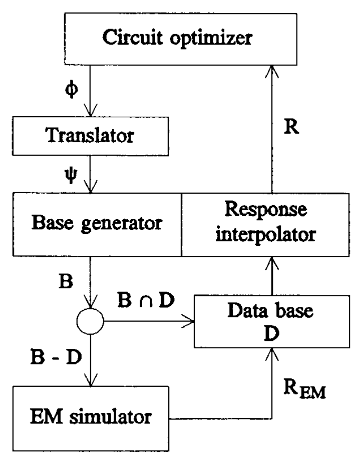


Fig. 1. Flow diagram illustrating the interconnection between a circuit optimizer and a numerical EM simulator.

Updating the data base D is a separate issue. Between the two extremes: (1) all simulated results are saved, and (2) only results for the latest interpolation base are saved, many schemes can be adopted depending on such factors as required memory, access time, repeated simulations, etc. In any case, it is worthwhile to remember the current (active) interpolation base.

DESIGN OF DOUBLE FOLDED MICROSTRIP STRUCTURE

A double folded stub microstrip structure for band-stop filter applications, shown in Fig. 2, may substantially reduce the filter area while achieving the same goal as the conventional double stub structure shown in Fig. 3 [9]. The symmetrical double folded stub can be described by 4 parameters: width, spacing and two lengths W, S, L_1 and L_2, as marked in Fig. 2.

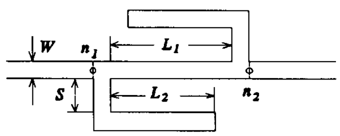


Fig. 2. Double folded stub microstrip structure for band-stop filter applications.

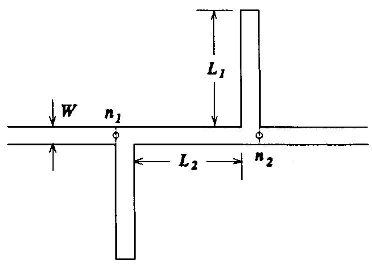


Fig. 3. Double stub microstrip structure.

We used minimax optimization, with W fixed at 4.8 mils and L_1, L_2 and S as variables, to move the center frequency of the stop band from 15 GHz to 13 GHz starting from the values given by [9]. Design specifications were taken as

$$|S_{21}| > -3 \text{ dB} \quad \text{for } f < 9.5 \text{ GHz and } f > 16.5 \text{ GHz}$$

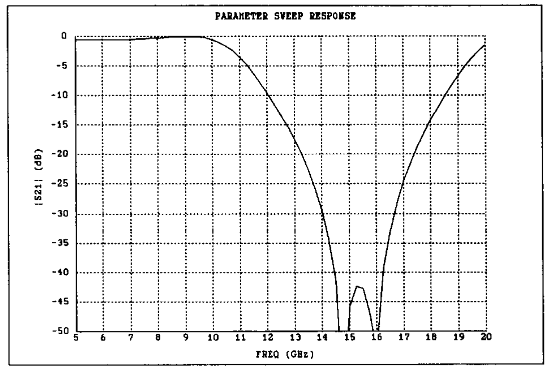
$$|S_{21}| < -30 \text{ dB} \quad \text{for } 12 \text{ GHz} < f < 14 \text{ GHz}$$

The substrate thickness and the relative dielectric constant were 5 mils and 9.9, respectively.

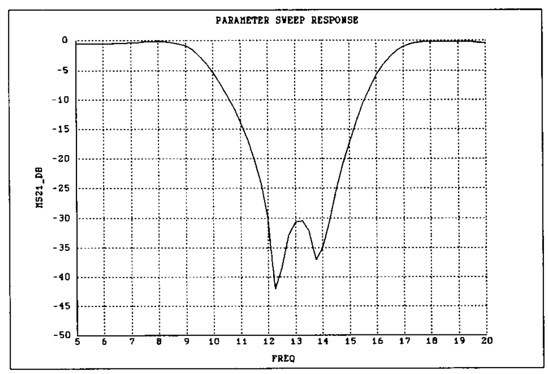
Using OSA90/hope™ [10] and ***em***™ [5] interfaced through Empipe™ [11], optimization was carried out in two steps. First, we applied identical $\Delta x = \Delta y = 2.4$ mils grid size in both x and y directions. Then the grid size was reduced to $\Delta x = \Delta y = 1.6$ mils for fine resolution. The optimization variables before and after optimization are listed in Table I. Fig. 4 shows the magnitude of S_{21} vs. frequency before and after optimization.

TABLE I
PARAMETER VALUES FOR THE DOUBLE FOLDED STUB BEFORE AND AFTER OPTIMIZATION

Parameter	Before optimization (mil)	After optimization (mil)
L_1	74.0	91.82
L_2	62.0	84.71
S	13.0	4.80



(a)



(b)

Fig. 4. Double folded stub band-stop filter structure simulation: (a) before optimization, and (b) after optimization.

DESIGN OF AN INTERDIGITAL MICROSTRIP FILTER

A 26-40 GHz millimeter-wave bandpass filter [12] was built on a 10 mils thick substrate with relative dielectric constant of 2.25. The filter, shown in Fig. 5, utilized thin microstrip lines and interdigital capacitors to realize inductances and capacitances of a synthesized lumped ladder circuit. The filter was designed to satisfy the specifications

$$|S_{11}| < -20 \text{ dB} \quad \text{and} \quad |S_{21}| > -0.04 \text{ dB}$$

for 26 GHz < f < 40 GHz. The original microstrip design was determined by matching the lumped prototype at the center frequency using ***em*** [5]. However, when the filter was simulated by ***em*** in the whole frequency range the results exhibited significant discrepancies w.r.t. the prototype. It necessitated manual adjustment and made a satisfactory design very difficult to achieve. The filter was then built and measured.

As for the double folded microstrip structure, design of the interdigital filter was carried out using ***em*** [5] driven by the minimax gradient optimizer of OSA90/hope [10] through Empipe [11]. There was a total of 13 designable parameters including the distance between the patches L_1, the finger length L_2 and two patch widths W_1 and W_2 for each of the three interdigital capacitors, and the length L of the end capacitor, as shown in Fig. 5. The transmission lines between the capacitors were fixed at the originally designed values. The second half of the circuit, to the right of the plane of symmetry, is assumed identical to the first half, so it contains no additional variables.

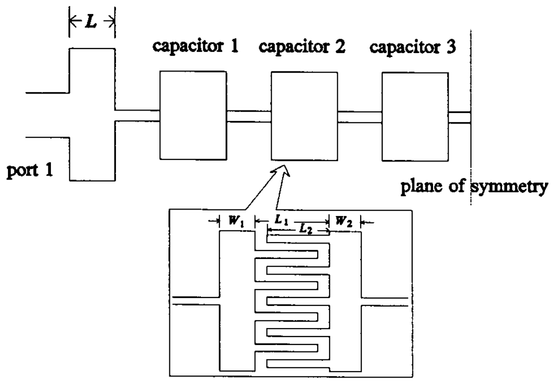


Fig. 5. 26-40 GHz interdigital capacitor filter. The dielectric constant is 2.25. Substrate thickness and shielding height are 10 and 120 mils, respectively. The optimization variables include L_1, L_2, W_1, W_2 for each of the three capacitors, and L for the end capacitor, totalling 13.

A typical minimax equal-ripple response of the filter was achieved after a series of consecutive optimizations with different subsets of optimization variables and frequency points. The resulting geometrical dimensions were finally rounded to 0.1 mil resolution. Fig. 6 shows the simulated filter response after optimization.

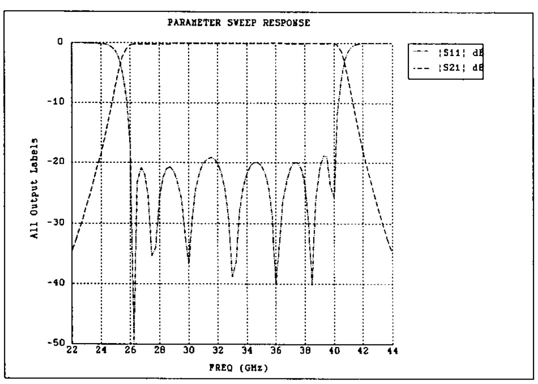


Fig. 6. 26-40 GHz interdigital capacitor filter simulation after optimization. All the optimization variables have been rounded to 0.1 mil resolution.

CONCLUSIONS

For the first time we have presented a comprehensive approach to microwave filter design which exploits accurate field simulations driven directly by a gradient based minimax optimizer. The benefits of electromagnetic simulations are thus significantly extended. Our approach, illustrated by minimax design of two filters, paves the way for direct use of field theory based simulation in practical optimization-driven microwave circuit design.

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