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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 in reconciling discretization of geometrical dimensions with continuity of optimization variables are addressed by a three stage attack: (1) efficient response interpolation, (2) smooth gradient estimation, and (3) dynamic data base updating. Simulation of a microstrip structure and design of two filters illustrate our technique.

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SUMMARY

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 and go beyond the prevailing use of stand alone EM simulators, namely, validation of designs obtained through less accurate techniques.

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.

This paper addresses several challenges arising when EM simulations are to be put directly into the optimization loop. We consider here the advantages of on-line EM simulations (performed on request) as opposed to up-front simulations, as in Jansen's look-up table approach [3,4]. 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.

Minimax Design Optimization

Frequency domain design of microwave filters involves upper (S_{uj}) and/or lower ($S_{\ell j}$) design specifications on the responses $R_j(\boldsymbol{\phi})$. Minimax design optimization is defined as

$$\underset{\boldsymbol{\phi}}{\text{minimize}} \; \{ \; \underset{j}{\max} \; (e_j(\boldsymbol{\phi})) \; \} \tag{1}$$

where $\boldsymbol{\phi}$ is a given vector of designable variables and the error functions $e_j(\boldsymbol{\phi})$ are determined by deviation of the responses w.r.t. design specifications at the same frequency points at which the specifications are selected. Effective minimax optimization requires a dedicated optimizer, such as [8], and accurate gradients of individual errors w.r.t. the optimization variables $\boldsymbol{\phi}$.

Geometrical Interpolation

The geometrical parameters $\boldsymbol{\psi}$ of a microstrip structure may depend on the optimization variables $\boldsymbol{\phi}$, either directly or indirectly.

Numerical EM simulation is performed for discretized values of $\boldsymbol{\psi}$. The grid is defined by the discretization matrix $\boldsymbol{\delta}$. 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 B*. It is defined by the *centre base point* $\boldsymbol{\psi}^c$ and a *relative interpolation base* B^η 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, denoted by $\boldsymbol{\theta}$, 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. It will be shown in the full paper that

$$R(\boldsymbol{\psi}) = R_{EM}(\boldsymbol{\psi}^c) + \boldsymbol{f}^{\mathrm{T}}(\boldsymbol{\delta\theta})\ \boldsymbol{F}^{-1}(\boldsymbol{S\delta},\ B^\eta)\ \Delta\boldsymbol{R}_{EM}(B) \tag{2}$$

where $\boldsymbol{f}(\boldsymbol{\delta\theta})$ is the vector of *fundamental interpolating functions* and $\Delta\boldsymbol{R}_{EM}(B)$ 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 $\boldsymbol{F}^{-1}(\boldsymbol{S\delta},\ B^\eta)$ depends only on the selection of the fundamental interpolating functions and the relative interpolation base B^η 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 a gradient minimax optimizer we need to provide the gradients of the responses $R_j(\boldsymbol{\phi})$. It will be shown in the full paper that the gradient of the functions actually returned to the optimizer can be expressed as

$$\nabla_{\phi} R_j(\boldsymbol{\phi}) = \nabla_{\phi}\boldsymbol{\psi}^{\mathrm{T}}(\boldsymbol{\phi})\ \nabla_{\delta\theta}\boldsymbol{f}^{\mathrm{T}}(\boldsymbol{\delta\theta})\ \boldsymbol{F}^{-1}(\boldsymbol{S\delta},\ B^\eta)\ \Delta\boldsymbol{R}_{EM}(B) \tag{3}$$

In evaluating (3), $\boldsymbol{F}^{-1}(\boldsymbol{S\delta},\ B^\eta)$ and $\Delta\boldsymbol{R}_{EM}(B)$ are already available from response interpolation.

Updating Data Base of Simulated Results

EM simulation is still quite expensive. In order to efficiently utilize EM simulations and to reduce their number 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.

Design of Double Folded Microstrip Structure

A double folded stub microstrip structure shown in Fig. 2 may substantially reduce the filter area while achieving the same goal as the conventional design shown in Fig. 3 [11]. The structure is described by 4 parameters marked in Fig. 2.

We used minimax optimization, with L_1, L_2 and S selected as variables and W fixed at 4.8 mils, to move the center frequency of the stop band from 15 GHz to 13 GHz starting from the values given by [11]. Design specifications were taken as

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

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

Optimization was carried out in two steps. The values of the optimization variables before and after optimization are reported in Table I. Figs. 4(a) and 4(b) show the magnitude of S_{21} before and after optimization, respectively.

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 following 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.

We carried out design of the filter using ***em*** driven directly by a minimax gradient optimizer. A typical equal-ripple response of the filter was achieved after a series of consecutive optimizations with different subsets of optimization variables and frequency points. Fig. 6 shows the simulated filter response after optimization. The full paper will also contain the measured response for the filter realized according to this design.

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 EM simulations are thus significantly extended. Our approach, illustrated by minimax design of two filters, paves the way for direct use of EM simulation in practical optimization-driven microwave circuit design.

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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

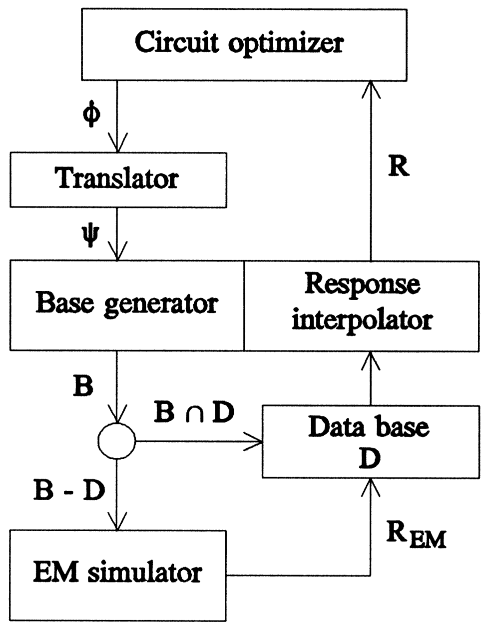


Fig. 1. Flow diagram illustrating the interconnection between a circuit optimizer and a numerical EM simulator.

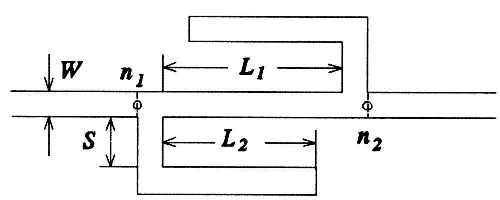


Fig. 2. Double folded stub microstrip structure for band-stop filter applications.

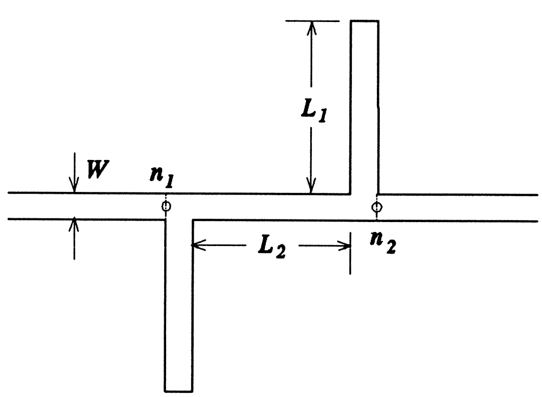
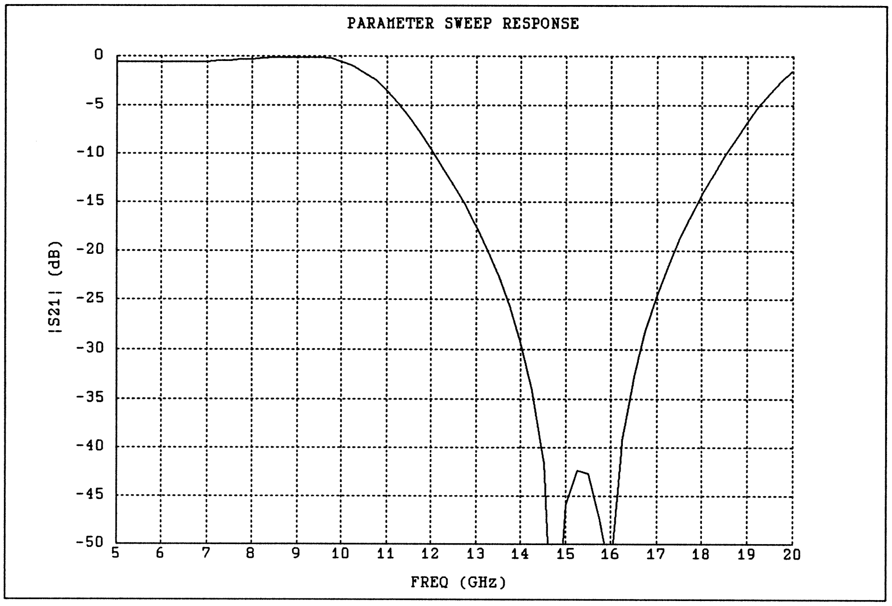
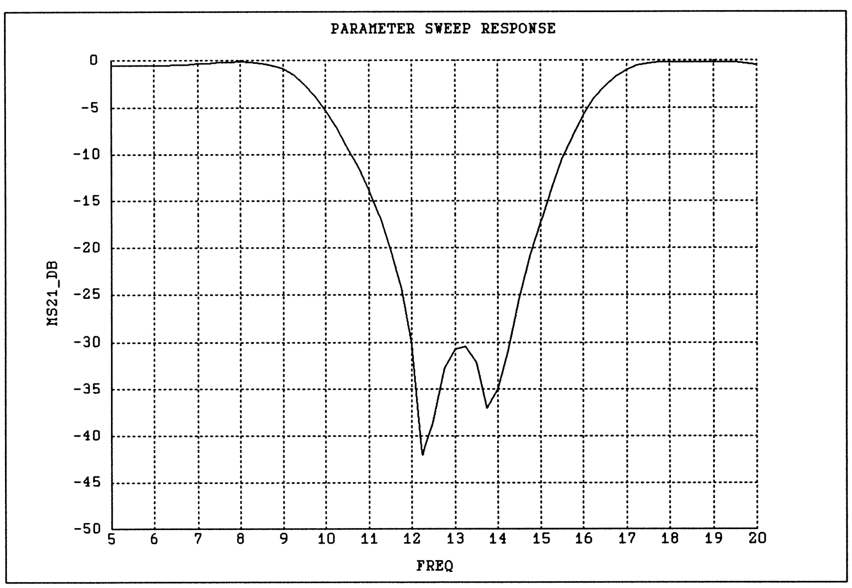


Fig. 3. Double stub microstrip structure.



(a)



(b)

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

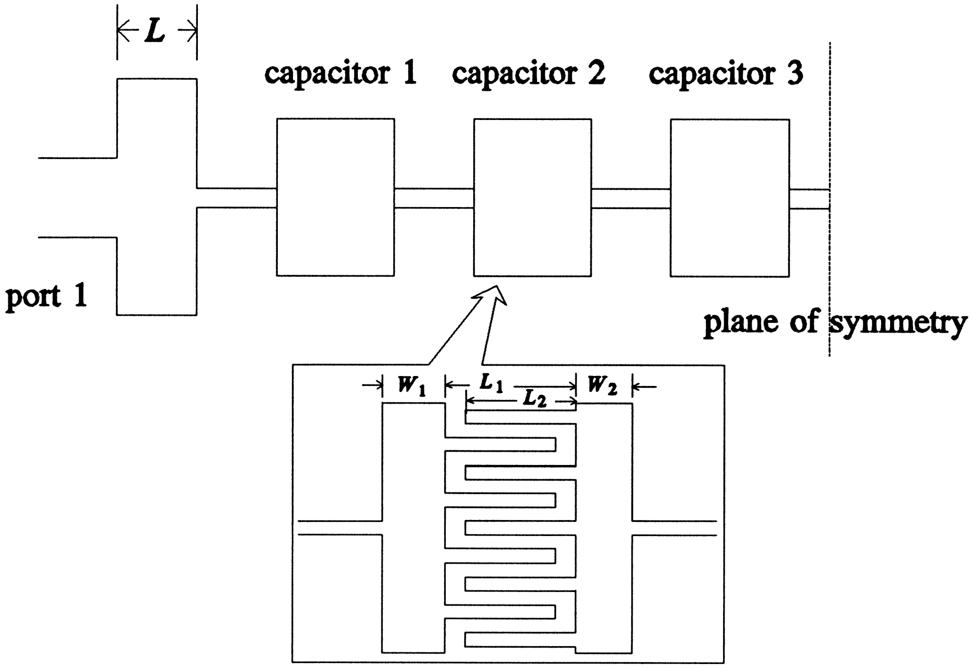


Fig. 5. 26-40 GHz interdigital capacitor filter. Substrate thickness, dielectric constant and shielding height are 10, 2.25 and 120 mils, respectively. The optimization variables include L, L_1, L_2, W_1 and W_2, totalling 13.

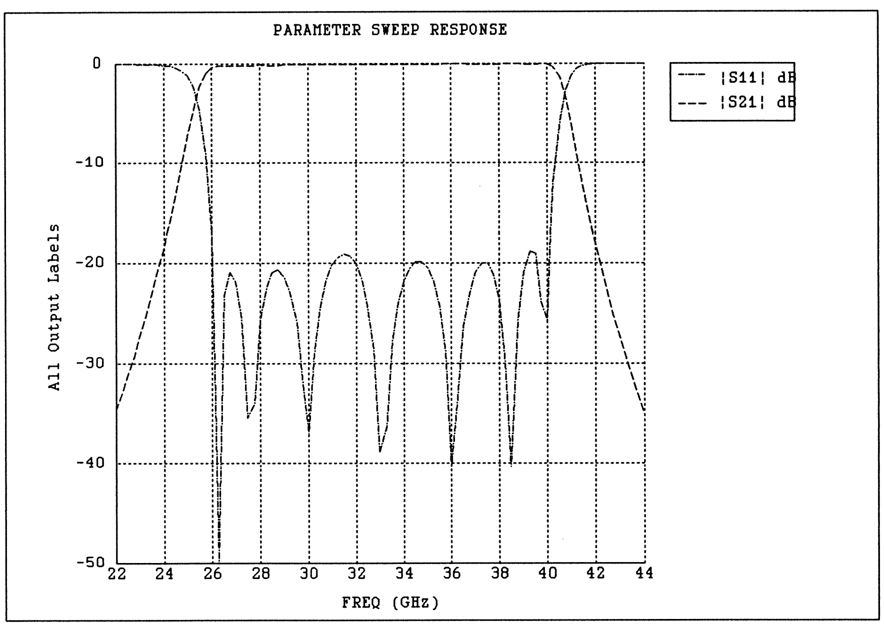


Fig. 6. 26-40 GHz interdigital capacitor filter simulation after optimization. All the optimization variables have been rounded to 0.1mil resolution.