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 exploit recent advances in EM simulation which give the designer the opportunity to accurately simulate passive circuit components, in particular microstrip structures

we go beyond the prevailing use of EM simulators, namely, validation of designs

EM simulators are regarded as accurate at microwave frequencies, extending the validity of models to higher frequencies, and cover wider parameter ranges

EM simulators will not realize their full potential to the designer unless they are optimizer-driven

this paper addresses several challenges arising when EM simulations are to be put directly into the optimization loop

- advantages of on-line EM simulations (performed on request) as opposed to up-front simulations

- continuity of optimization variables to be reconciled with inherent discretization of geometrical parameters

- providing the optimizer with smooth and accurate gradient information

minimax design of two microstrip filters illustrates our technique

Minimax Design Optimization

$$\underset{\phi}{\text{minimize}} \; \{ \; \underset{j}{\max} \, (e_j(\phi)) \; \}$$

where

ϕ the vector of optimization variables

$R_j(\phi)$ j=1,2,.. - the circuit responses (S parameters, return loss, insertion loss, etc.)

S_{uj}, $S_{\ell j}$ upper/lower specification on $R_j(\phi)$

the individual errors $e_j(\phi)$ are of the form

$$e_j(\phi) = R_j(\phi) - S_{uj}$$

or

$$e_j(\phi) = S_{\ell j} - R_j(\phi)$$

negative/positive error value indicates that the corresponding specification is satisfied/violated

effective minimax optimization requires a dedicated optimizer and accurate gradients of individual errors w.r.t. the optimization variables ϕ

Geometrical Parameters

the vector ψ of all geometrical parameters (structure lengths, widths, spacings, etc.) can be written as

$$\psi = [\psi_{opt}{}^T(\phi) \quad \psi_{fix}{}^T]^T$$

where

$\psi_{opt}(\phi)$ designable geometrical parameters which are either directly the optimization variables or are functions of the optimization variables ϕ

ψ_{fix} fixed geometrical parameters

each component of ψ belongs to one of the three physical orientations (x, y, or z) and the vector ψ can be rearranged as

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

numerical EM simulation is performed for discretized values of geometrical parameters ψ

the discretization matrix δ is defined by the grid sizes Δx_i, Δy_i and Δz_i as

$$\delta = \text{diag}\{\delta_i\} = \text{diag}\{\Delta x_1, \Delta x_2, ..., \Delta y_1, \Delta y_2, ..., \Delta z_1, \Delta z_2, ...\}$$

Interpolation Base

if the point is off-the-grid we use interpolation to determine each response $R(\psi)$

the interpolation base B is defined as a set of grid points in the space of geometrical parameters

$$B = \{\psi^c\} \cup \{\psi \mid \psi = \psi^c + S\,\delta\,\eta,\ \ \eta \in B^{\eta}\}$$

where

ψ^c	the centre base point
B^{η}	the relative interpolation base (a set of selected integer vectors)
S	the symmetry matrix accounting for double grid size increments for parameters whose dimensions are modified by extending or contracting both ends simultaneously

while the centre point may move during optimization the relative interpolation base is fixed

the interpolation base is used as the set of *base points* ψ^c and ψ^{bj} at which EM simulation is invoked to evaluate the corresponding responses

Geometrical Interpolation

the relative deviation θ of ψ from the centre base point ψ^c is defined by the equation

$$\psi = \psi^c + \delta\theta$$

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

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

where

$f(\delta\theta)$ — the vector of fundamental interpolating functions

$\Delta R_{EM}(B)$ — the vector of response deviations at the base points:

$$\Delta R_{EM}(\psi^{bj}) = R_{EM}(\psi^{bj}) - R_{EM}(\psi^c)$$

the matrix $F^{-1}(S\delta, B^\eta)$ 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

Gradient Estimation

facilitates the use of an efficient and robust dedicated gradient minimax optimizer

we need to provide the gradients of the error functions

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

the first factor is readily available

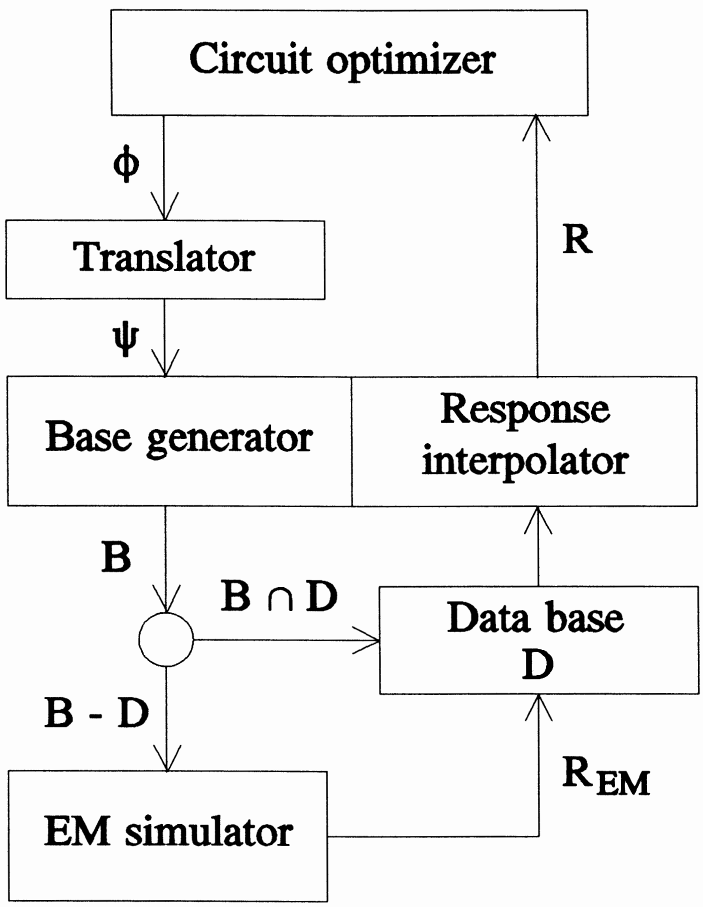
the second factor must be determined using EM simulations; it is most appropriate from the optimizer's point of view to provide the gradient of the interpolating function, i.e., the function that is actually returned to the optimizer

$$\nabla_{\psi} R(\psi) = \nabla_{\delta\theta} f^T(\delta\theta)\, F^{-1}(S\delta, B^{\eta})\, R_{EM}(\psi^c)$$

this gives accurate gradient information for the optimizer in a simple, straightforward and efficient manner

note that $F^{-1}(S\delta, B^{\eta})$ and $R_{EM}(\psi^c)$ are already available from response interpolation

Interconnection Between a Circuit Optimizer and a Numerical EM Simulator



Updating Data Base of Simulated Results

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

data base D of base points and the corresponding responses obtained from exact EM simulations is stored and accessed when necessary

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)

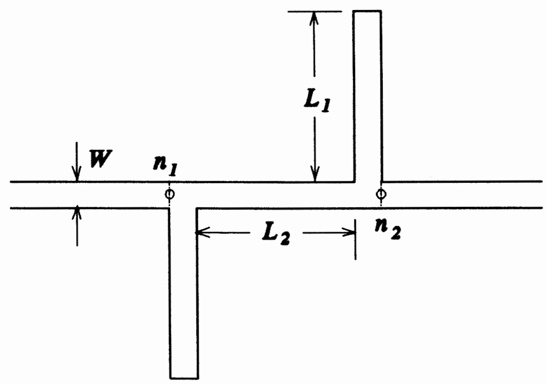
results for the base points already present in the data base ($B \cap D$) are simply retrieved from D and used for interpolation

updating the data base D - any scheme between two extremes

all simulated results are saved

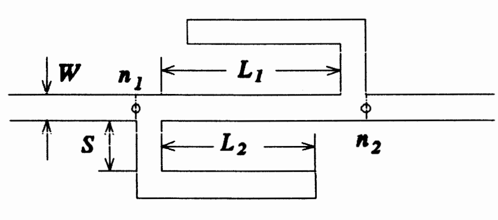
only results for the latest interpolation base are saved

Conventional Double Stub Microstrip Structure



for band-stop filter applications

Double Folded Stub Microstrip Structure
(Rautio, 1992)



substantially reduces the filter area while achieving the same goal as the conventional double stub structure

can be described by 4 parameters: width, spacing and two lengths W, S, L_1 and L_2

Design of the Double Folded Microstrip Structure

minimax optimization to move the center frequency of the stop band from 15 GHz to 13 GHz

W fixed at 4.8 mils

L_1, L_2 and S - variables (designable parameters)

design specifications

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

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

substrate thickness - 5 mils

relative dielectric constant - 9.9

em™ driven by the minimax gradient optimizer of OSA90/hope™ through Empipe™

optimization was carried out in two steps

(1) $\Delta x = \Delta y = 2.4$ mils

(2) the grid size was reduced to $\Delta x = \Delta y = 1.6$ mils for fine resolution

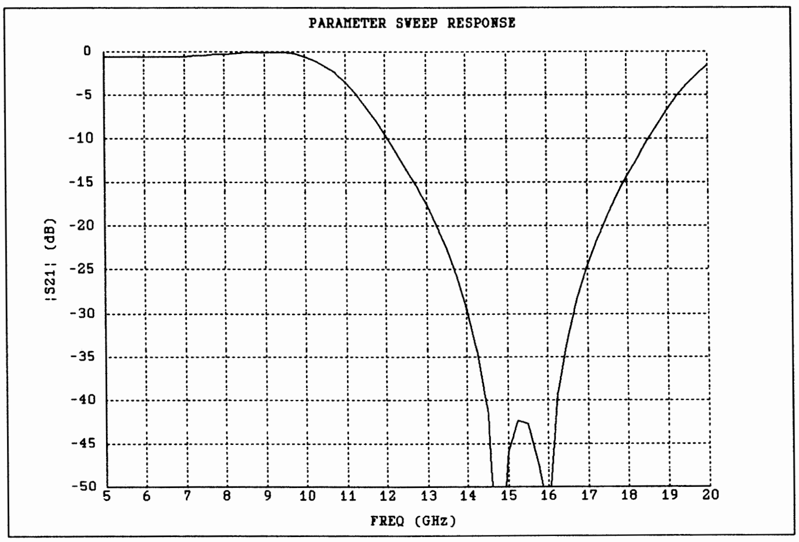
Minimax Optimization of the Double Folded Microstrip Structure

PARAMETER VALUES FOR THE DOUBLE FOLDED STUB
BEFORE AND AFTER OPTIMIZATION

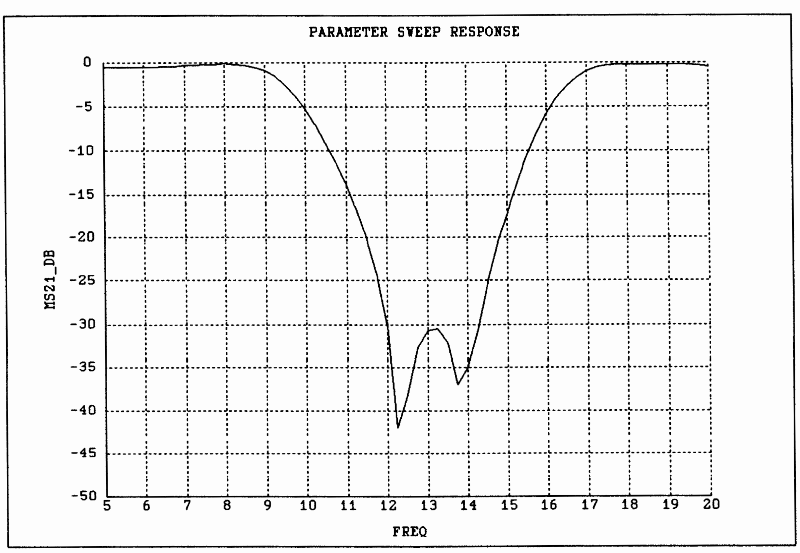
Parameter	Before optimization (mils)	After optimization (mils)
L_1	74.0	91.82
L_2	62.0	84.71
S	13.0	4.80

Results for the Double Folded Microstrip Structure

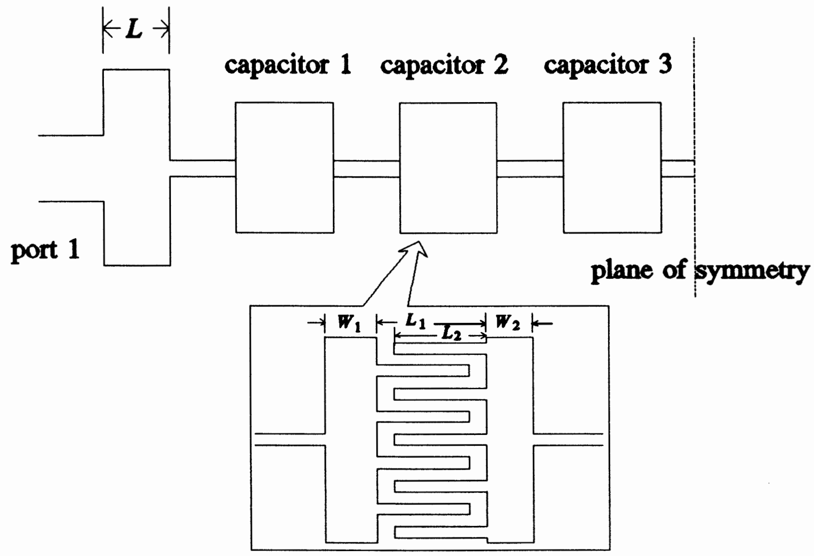
Before Optimization



After Optimization



26-40 GHz Interdigital Microstrip Bandpass Filter



utilizes thin microstrip lines and interdigital capacitors to realize inductances and capacitances of a synthesized lumped ladder circuit

the original microstrip design was determined by matching the lumped prototype at the center frequency using *em*™

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

Design of the 26-40 GHz Interdigital Microstrip Filter

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

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

the transmission lines between the capacitors were fixed at the originally designed values

design specifications

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

$$\text{for } 26 \text{ GHz} < f < 40 \text{ GHz}$$

substrate thickness - 10 mils

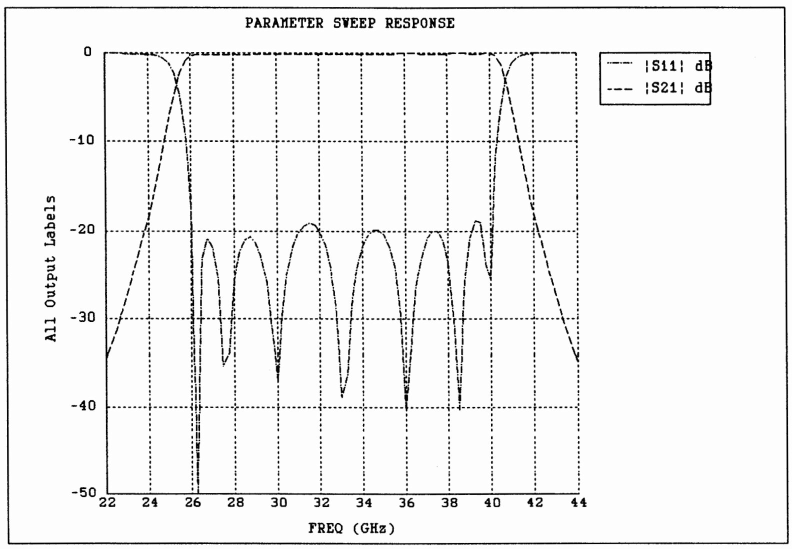
dielectric constant - 2.25

shielding height - 120 mils

em™ driven by the minimax gradient optimizer of OSA90/hope™ through Empipe™

Simulation of the 26-40 GHz Interdigital Capacitor Filter After Optimization

filter response after optimization

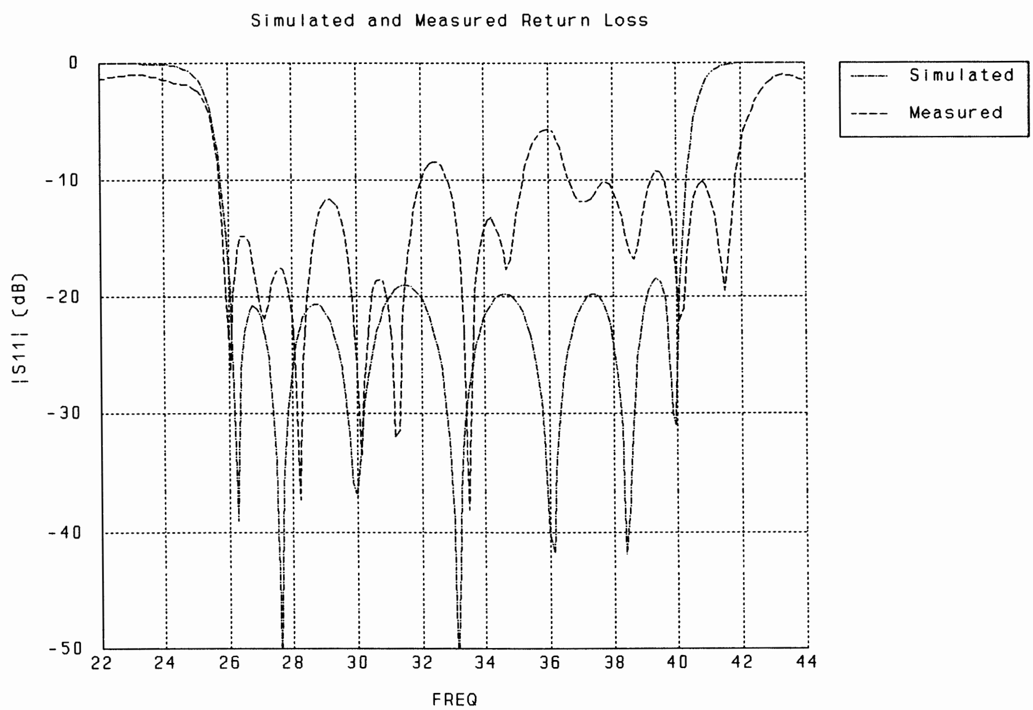


a typical minimax equal-ripple response of the filter was achieved after a series of consecutive optimizations with different subsets of optimization variables and frequency points

the resulting geometrical dimensions were finally rounded to 0.1 mil resolution

Measurements of the 26-40 GHz Interdigital Capacitor Filter - Return Loss After Optimization

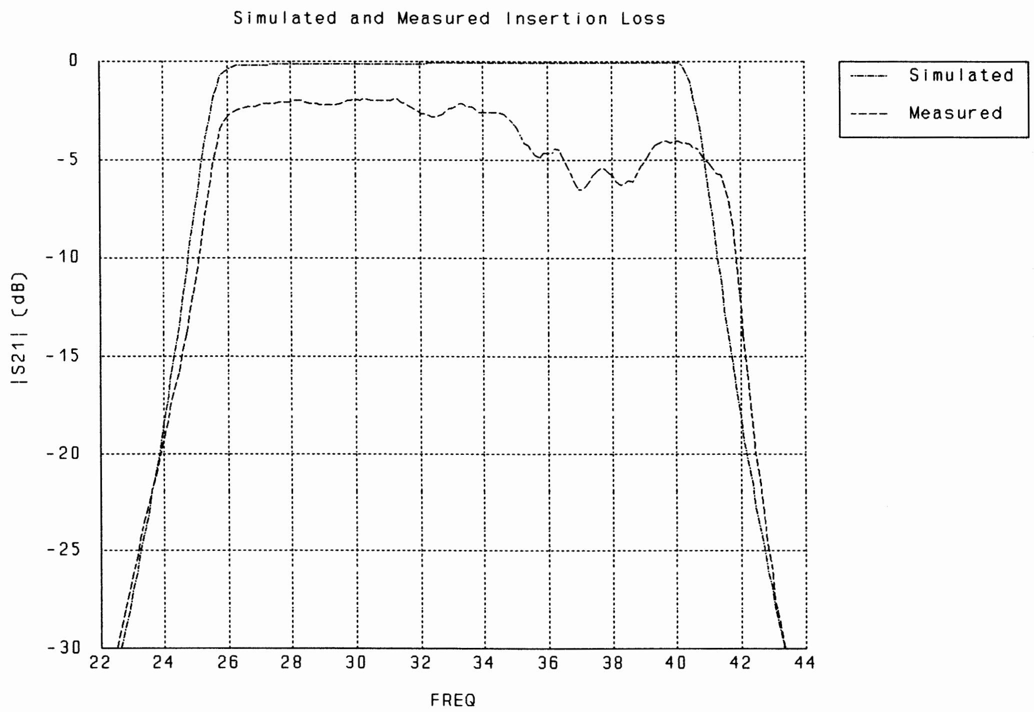
measured and simulated $|S_{11}|$ of the filter after manufacturing



recent improvements in the field solver analysis of interdigital capacitors will improve the accuracy of the bandwidth prediction

Measurements of the 26-40 GHz Interdigital Capacitor Filter - Insertion Loss After Optimization

measured and simulated $|S_{21}|$ of the filter after manufacturing



the insertion loss flatness will clearly improve after return loss has been tuned

Conclusions

a comprehensive approach to microwave filter design

accurate field simulations driven directly by a gradient based minimax optimizer

the benefits of electromagnetic simulations are significantly extended

our approach paves the way for direct use of field theory based simulation in practical optimization-driven microwave circuit design

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