

**A CAD ENVIRONMENT FOR PERFORMANCE AND  
YIELD DRIVEN CIRCUIT DESIGN EMPLOYING  
ELECTROMAGNETIC FIELD SIMULATORS**

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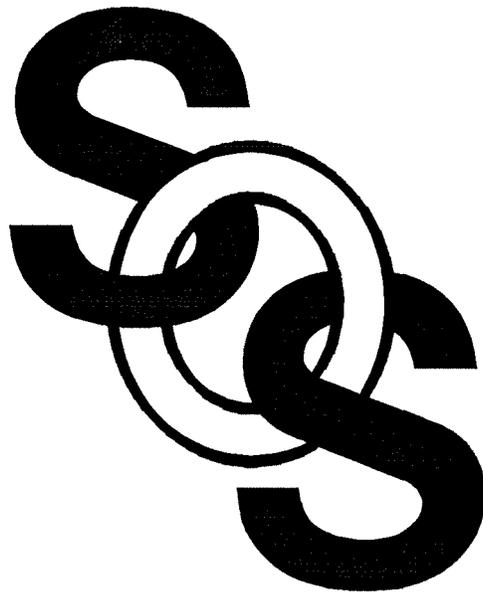
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## **Introduction**

electromagnetic (EM) field simulators

regarded as highly accurate at microwave frequencies  
increasingly available  
computationally intensive

it is very tempting to include EM simulators in performance-driven and even in yield-driven circuit optimization

EM simulations invoked directly within the optimization loop

feasibility of such optimization has already been shown  
(*Bandler et al. 1993*)

we use geometrical interpolation to reconcile inherent discretization of geometrical parameters with continuously varying optimization variables

we employ an efficient response modeling technique for computationally intensive statistical design centering  
(*Biernacki et al. 1986, 1989, 1991*)



## Outline

we unify geometrical interpolation, response modeling and EM simulation with versatile optimization

we effectively create an open architecture CAD environment for EM driven design

implemented in Empipe (OSA) which interfaces the CAD system OSA90/hope (OSA) and the *em* field simulator (Sonnet)

we report new results on EM circuit design

simulation of a microstrip line demonstrates the flexibility of our interpolation and modeling technique

a 3-section microstrip impedance transformer illustrates nominal and yield-driven design optimization

a frequency doubler illustrates various approaches to EM simulation and optimization of passive subcircuits



## Efficient Interpolation/Modeling

numerical EM simulation requires discretized values of geometrical parameters (on-the-grid)

typical optimizers assume continuously varying parameters

to reconcile the two requirements we interpolate responses at off-the-grid points using multidimensional polynomials

$$q(\mathbf{x}) = a_0 + \sum_{i=1}^n a_i (x_i - r_i) + \sum_{\substack{i=1 \\ j \geq i}}^n a_{ij} (x_i - r_i) (x_j - r_j)$$

where

$$\begin{aligned} \mathbf{x} &= [x_1 \ x_2 \ \dots \ x_n]^T && \text{vector of circuit parameters} \\ \mathbf{r} &= [r_1 \ r_2 \ \dots \ r_n]^T && \text{the reference point} \end{aligned}$$

EM simulation is invoked at some  $m$  base points

for a quadratic  $Q$ -model we use  $n + 1 < m \leq 2n + 1$

for a linear  $L$ -model we use  $m = n$



## Discretization of the Model Parameter Space

we consider

simulation grid

modeling grid

the simulation grid  $\delta_S = [\delta_{S1} \delta_{S2} \dots \delta_{Sn}]^T$  is imposed by EM simulator; each  $\delta_{Si}$  is a floating point number and has the same unit as the corresponding parameter

the modeling grid is implied by positive dimensionless integer multipliers  $\delta_M = [\delta_{M1} \delta_{M2} \dots \delta_{Mn}]^T$

the distance between adjacent modeling grid points is  $\delta_{Mi} \delta_{Si}$

model parameters are discretized according to the modeling grid

to create the interpolation models we invoke EM simulations at the modeling grid points only

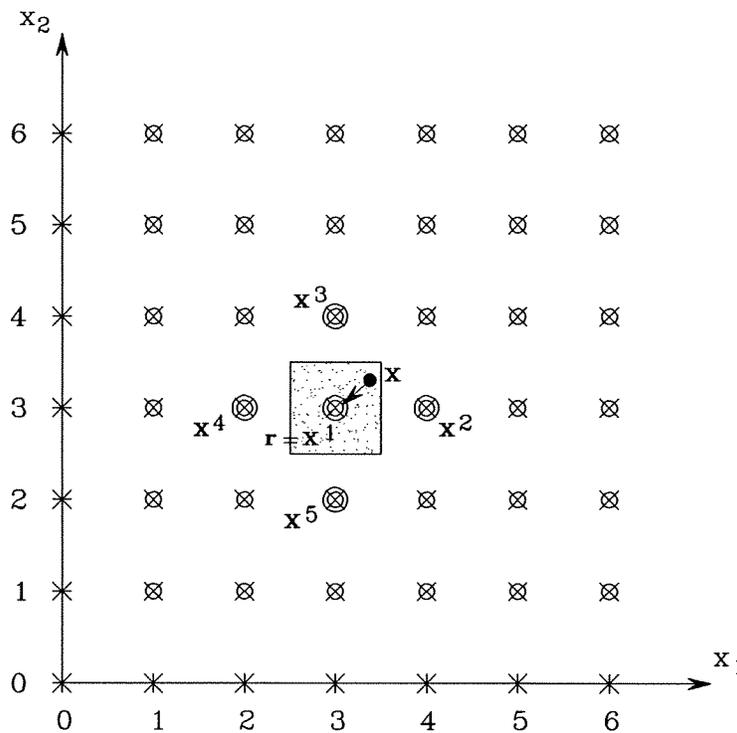


## The Model Validity Region

for each model we define a validity region  $V$

one possible choice for  $V$  in the case of  $Q$ -models is given by

$$V = \left\{ x \mid \frac{-\delta_{Si} \delta_{Mi}}{2} < (x_i - r_i) \leq \frac{\delta_{Si} \delta_{Mi}}{2} \right\}, i = 1, 2, \dots, n$$



if  $x \in V$  than we assume that  $q(x) \approx f(x)$



## **Data Base/Modeling Integration**

during optimization the nominal point and statistical outcomes may move outside the current model validity region  $V$

if any point falls outside the current  $V$  then we

generate new base points

perform EM simulation at the new base points

update the models

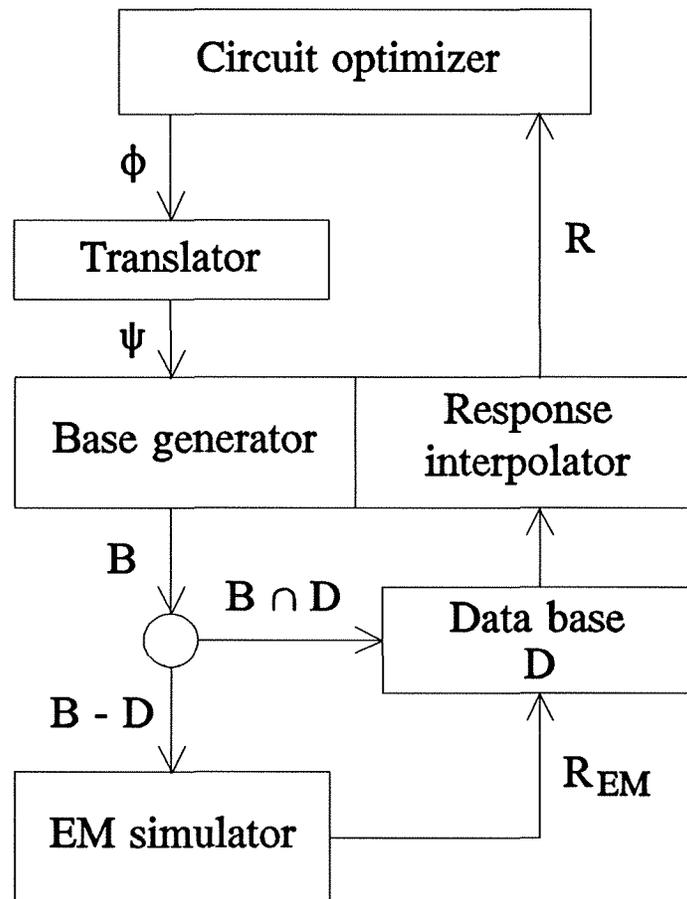
any additional EM simulation is performed only if no prior simulation has been performed at the new base points

to facilitate this we maintain and automatically update a data base of base points with the corresponding responses

our scheme dynamically integrates interpolation models and data base updating in real optimization time



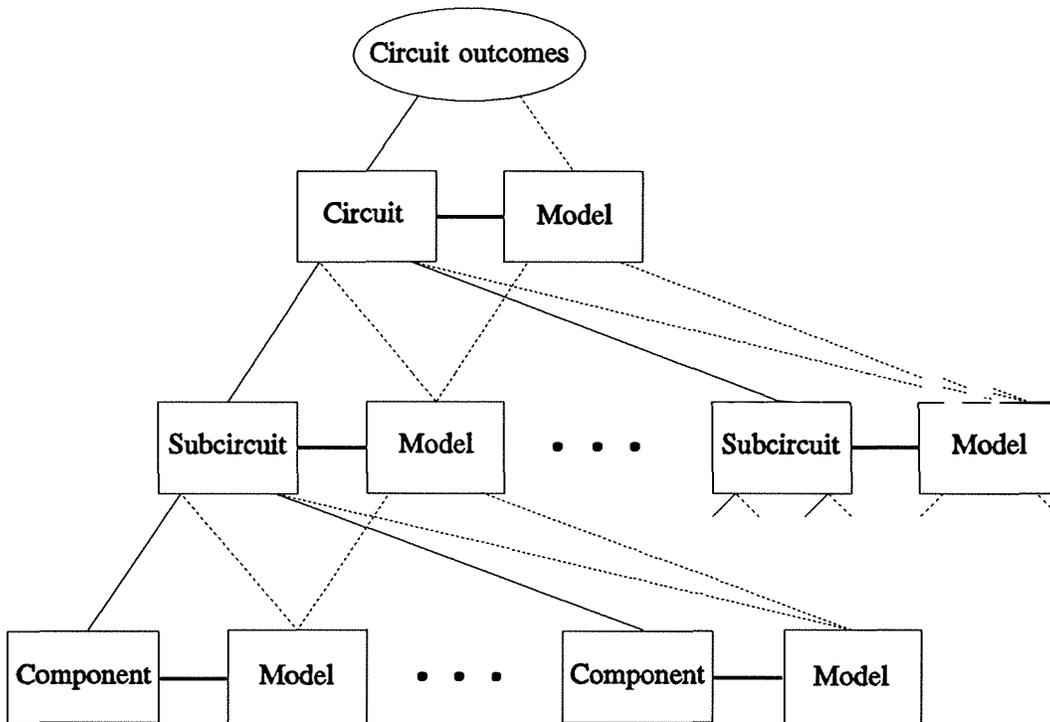
## Interconnection Between a Circuit Optimizer and a Numerical EM Simulator





## Multilevel Quadratic Modeling

(Bandler et al. 1993)



a  $Q$ -model can be established at any level for some or all subcircuits and components

the models are built from simulations of the corresponding components, subcircuits, or the overall circuit

many  $Q$ -models may exist changing the path of calculations as indicated by different links in the figure



## A Microstrip Line Study

a microstrip line with

the width fixed at  $W = 25$  mil

the length  $L$  varied from 100 to 202.5 mils with a 2.5 mil step for different simulation and modeling grids

reference data is obtained with fine simulation ( $\delta_{SL} = 2.5$  mil) and modeling ( $\delta_{ML} = 1$ ) grids; no interpolation is needed

two experiments

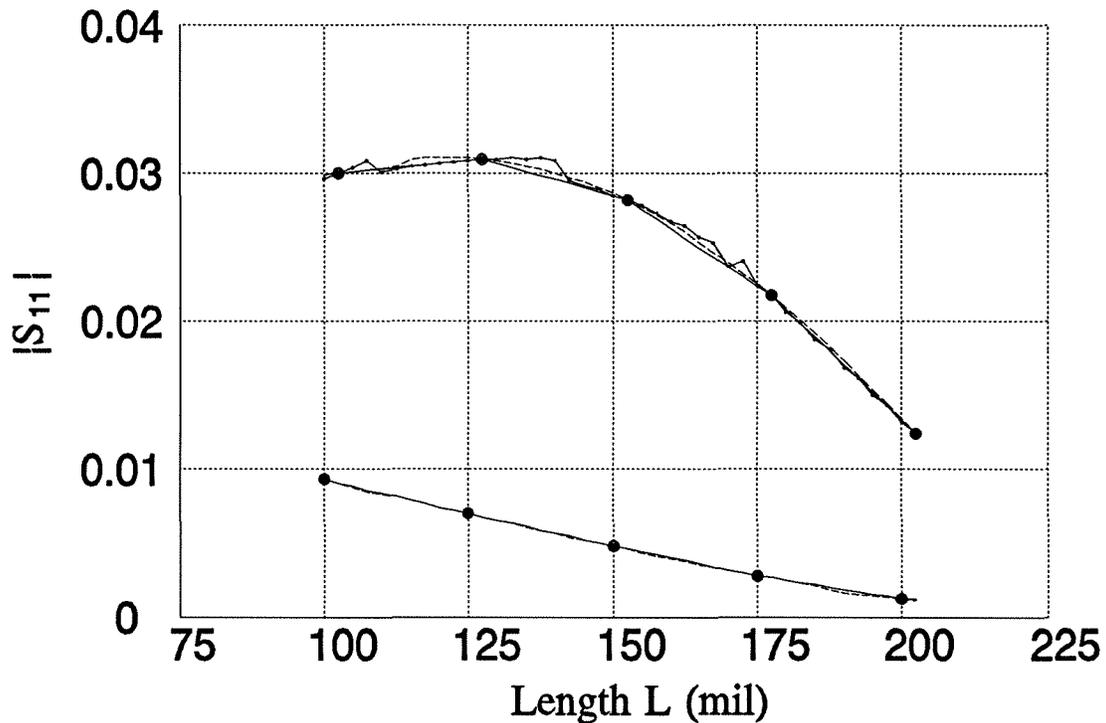
coarse simulation ( $\delta_{SL} = 25$  mil) grid and small modeling multiplier ( $\delta_{ML} = 1$ )

fine simulation ( $\delta_{SL} = 2.5$  mil) grid and large modeling multiplier ( $\delta_{ML} = 10$ )

we build and examine the  $L$ -models as well as the  $Q$ -models



## A Microstrip Line Study - Results



upper curves: the reference data and the responses of the  $L$ - and  $Q$ -models built using the fine simulation and coarse modeling grids

lower curves: the responses of the  $L$ - and  $Q$ -models built using the coarse simulation grid

$L$ -models (—),  $Q$ -models (---), EM simulations (•)



## **A Microstrip Line Study - Conclusions**

responses of the models built using the fine simulation grid are much closer to the reference data, even if the modeling grid is coarse

the loss of accuracy in using interpolation models is likely to be due to too coarse simulation grid

a specific modeling technique may not be critical for the accuracy of the model as long as the validity region is not too large

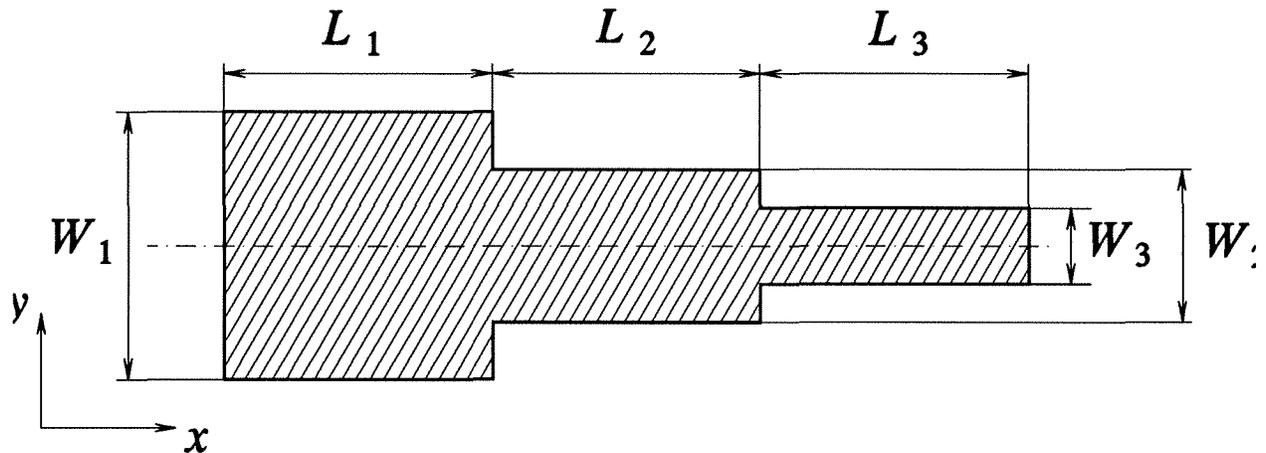
Sun SPARCstation 10

0.3 CPU seconds per frequency point for coarse grid simulation

5 CPU seconds per frequency point for fine grid simulation



### A 3-Section Microstrip Impedance Transformer



$W_1$ ,  $W_2$  and  $W_3$  are optimization variables

$L_1$ ,  $L_2$  and  $L_3$  are fixed

substrate is 0.635 mm thick

$\epsilon_r$  is 9.7

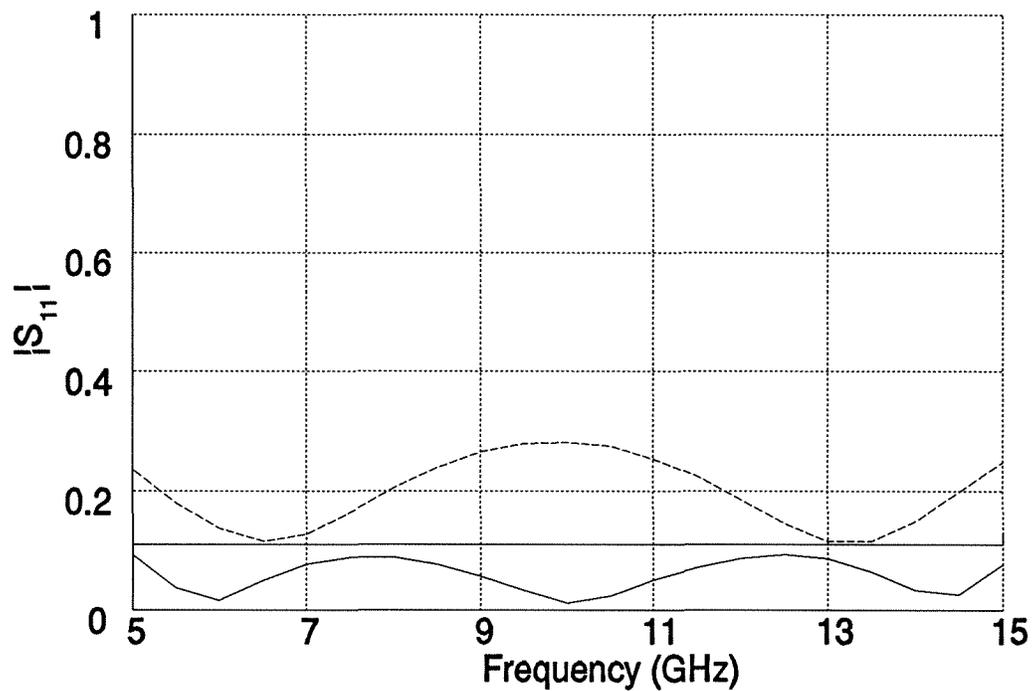
source and load impedances are 50 and 150  $\Omega$ , respectively



## Minimax Design of the Microstrip Transformer

design specifications

$$|S_{11}| \leq 0.11, \text{ from 5 GHz to 15 GHz}$$

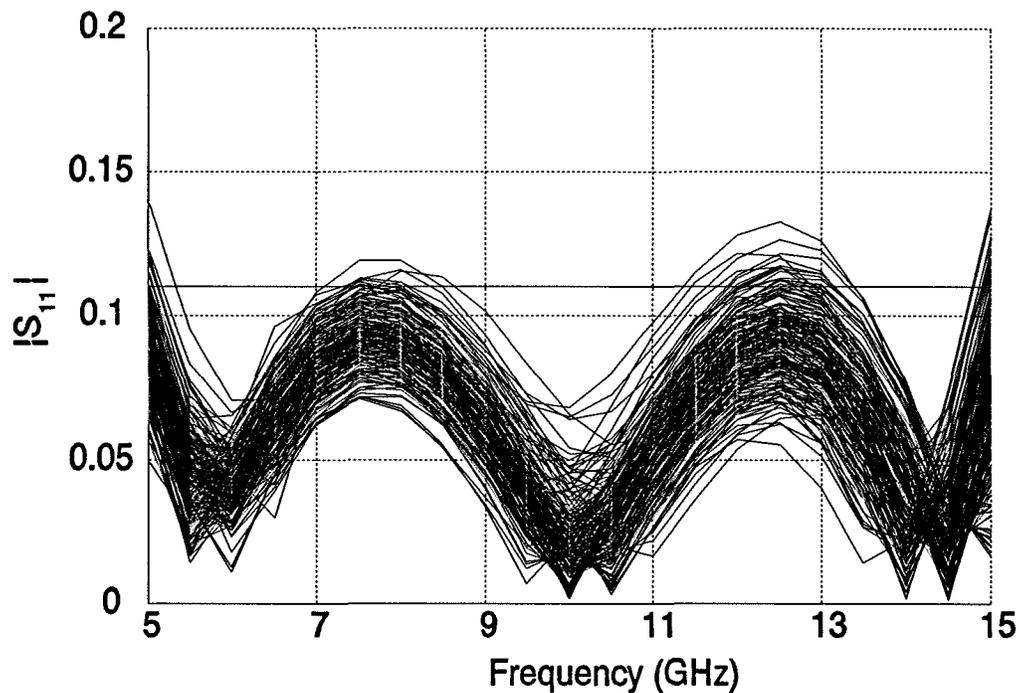


$|S_{11}|$  before (---) and after (—) optimization



## **Yield-driven Design of the Impedance Transformer**

Monte Carlo sweep at the centered solution



yield is increased from 61% (at the minimax solution) to 77%  
at the centered solution

yields are estimated from 250 Monte Carlo outcomes



## **Yield-driven Design of the Microstrip Transformer - Results**

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Parameter	Starting point (mm)	Minimax solution (mm)	Centered solution (mm)
$W_1$	0.65	0.349	0.373
$W_2$	0.35	0.139	0.165
$W_3$	0.15	0.039	0.049
Yield	-	61%	77%

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$L_1$ ,  $L_2$  and  $L_3$  are fixed at 3 mm.

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normal distributions of all six geometrical parameters

standard deviations of 0.005 mm and 2% for the lengths and widths, respectively

100 outcomes used in yield optimization



## **Conclusions**

a CAD environment for circuit design employing accurate EM field simulations within the optimization loop

efficient modeling is now combined and unified with geometrical interpolation imposed by EM simulation

the data base system is integral to the modeling techniques and absolutely essential for efficient EM design

multilevel modeling offers additional computational saving

recent studies lead to breakthrough space mapping technique which allows effective utilization of coarse EM models without loss of accuracy offered by fine EM models

recent developments allow automated EM optimization of structures of arbitrary geometry