AUTOMATED EM OPTIMIZATION OF LINEAR AND NONLINEAR CIRCUITS, WITH GEOMETRY CAPTURE FOR ARBITRARY PLANAR STRUCTURES

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Critical Issues of Automated EM Optimization

interfaces between gradient-based optimizers and discretized EM field solvers: interpolation and database

integration of EM analysis with circuit simulation, including harmonic balance simulation of nonlinear circuits

Geometry Capture™: user-defined optimizable structures of arbitrary geometry

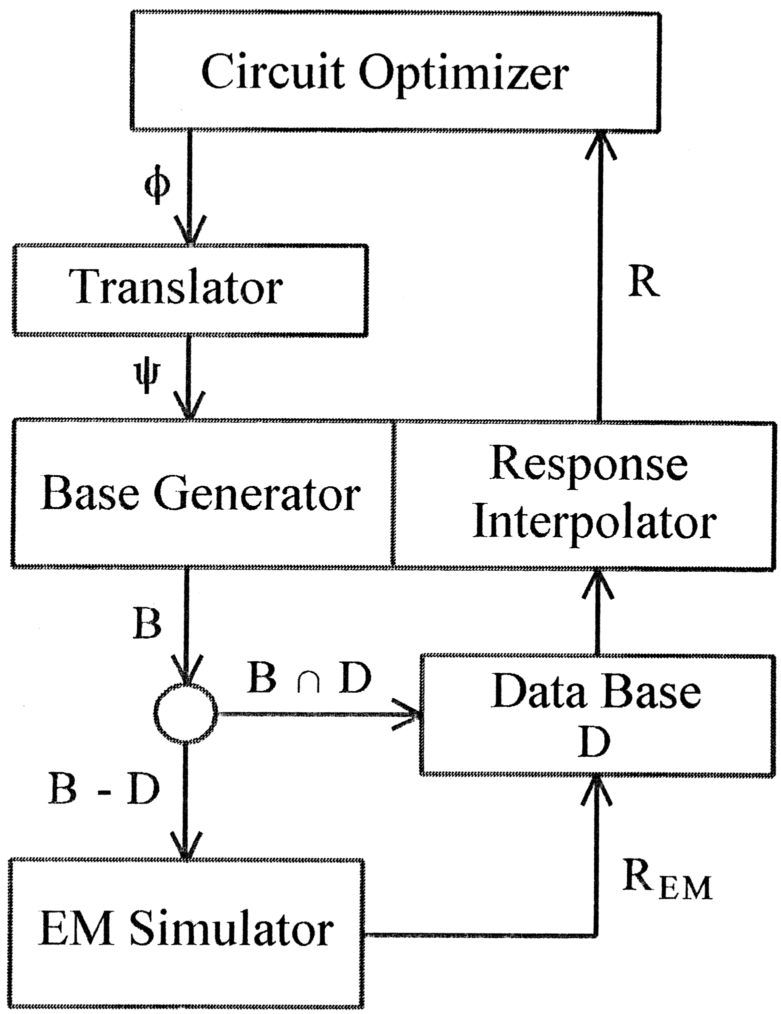
Space Mapping™ optimization: intelligent correlation between engineering models: EM models, empirical models and equivalent circuit models

smoothness and continuity of response interpolation

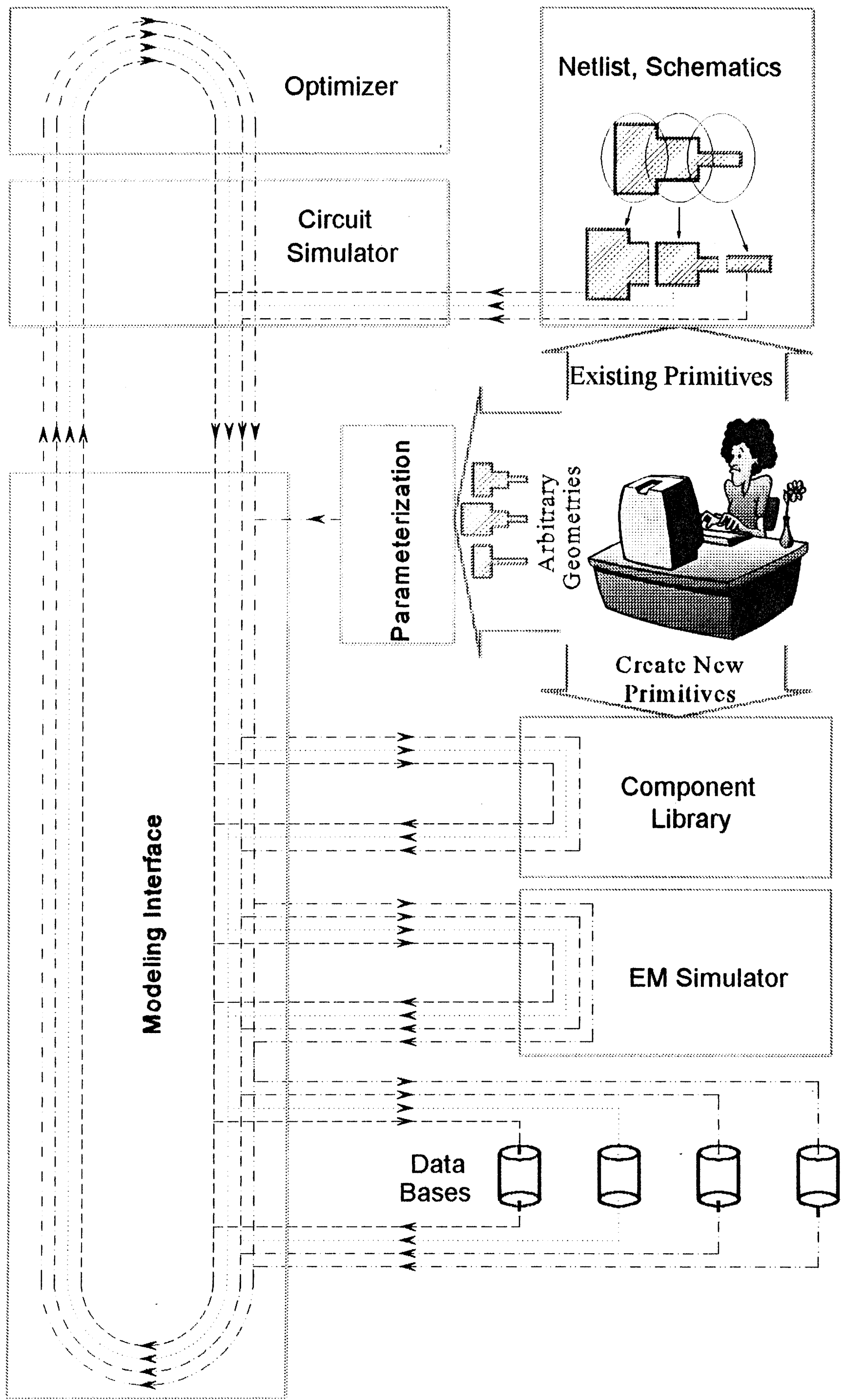
robustness of optimization algorithms and uniqueness of the solutions

parallel and massively parallel EM analyses

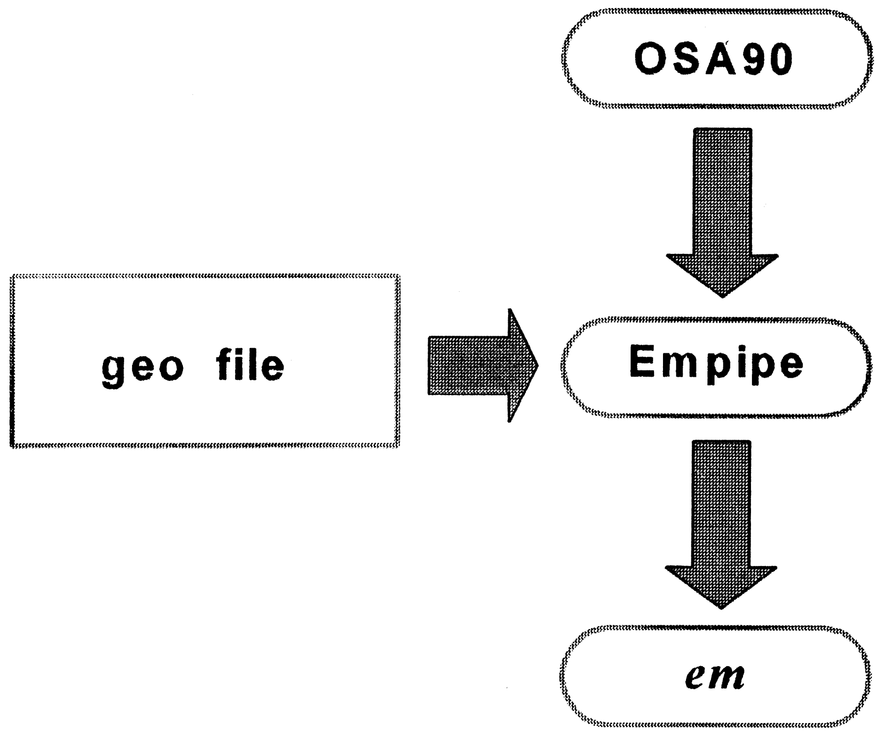
Interface Between Optimizer and EM Solver
(*Bandler et al., 1993*)



EM Optimization Environment



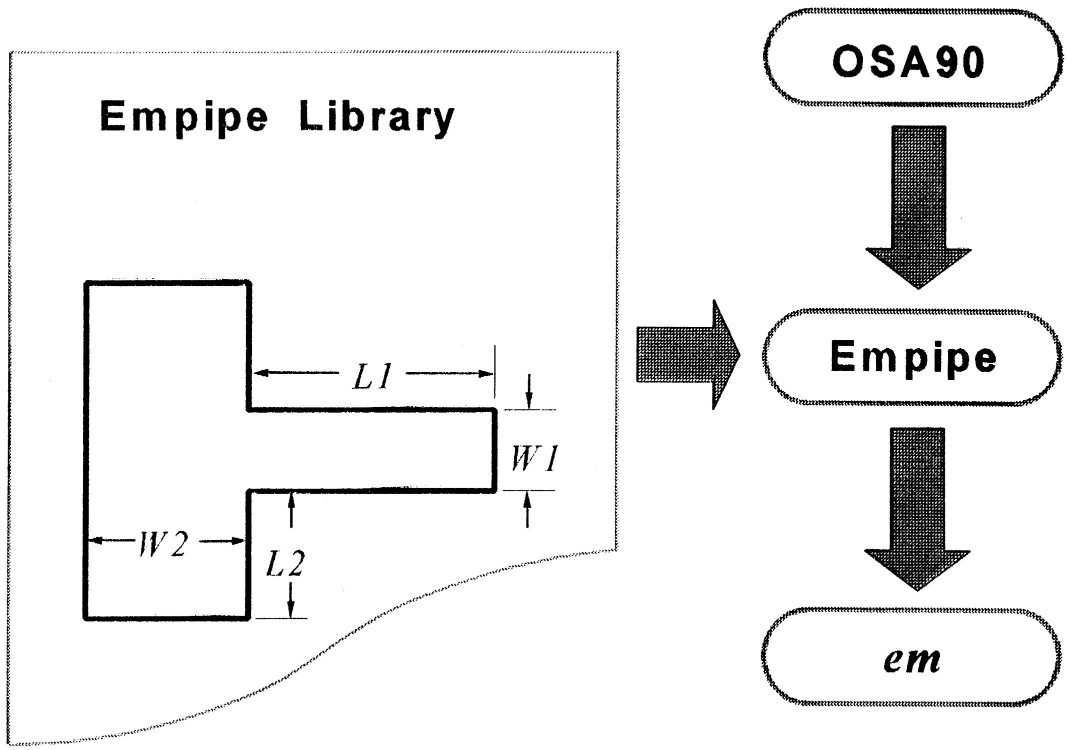
Simulation of Static Structures via Empipe™
(*OSA, 1992*)



useful for analyzing circuits of mixed EM and empirical models

unsuitable for EM optimization

Empipe™ Optimizable Library Structures
(*OSA, 1992*)



preprogrammed, ready to use

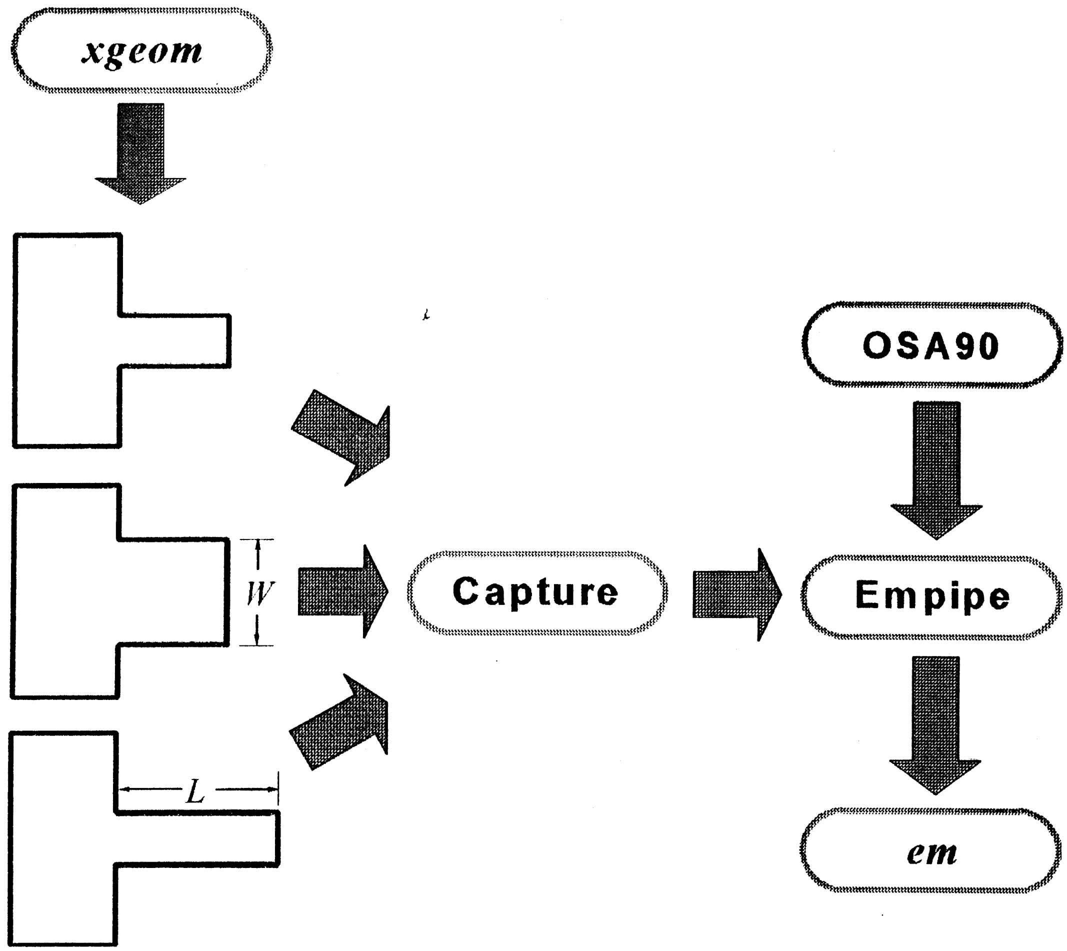
limited selection

complex structure decomposed into elementary structures connected by circuit theory, neglecting couplings between the elements

Empipe™ Library of Microstrip Structures

bend
cross junction
double patch capacitors
interdigital capacitors
line
mitered bend
open stub
overlay double patch capacitors
rectangular structure
spiral inductors
step junction
symmetrical and asymmetrical folded double stubs
symmetrical and asymmetrical gaps
symmetrical and asymmetrical double stubs
T junction

Geometry Capture™
(*OSA, 1994*)

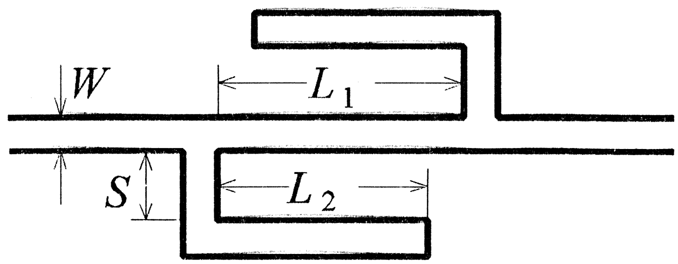


intuitive and totally flexible

graphical description of parameters and constraints

optimization not limited to geometrical dimensions but can also include substrate/metallization parameters

Microstrip Double Folded Stub Filter
(*Rautio, 1992*)



em™ driven by OSA90/hope™ through Empipe™

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 are variables

substrate thickness: 5 mils

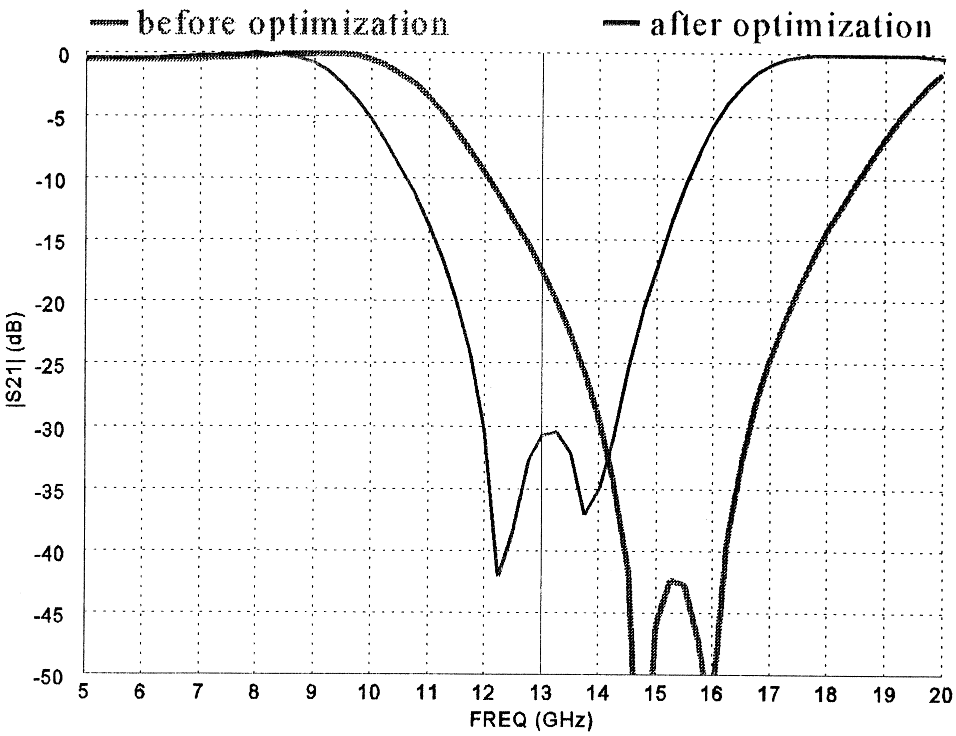
relative dielectric constant: 9.9

design specifications

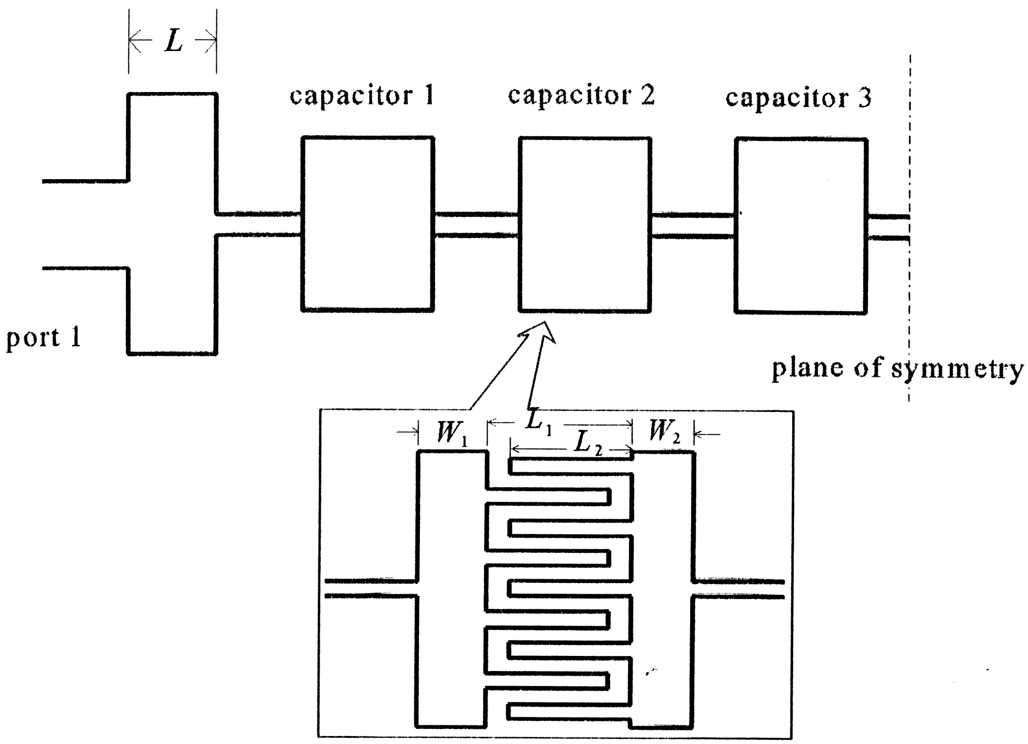
$\|S_{21}\| > -3$ dB	for $f < 9.5$ GHz and $f > 16.5$ GHz
$\|S_{21}\| < -30$ dB	for 12 GHz $< f <$ 14 GHz

Optimization Systems Associates Inc.

EM Simulation of the Double Folded Stub Filter



26-40 GHz Interdigital Bandpass Filter
(*Swanson, 1992*)



the initial design was obtained by matching a synthesized lumped ladder prototype at the center frequency using ***em***™

when the filter was simulated by ***em***™ in the whole frequency range, significant discrepancies w.r.t. the prototype necessitated manual adjustment and made a satisfactory design very difficult to achieve

EM Optimization of the Interdigital Bandpass 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

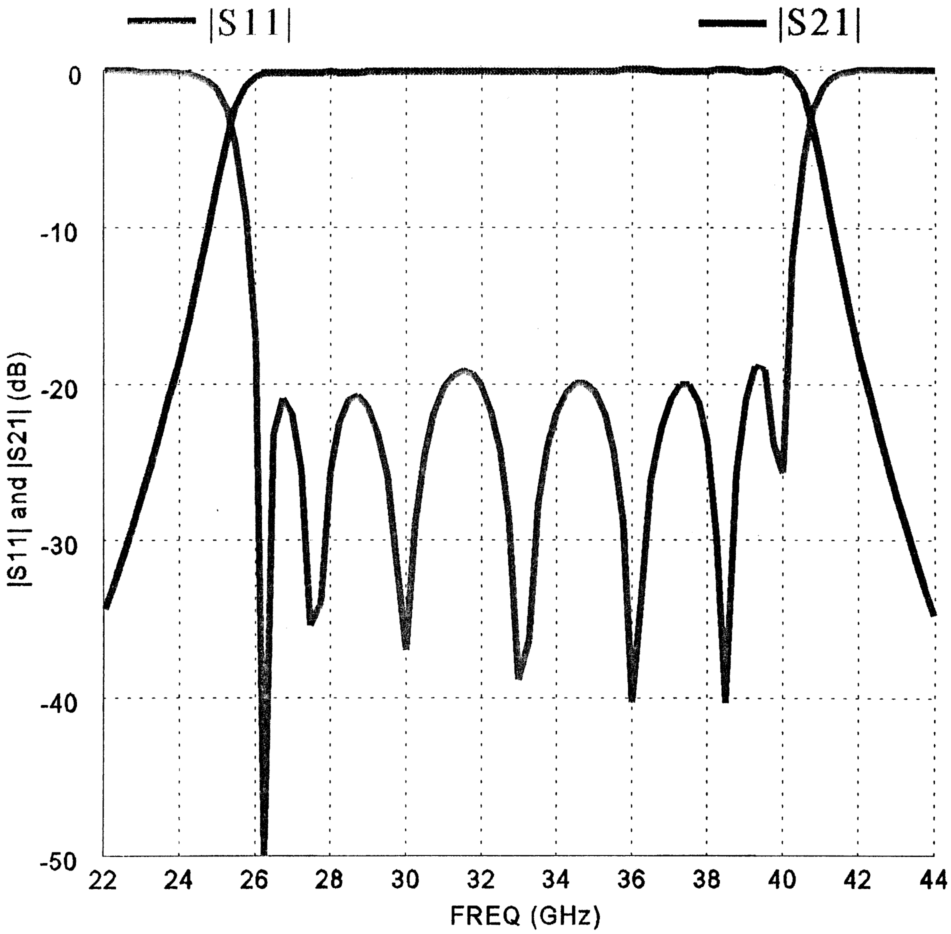
$|S_{11}|$ < -20 dB and $|S_{21}|$ > -0.04 dB

for 26 GHz < f < 40 GHz

substrate thickness: 10 mils

dielectric constant: 2.25

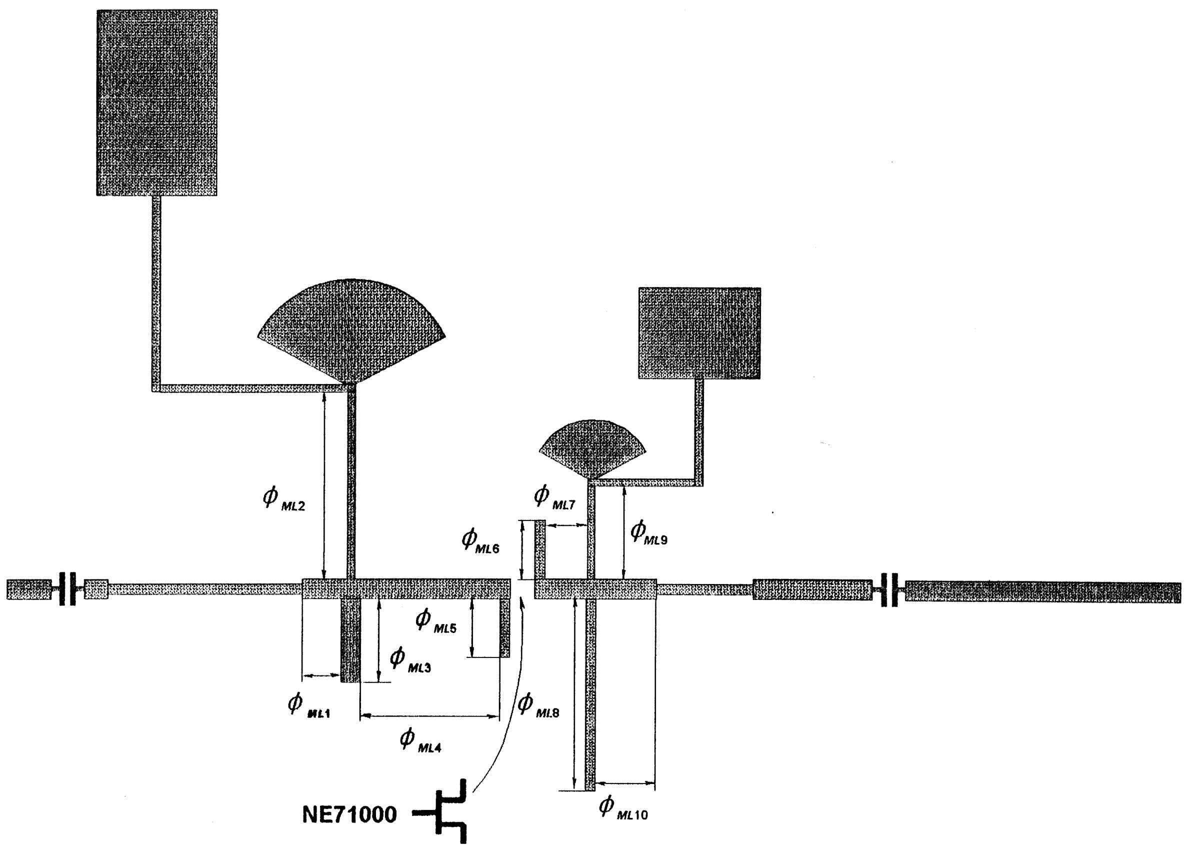
Simulation of the Interdigital Bandpass Filter After Optimization



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 rounded to 0.1 mil resolution

Nonlinear FET Class B Frequency Doubler
(*Microwave Engineering Europe, 1994*)

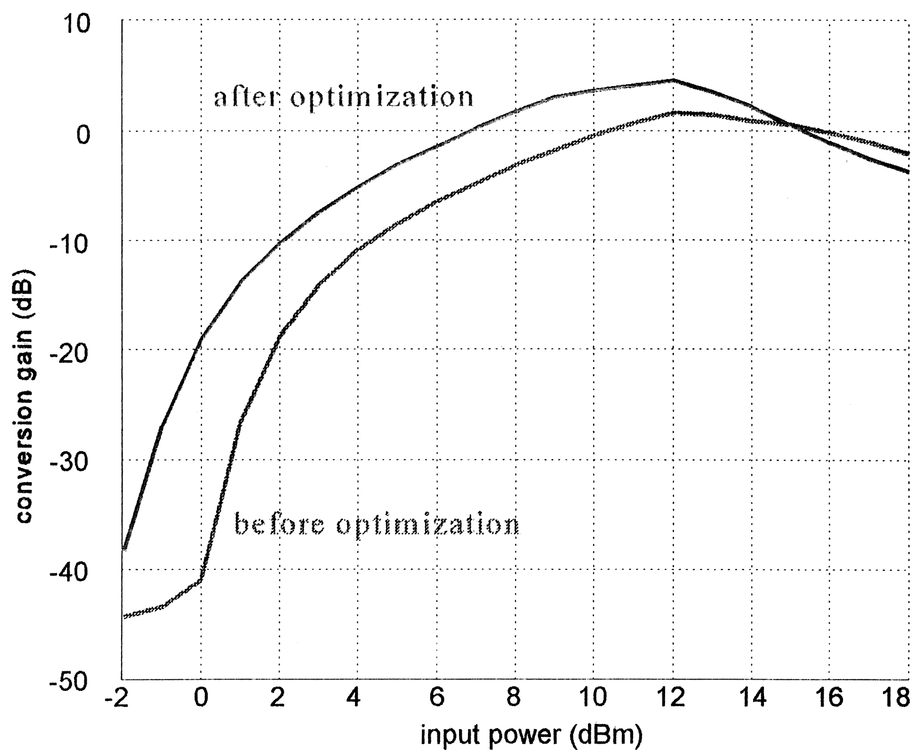


CAD benchmark example

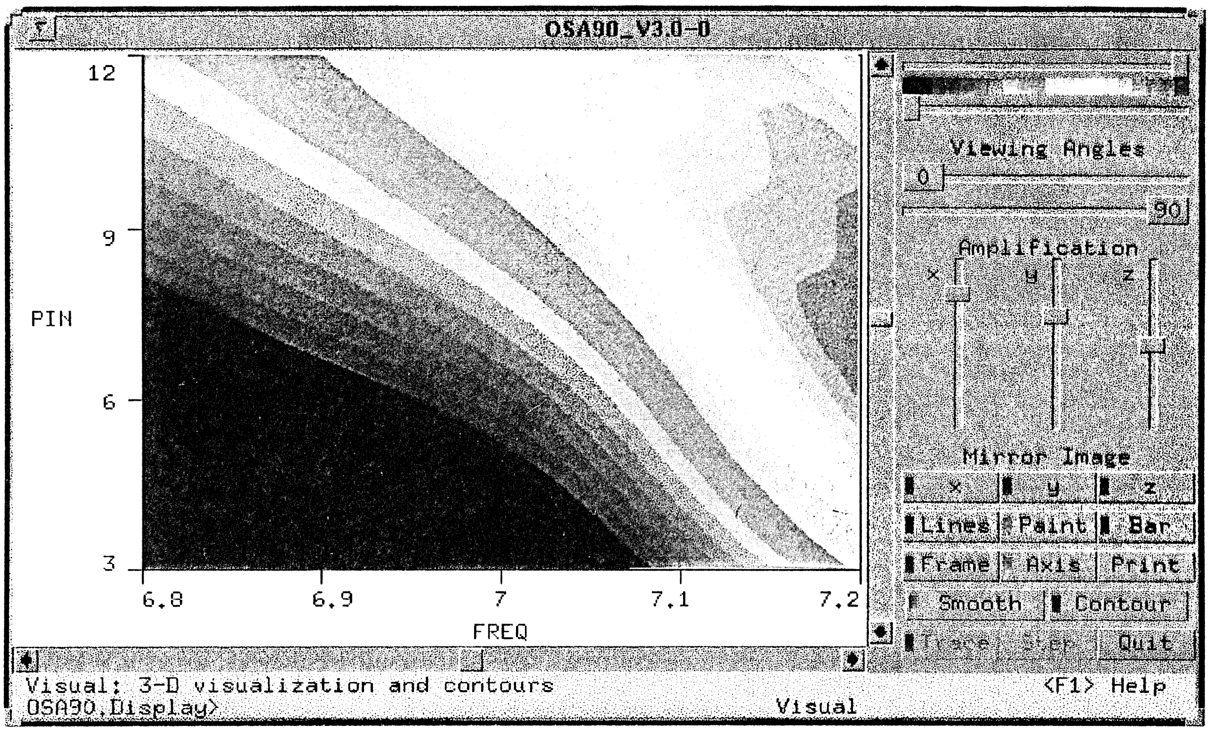
a single FET (NE71000) and a number of microstrip elements including two radial stubs and two large bias pads

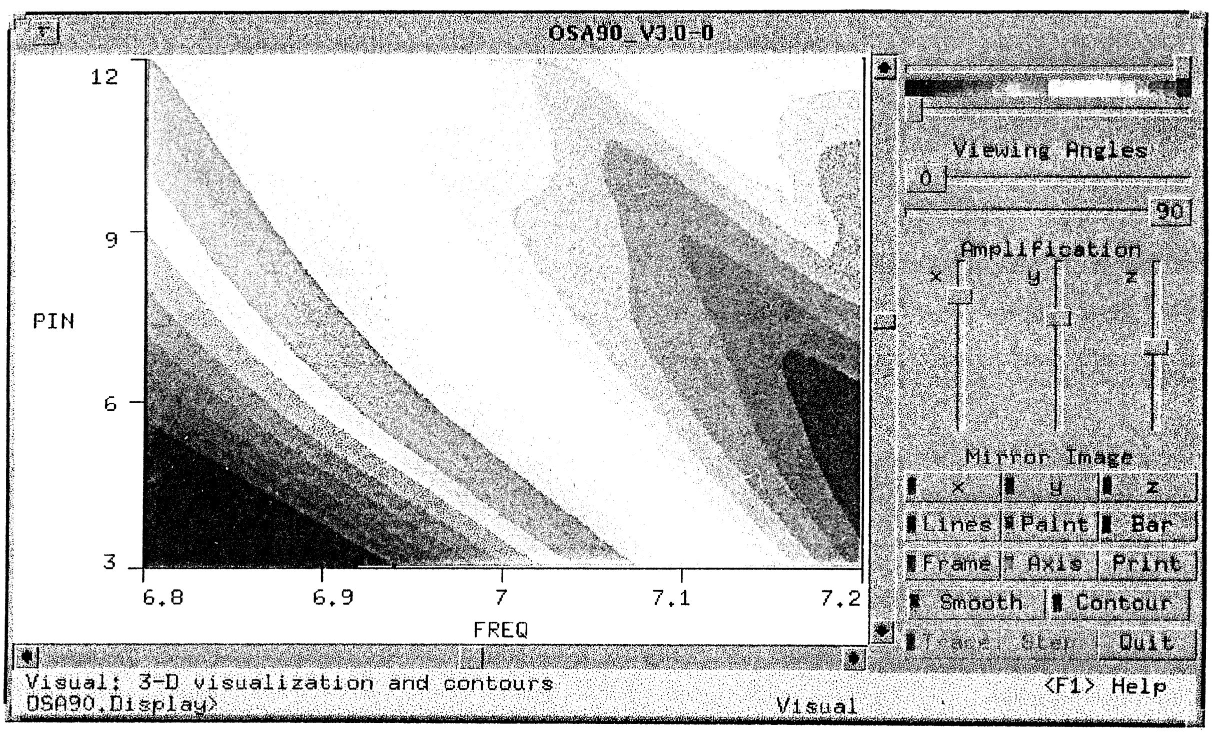
significant couplings between the microstrip elements

Conversion Gain Before and After Optimization

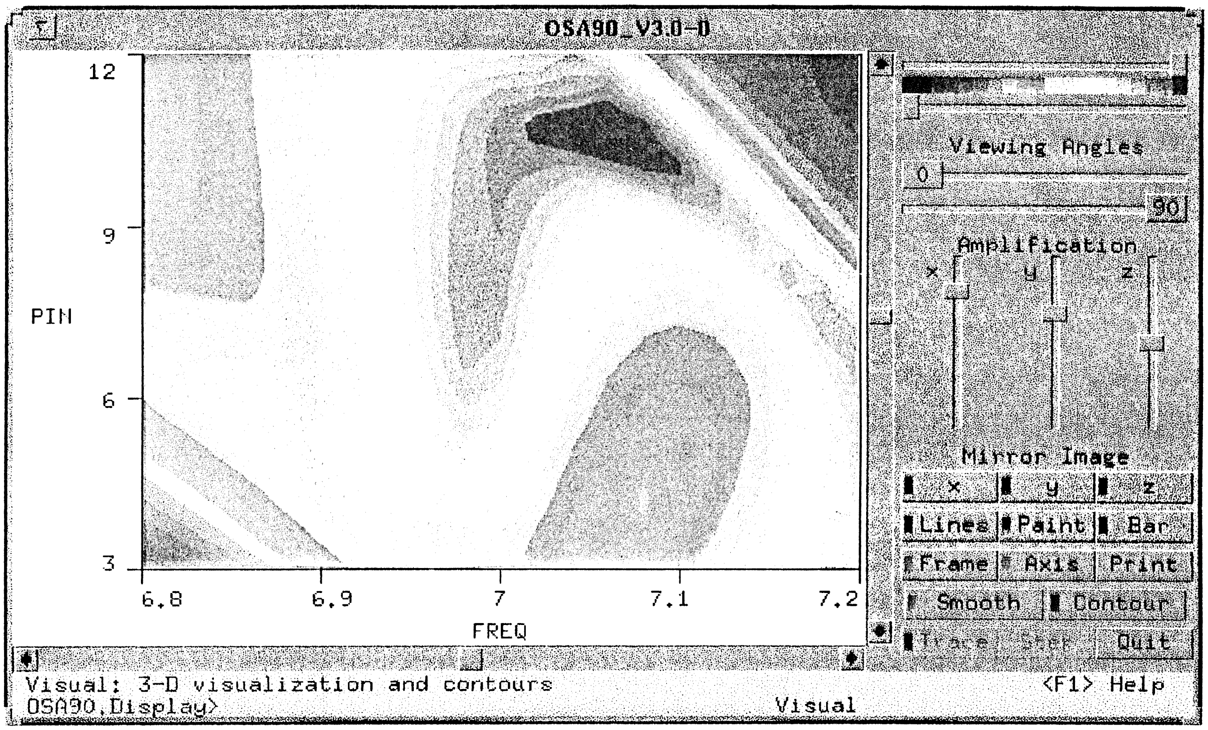


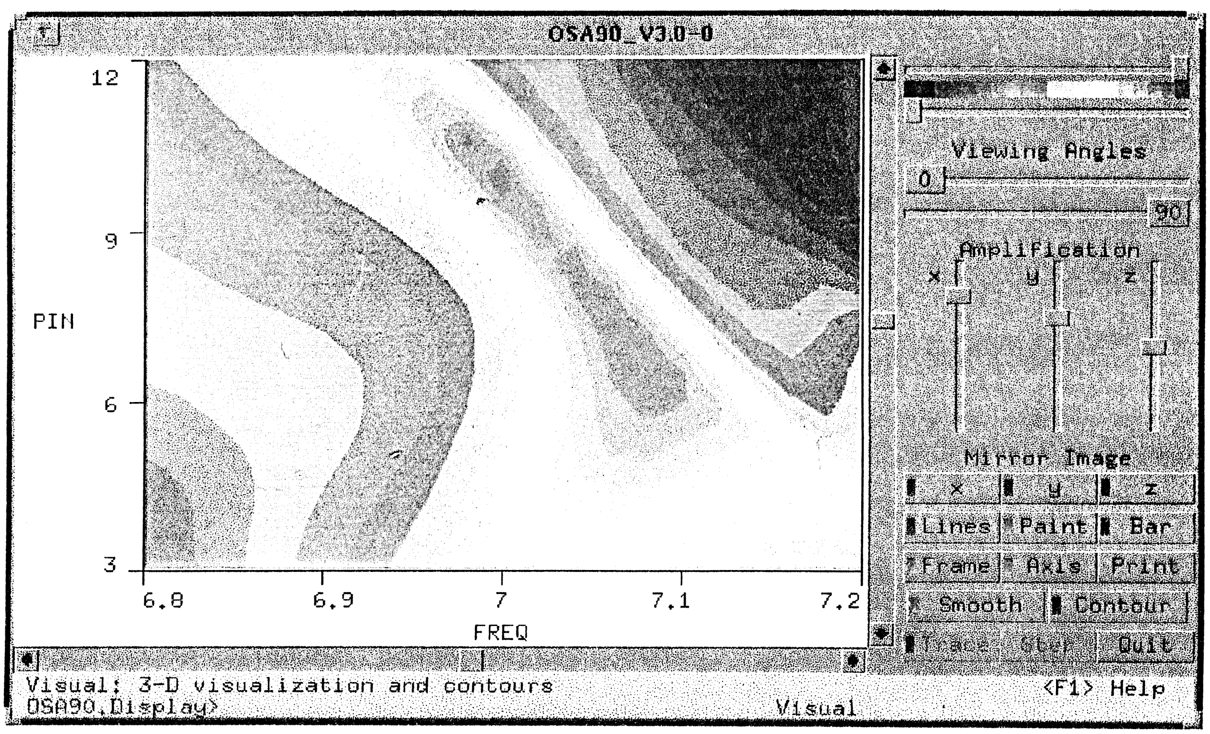
Conversion Gain Before and After Optimization



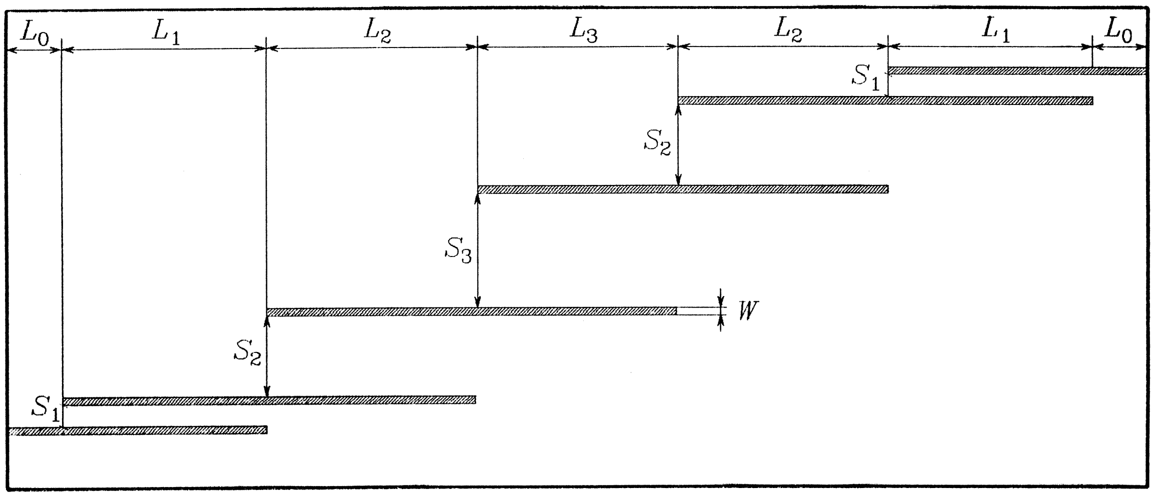


Spectral Purity Before and After Optimization





The HTS Quarter-Wave Parallel Coupled-Line Filter
(*Westinghouse, 1993*)



20 mil thick lanthanum aluminate substrate

the dielectric constant is 23.4

the x and y grid sizes for ***em*** simulation are 1.0 and 1.75 mil

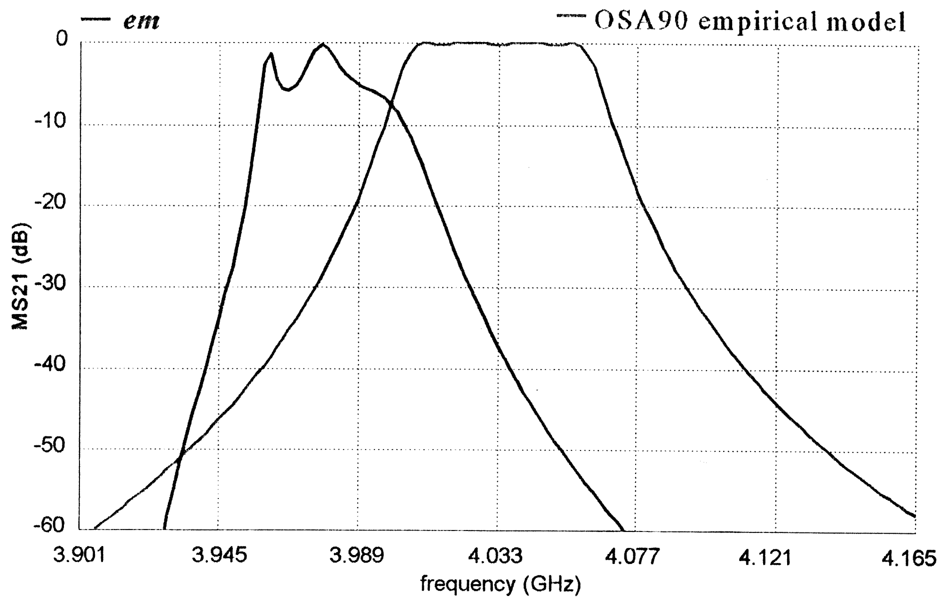
100 elapsed minutes are needed for ***em*** analysis at a single frequency on a Sun SPARCstation 10

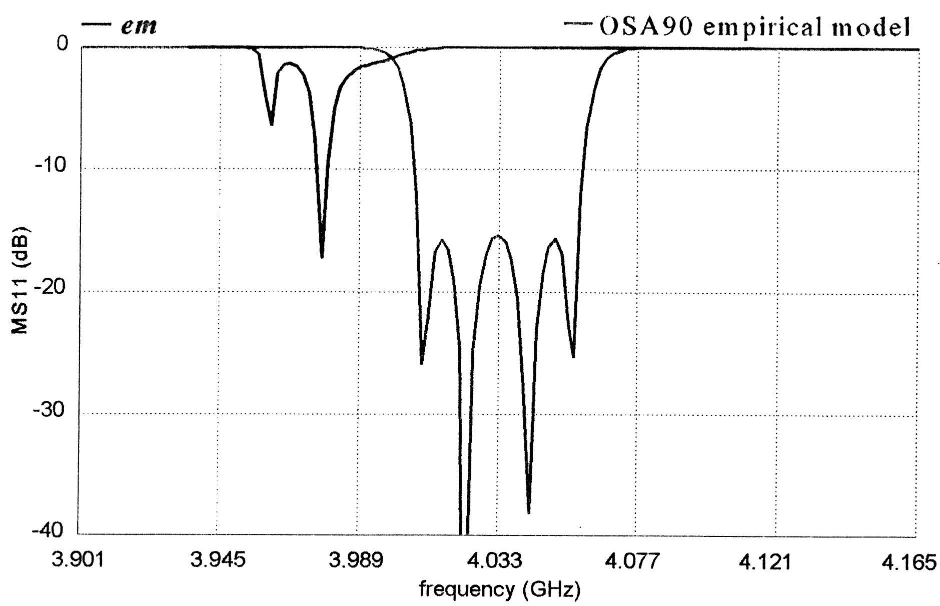
design specifications

$|S_{21}| < 0.05$ for $f < 3.967$ GHz and $f > 4.099$ GHz

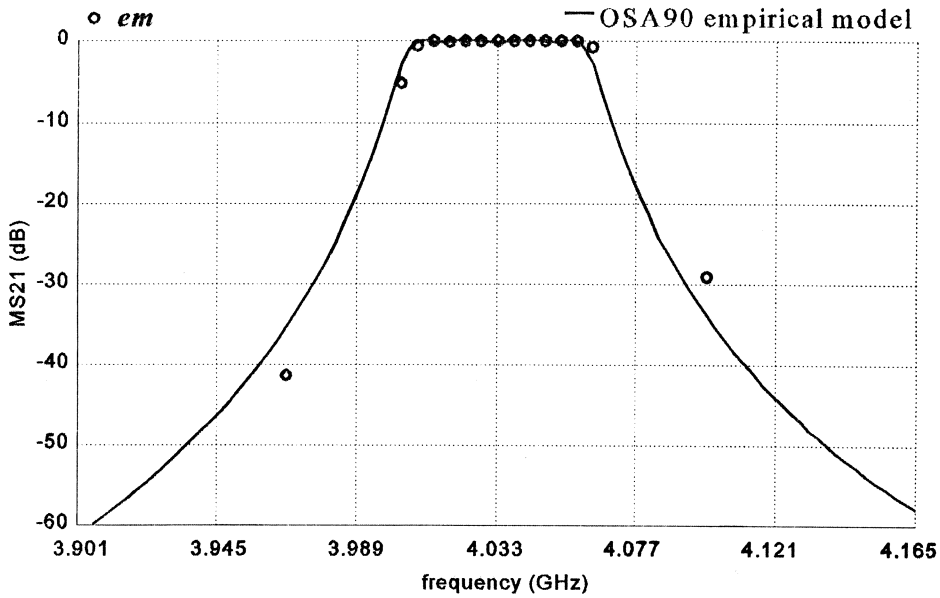
$|S_{21}| > 0.95$ for $4.008 \text{ GHz} < f < 4.058$ GHz

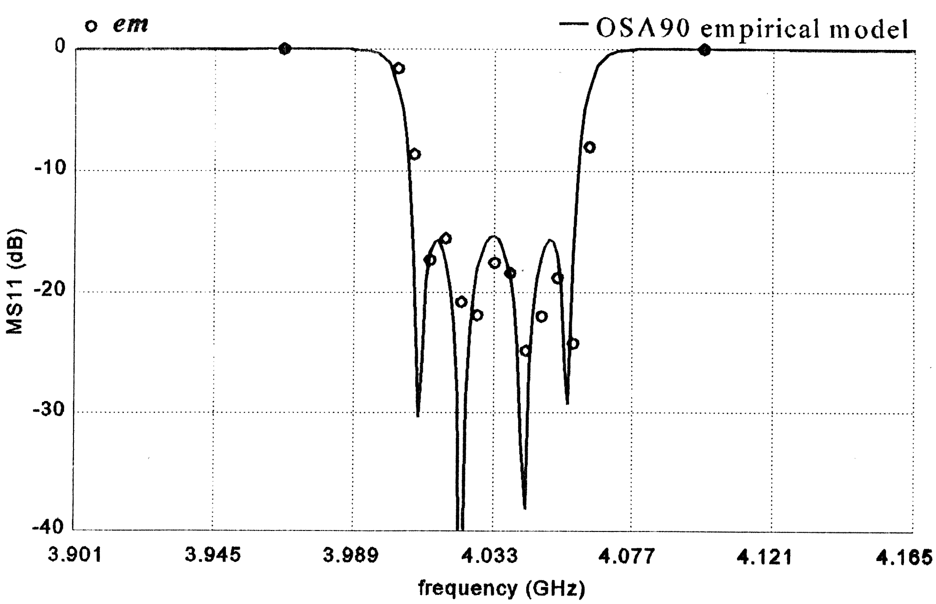
Starting Point of EM Optimization: Design Using Empirical Circuit Model



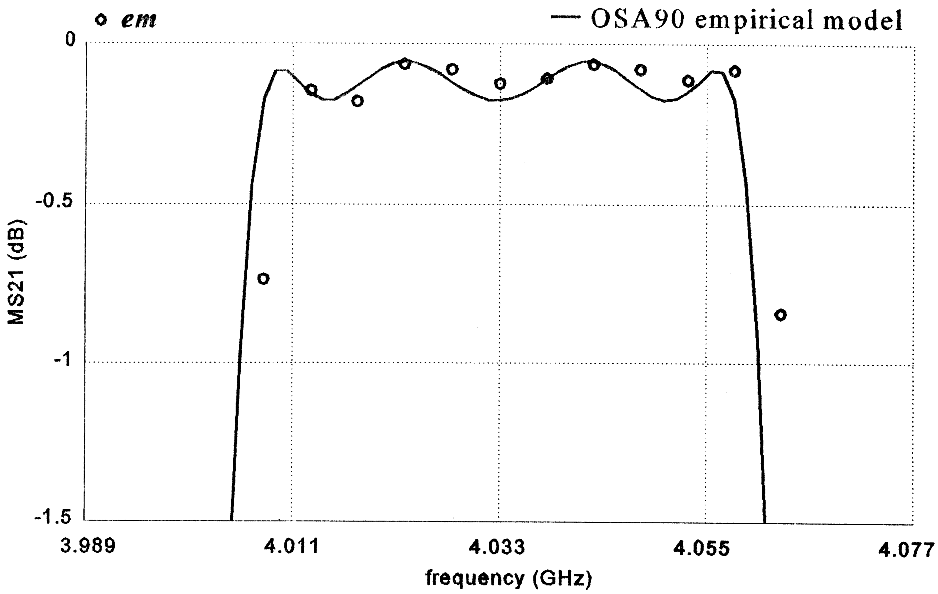


Solution by Aggressive Space Mapping After 3 Iterations

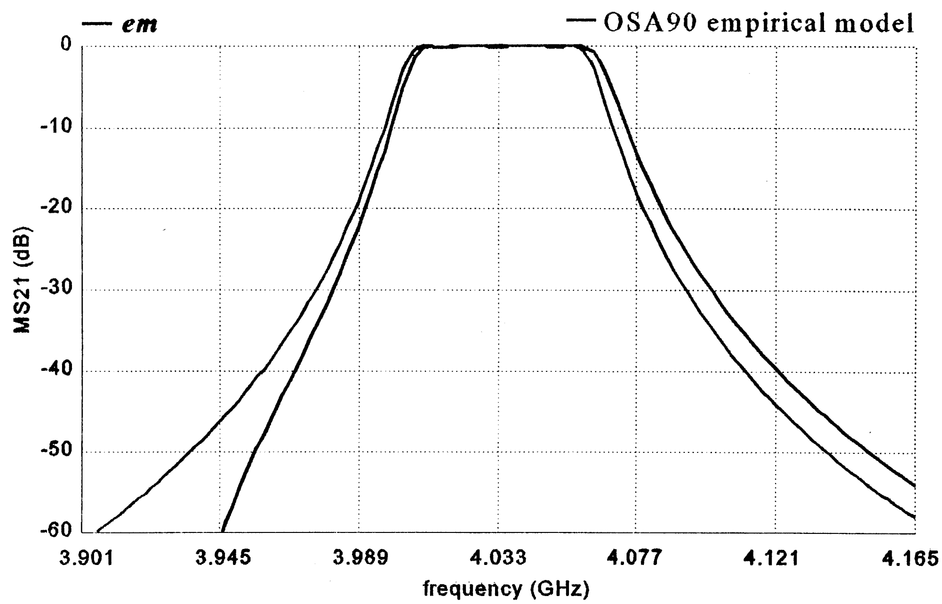


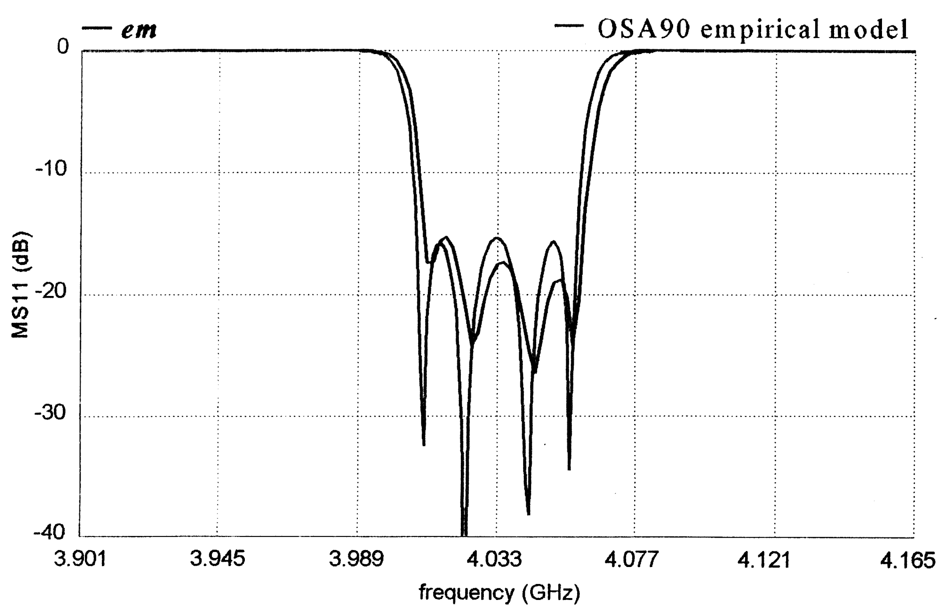


Solution by Aggressive Space Mapping
Detail of the Passband

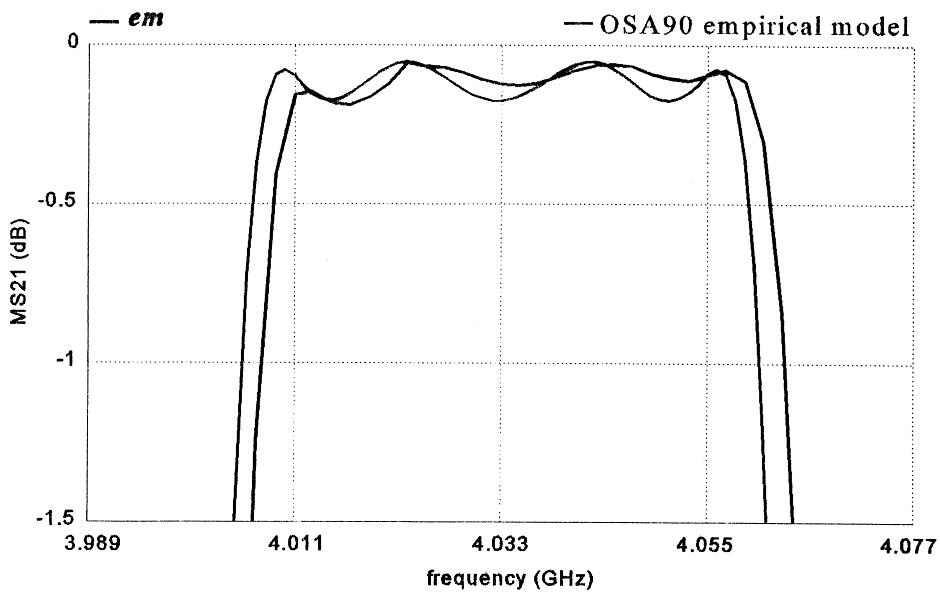


Solution by Aggressive Space Mapping
Fine Frequency Sweep

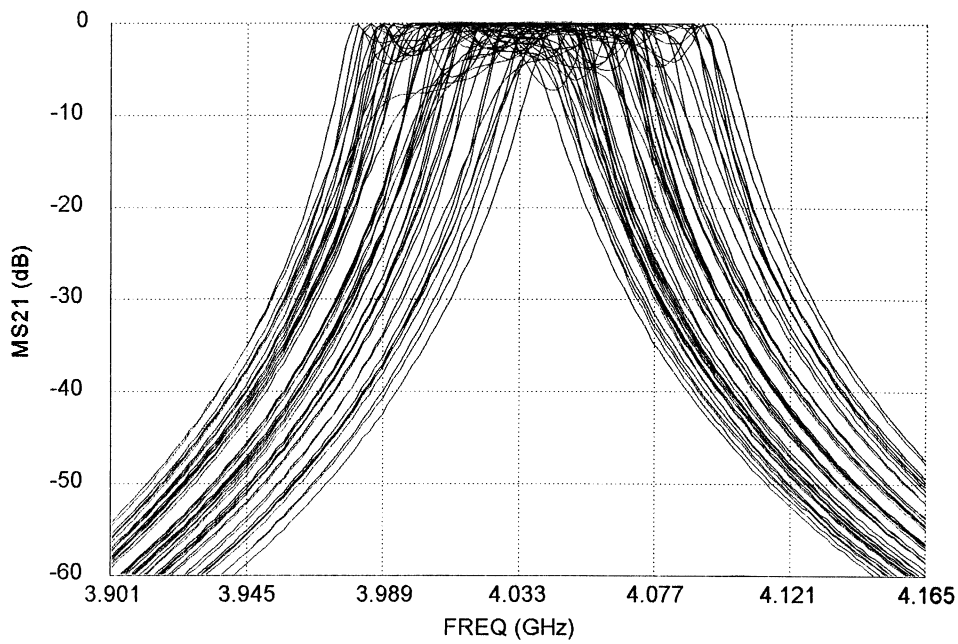


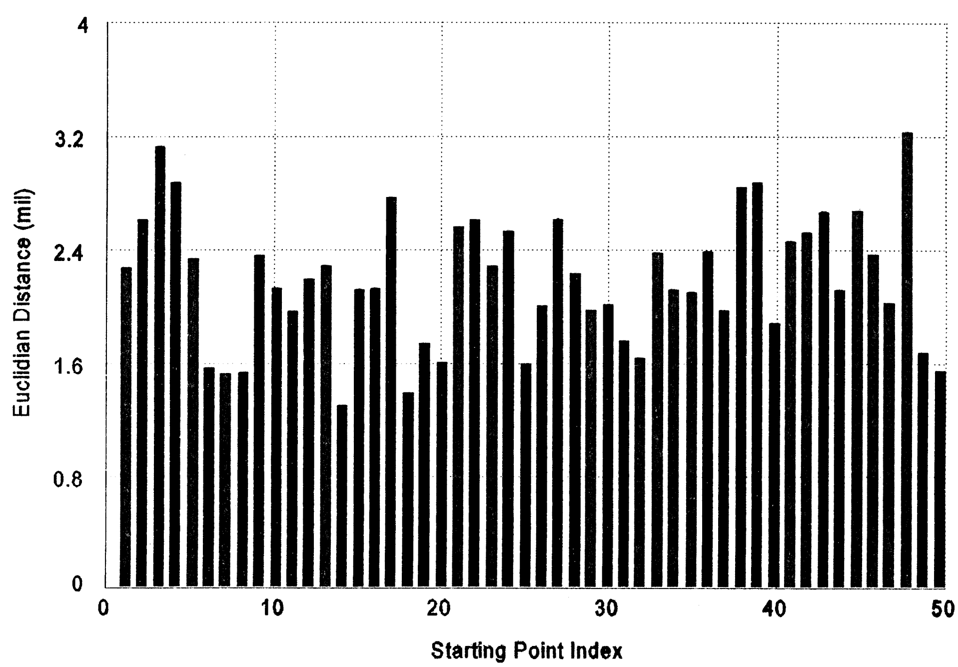


Solution by Aggressive Space Mapping
Detail of the Passband with Fine Frequency Sweep

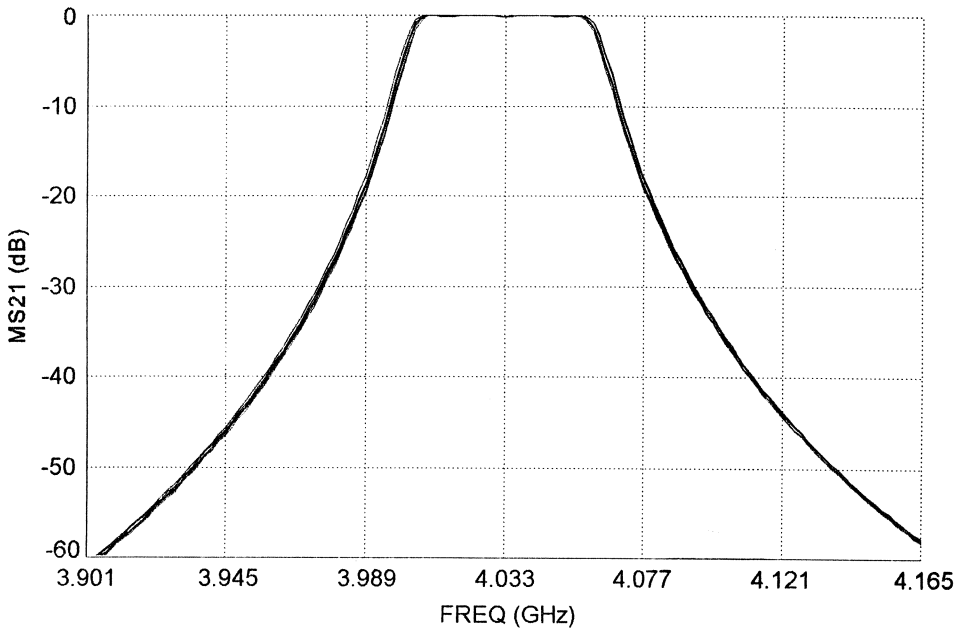


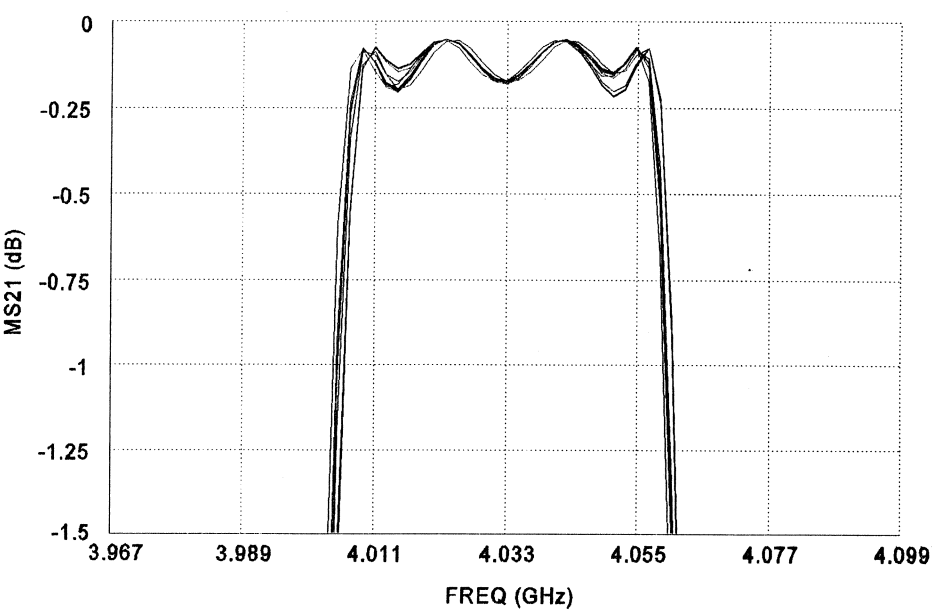
Solution Uniqueness Tested by Random Starting Points



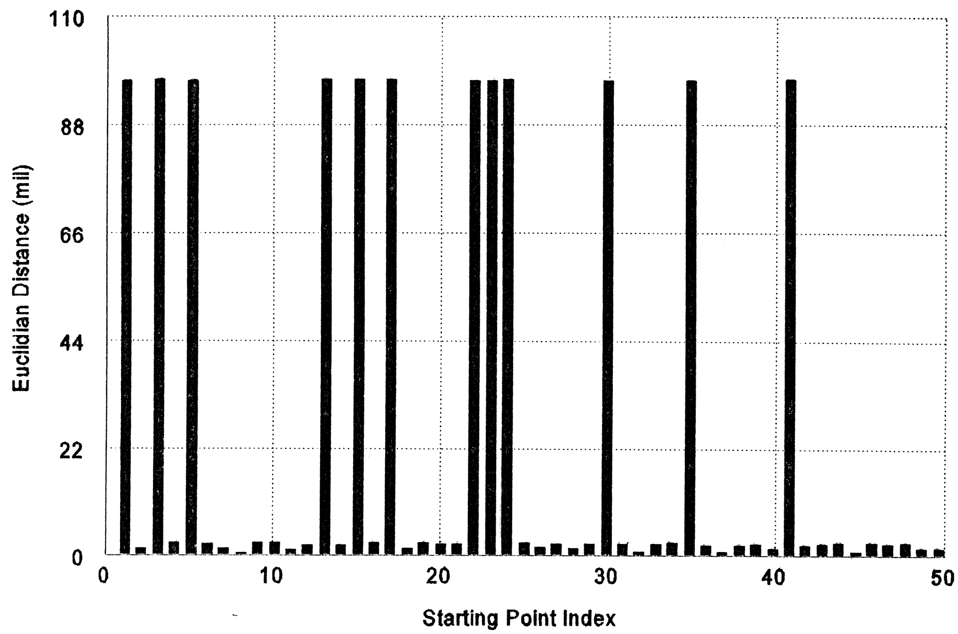


Solutions from the Random Starting Points

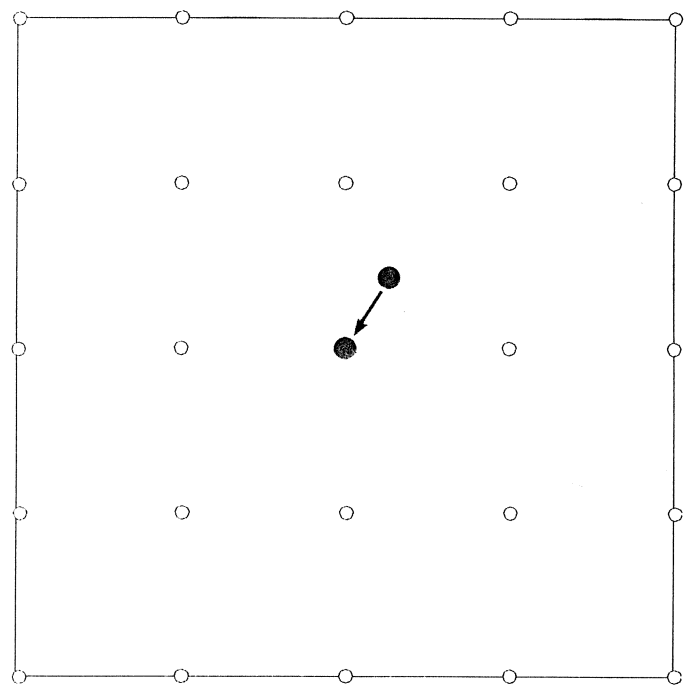




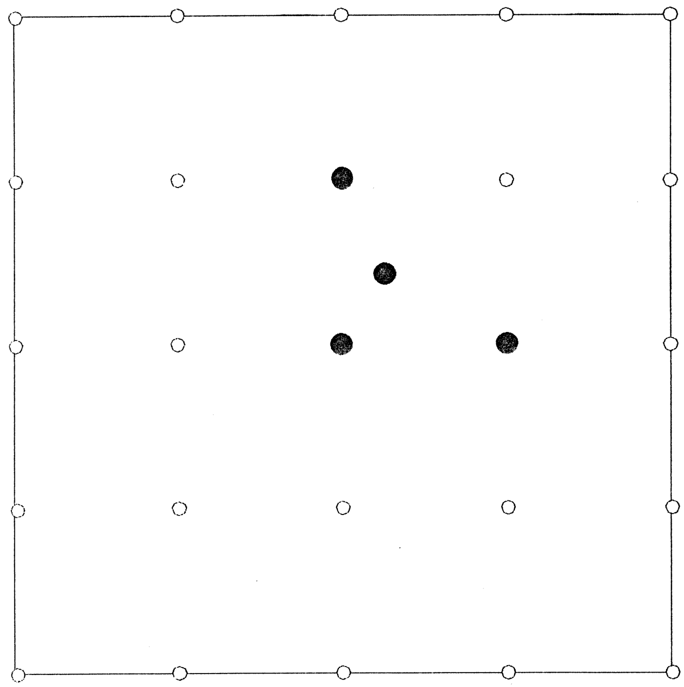
Two Distinct Solutions with Similar Responses



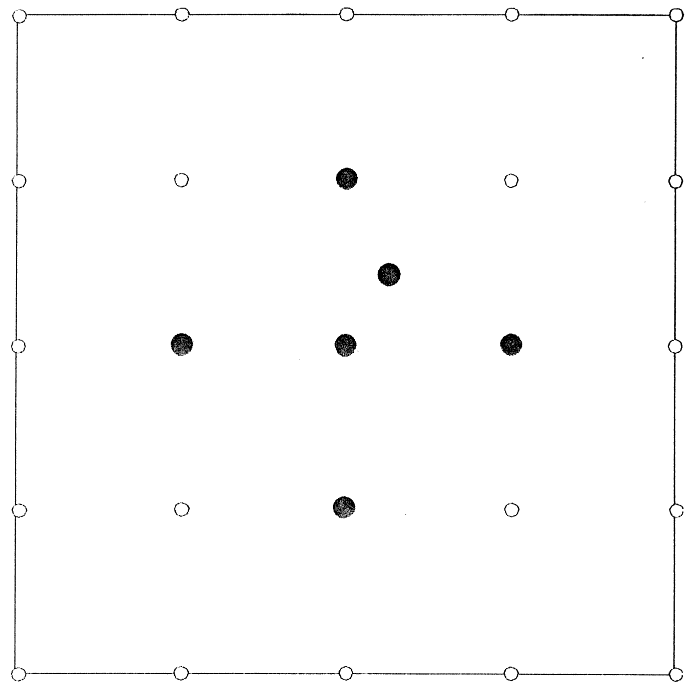
Truncation to the Nearest On-Grid Point



Linear Interpolation



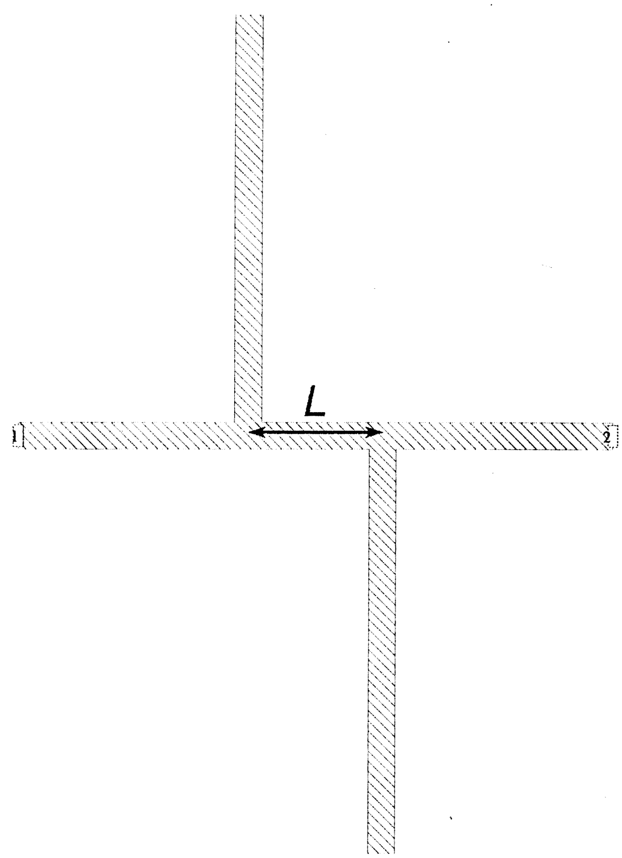
Quadratic Interpolation



Potential Pitfalls Associated with Interpolation

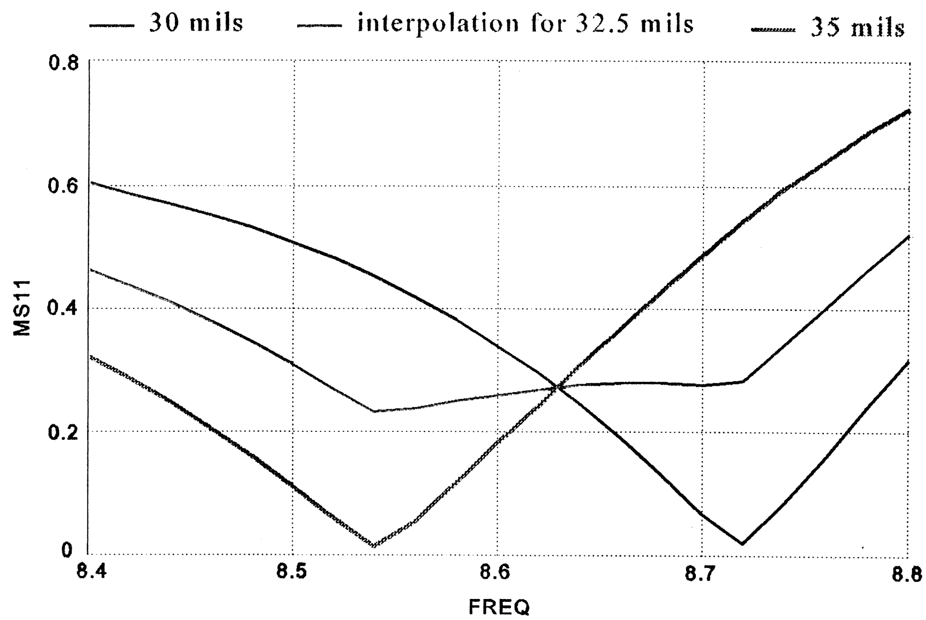
interpolation may lead to distorted results especially for structures with resonance(s)

double stub test circuit

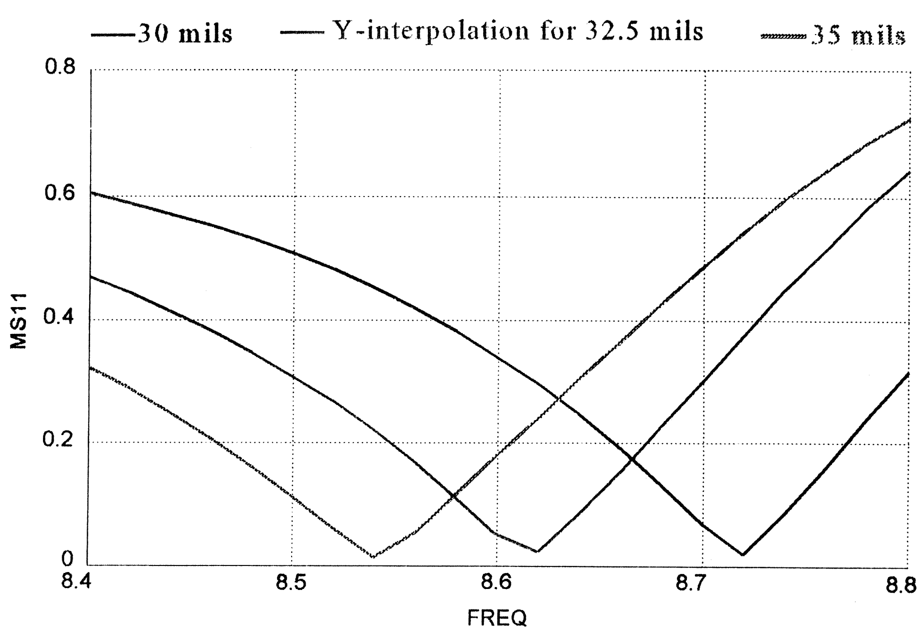


interpolate the parameter L between 30 mils and 35 mils (the grid size is 5 mils).

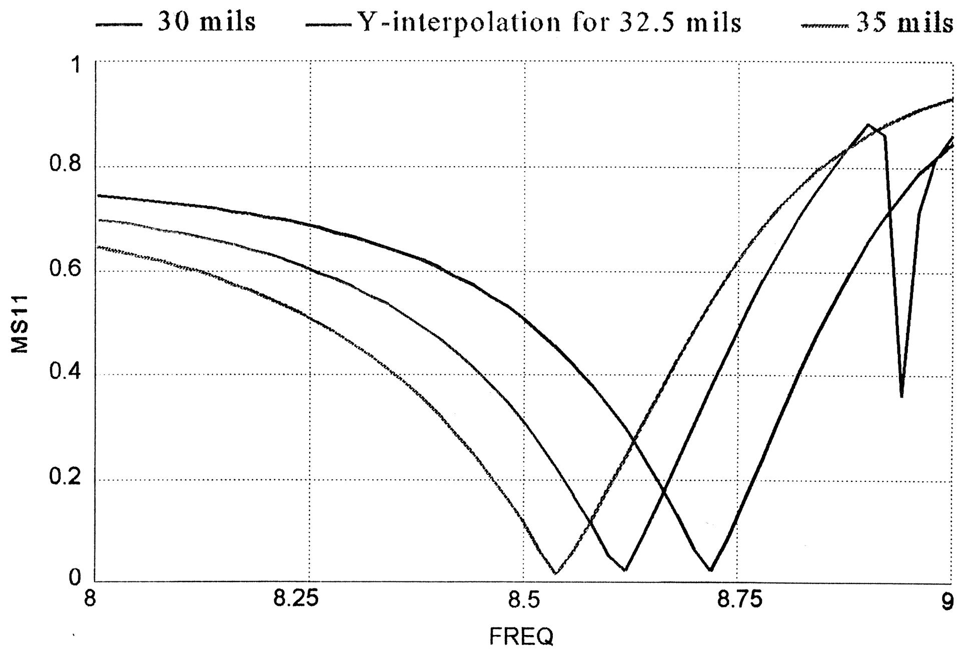
Linear Interpolation Based on *S* parameters

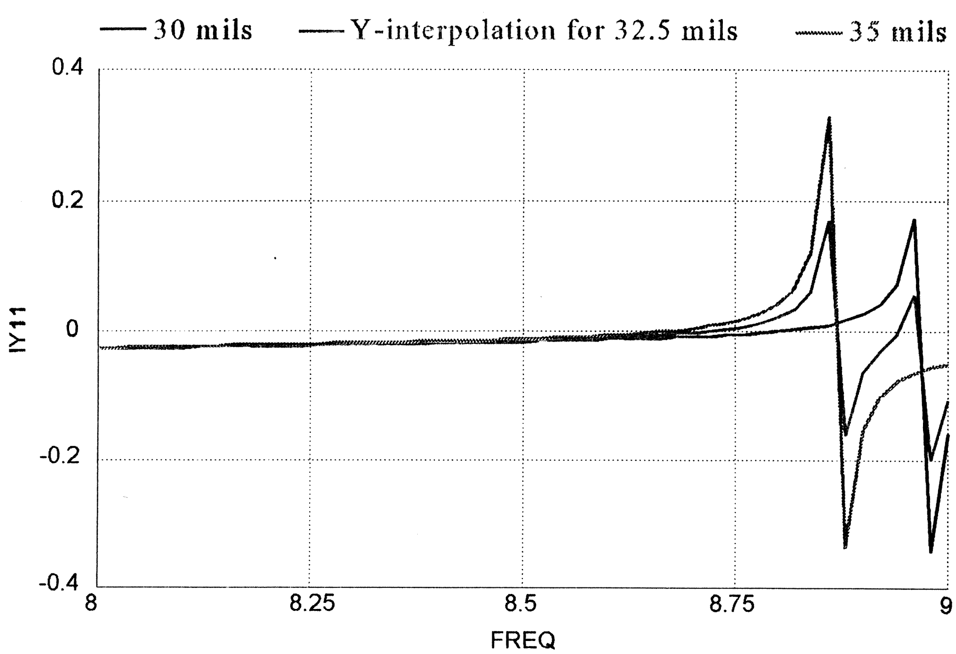


Linear Interpolation Based on *Y* Parameters



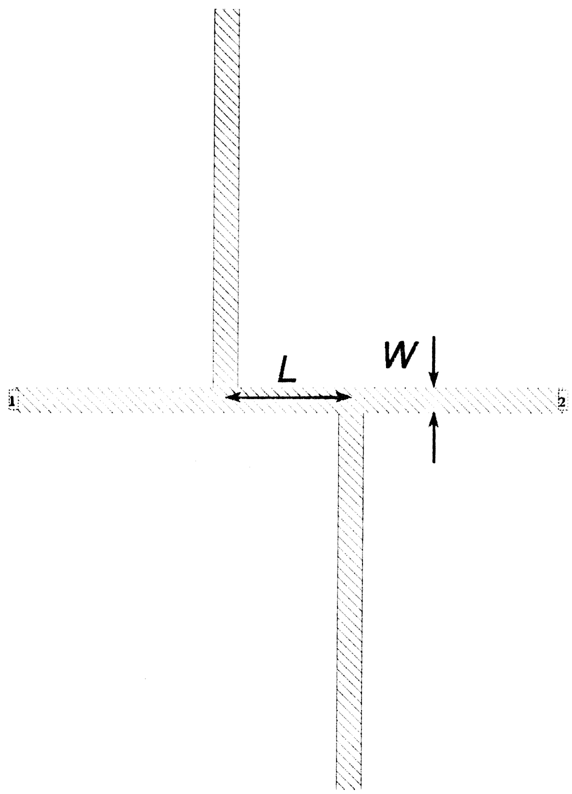
Y-Parameter-Interpolation May Also Have Problems



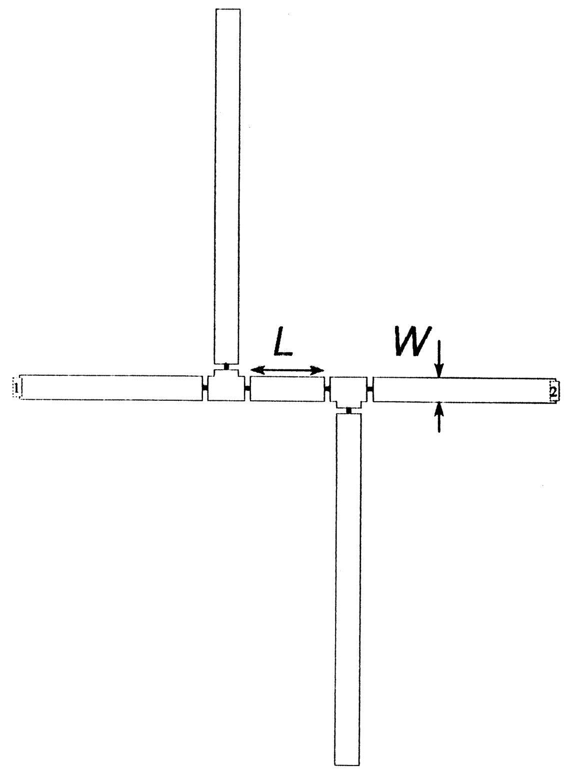


Empirical Circuit Model for Space Mapping

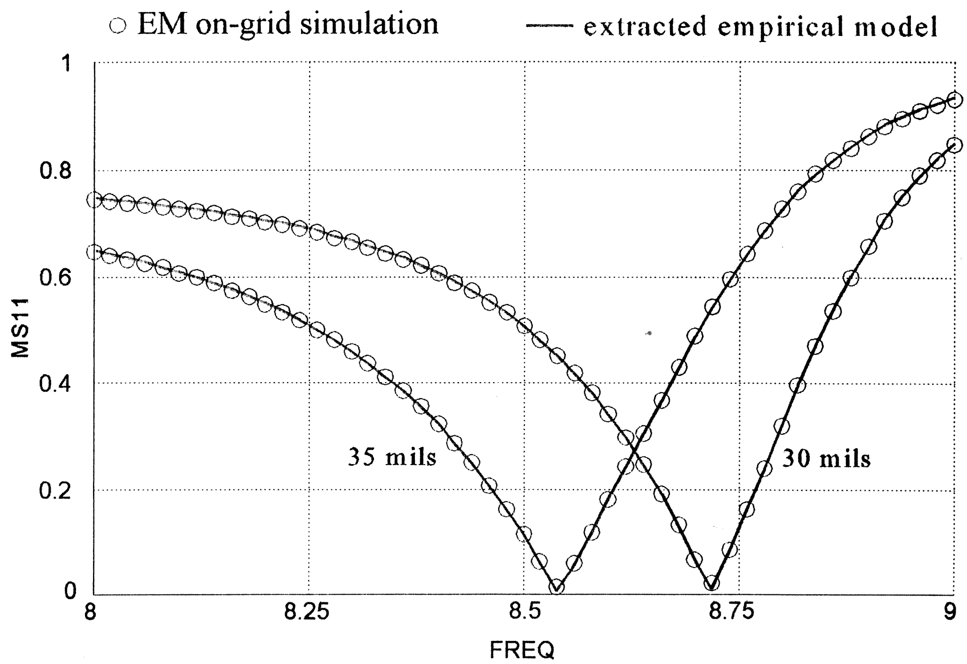
structure



empirical circuit model

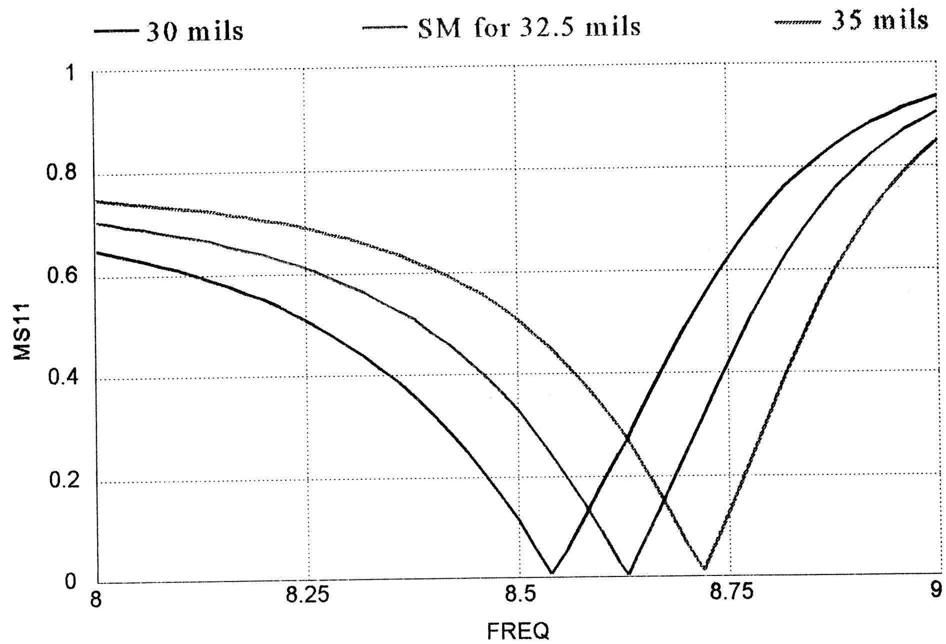


Parameter Extraction for Two On-Grid Points



EM Parameters		Empirical Model Parameters	
W	*L*	*W*	*L*
5 mils	30 mils	4.67 mils	32.1 mils
5 mils	35 mils	4.62 mils	37.2 mils

Space Mapping for Response Interpolation



Space Mapping for Response Interpolation

$$\boldsymbol{x}_{em} \triangleq [\, L_{em} \,]$$

$$\boldsymbol{x}_{os} \triangleq [\, W_{os} \quad L_{os} \,]^T$$

W_{em} is considered a constant since the interpolation is with respect to L_{em}

Space Mapping: $\boldsymbol{x}_{os} = \boldsymbol{P}(\boldsymbol{x}_{em})$

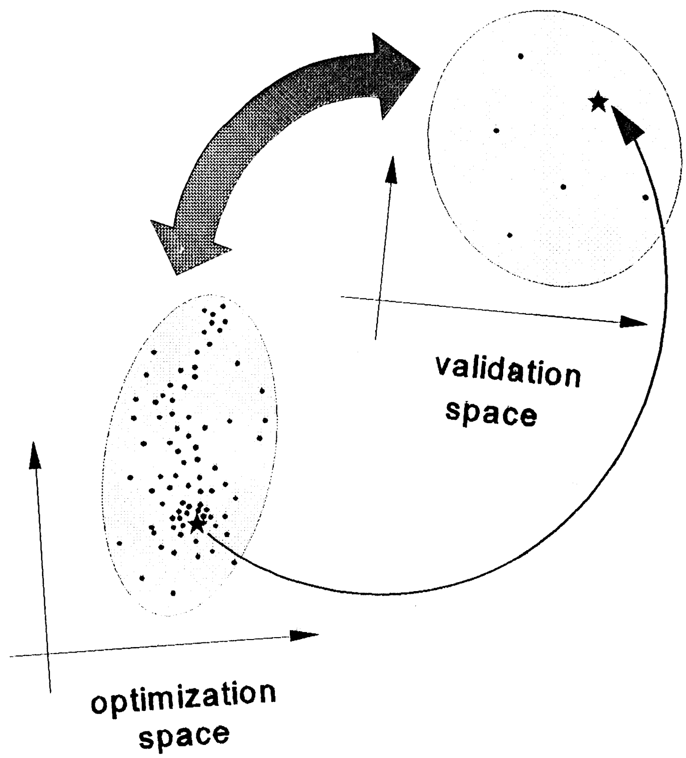
parameter extraction: $\boldsymbol{R}_{os}(\boldsymbol{x}_{os}) \approx \boldsymbol{R}_{em}(\boldsymbol{x}_{em})$

base points: L_{em} = 30 mils and 35 mils

interpolation: $\boldsymbol{x}_{os}^{i} = \boldsymbol{P}(L_{em} = 32.5 mils)$

interpolated response: $\boldsymbol{R}_{os}(\boldsymbol{x}_{os}^{i})$

Space Mapping™
(*Bandler et al., 1994*)



optimization model: $\boldsymbol{R}_{os}(\boldsymbol{x}_{os})$

EM model: $\boldsymbol{R}_{em}(\boldsymbol{x}_{em})$

Space Mapping: $\boldsymbol{x}_{os} = \boldsymbol{P}(\boldsymbol{x}_{em})$

such that $\boldsymbol{R}_{os}(\boldsymbol{P}(\boldsymbol{x}_{em})) \approx \boldsymbol{R}_{em}(\boldsymbol{x}_{em})$

Space Mapped solution: $\bar{\boldsymbol{x}}_{em} = \boldsymbol{P}^{-1}(\boldsymbol{x}^{*}_{os})$

Aggressive Space Mapping™
(*Bandler et al., 1995*)

new algorithm aggressively exploits *every* EM simulation

avoids upfront EM analyses at many base points

applies the classical Broyden update to the mapping

quasi-Newton iteration

$$x_{em}^{(j+1)} = x_{em}^{(j)} - B^{(j)^{-1}}(P^{(j)}(x_{em}^{(j)}) - x_{os}^{*})$$

Broyden update:

$$B^{(j+1)} = B^{(j)} + \frac{(P^{(j+1)}(x_{em}^{(j+1)}) - x_{os}^{*})\, h^{(j)^T}}{h^{(j)^T} h^{(j)}}$$

where

$$h^{(j)} = x_{em}^{(j+1)} - x_{em}^{(j)}$$

Conclusions

automated EM optimization is already a reality, providing solutions to practical problems

Geometry Capture™ empowers designers with user-definable capabilities never before considered possible

integrating EM and harmonic balance simulations elevates nonlinear circuit analysis and optimization to a new level of accuracy

Space Mapping™ is the key to combining previously disjoint simulation technologies, with wider applications yet to be explored

emerging new algorithms and implementations further improve the speed, robustness and user-friendliness of automated EM optimization