OPTIMIZATION TECHNIQUES AND APPLICATIONS USING ELECTROMAGNETIC SIMULATORS

John Bandler

OSA-97-OS-8-V

April 14, 1997

OPTIMIZATION TECHNIQUES AND APPLICATIONS USING ELECTROMAGNETIC SIMULATORS

J.W. Bandler

Optimization Systems Associates Inc.
P.O. Box 8083, Dundas, Ontario
Canada L9H 5E7

Email osa@osacad.com URL http://www.osacad.com

presented at

Gerhard-Mercator-Universitaet-GH-Duisburg
Dept. of Electromagnetic Theory and Engineering
Duisburg, Germany, April 17-18, 1997

Introduction

microwave CAD systems must link geometry, layout, physical and process parameters with performance, yield and system specifications

hierarchically structured CAD systems must integrate electromagnetic (EM) theory, circuit theory and system theory

fast, predictable, physics-based modeling and simulation of devices and circuits are important aspects of manufacturable mm-wave designs

CAD technology must account for statistical uncertainties and parameter spreads

CAD modules must facilitate an effective path from process, physical or geometrical description to a yield-driven, optimization-oriented design environment

First-Pass Success Approach

performance *and* cost specifications

automated optimization

accurate simulation models taking into account

- material and dimensional constraints
- operating environment
- production tolerances

Situations Needing Better Simulation Methodology

satellite system environmental temperature variations

cutting cost by lowering machining precision requirement

self-heating in high-density circuits

modulated and transient high-frequency signals

EM proximity couplings

Milestones I

The following is a list of achievement milestones of the OSA team.

computerized Smith chart plots (1966)

performance-driven optimization (1968)

optimization of waveguide circuits (1969)

adjoint sensitivities (1970)

cost-driven worst-case design with optimized tolerances (1972)

centering, tolerance assignment integrated with tuning at the design stage (1974)

integrated approach to microwave design with tolerances and uncertainties (1975)

yield-driven optimization for general statistical distributions (1976)

new results for cascaded circuits (1978)

optimal tuning and alignment at the production stage (1980)

Milestones II

fault diagnosis and parameter extraction (1980)

Optimization Systems Associates founded (1983)

world's fastest multiplexer optimizer (1984)

introduction of powerful minimax optimizers into commercial CAD/CAE products such as EEsof's Touchstone (1985)

large-scale microwave optimization (1986)

foundation of multi-circuit ℓ_1 modeling (1986)

world's first yield-driven design for Compact Software's Super-Compact® (1987)

enhancements to commercial CAD/CAE products including Compact Software's Microwave Harmonica™ (1988)

parameter extraction using large-scale concepts (1988)

nonlinear adjoint (harmonic balance) exact sensitivities (1988)

RoMPE™, world's first commercial product for FET parameter extraction featuring S-parameters and/or DC data (1988)

Milestones III

yield-driven design of nonlinear microwave circuits (1989)

FAST™, novel technique for high-speed nonlinear sensitivities (1989)

efficient large-signal FET parameter extraction using harmonics (1989)

HarPE™, world's first commercial product for harmonic balance driven FET parameter extraction (1989)

combined discrete/normal statistical modeling of active devices (1989)

efficient quadratic approximation for statistical design (1989)

nonlinear circuit optimization with dynamically integrated physical device models (1990)

analytically unified DC/small-signal/large-signal circuit design (1990)

OSA90™, world's first friendly optimization engine for performance- and yield-driven design (1990)

Milestones IV

Datapipe™ Technology, OSA90's interprocess communication system (1990)

OSA90/hope™, the microwave and RF harmonic optimization system (1991)

design optimization with external simulators, circuit-theoretic and field-theoretic (1991)

statistical modeling of GaAs MESFETs (1991)

gradient quadratic approximation for yield optimization (1991)

physics-based design and yield optimization of MMICs (1991)

Spicepipe™ connection of OSA90/hope™ with Zuberek's SPICE-PAC simulator (1992)

Empipe™ connection of OSA90/hope™ with Sonnet's Software's ***em***™ field simulator (1992)

predictable yield-driven circuit optimization (1992)

integrated physics-oriented statistical modeling, simulation and optimization (1992)

Milestones V

"fulfils the requirement of microwave engineers to model and simulate nonlinear active and passive systems without having a thorough knowledge of analysis, and optimization methods" - MEE 1992

Datapipe™ connection of OSA90/hope™with Hoefer's TLM electromagnetic field simulators (1993)

Datapipe™ connection of OSA90/hope™ with Nakhla/Zhang VLSI interconnect simulators (1993)

microstrip filter design using direct EM field simulation (1993)

yield-driven direct electromagnetic optimization (1993)

robustizing modeling and design using Huber functions (1993)

"CAD review: Non-linear CAD benchmark" by MEE (1993)

EM design of HTS microwave filters (1994)

CDF approach to statistical modeling (1994)

Milestones VI

Space Mapping™ - a fundamental new theory for design with CPU intensive simulators (1994)

"CAD review: the 7 GHz doubler circuit" by MEE (1994)

optimization of planar structures with arbitrary geometry (1994)

breakthrough Geometry Capture™ technique (1995)

aggressive Space Mapping™ for EM design (1995)

cost-driven physics-based large-signal simultaneous device and circuit design (1995)

integrated harmonic balance and EM optimization (1995)

novel heterogeneous parallel yield-driven EM CAD (1995)

mixed-domain multi-simulator statistical parameter extraction and yield-driven design (1995)

full-day MTT-S workshop on Automated Circuit Design Using Electromagnetic Simulators (Arndt, Bandler, Chen, Hoefer, Jain, Jansen, Pavio, Pucel, Sorrentino, Swanson, 1995)

Milestones VII

explosion of development and use of optimization-based technology for automated circuit design with EM simulators (1994, 1995)

Network Datapipe™ connection of OSA90/hope™ with Hoefer's TLM electromagnetic field simulators on massively parallel computers (1995)

Datapipe™ connections of OSA90/hope™ with Sorrentino's mode-matching electromagnetic field simulators with adjoint sensitivities (1995)

Datapipe™ connection of OSA90/hope™ with Arndt's waveguide component library (1995)

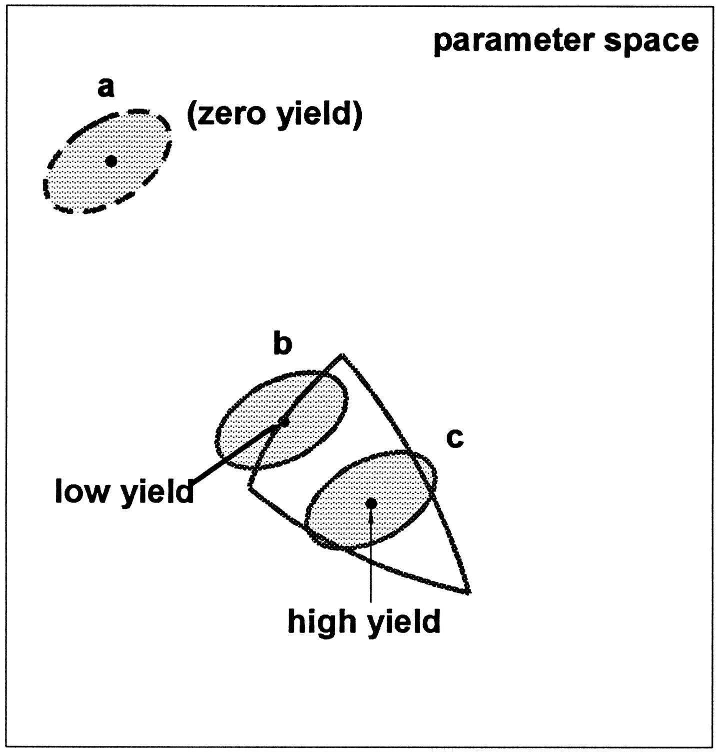
parameterization of arbitrary geometrical structures (1996)

fully-automated Space Mapping™ optimization of 3D structures (1996)

Empipe3D™ connection of OSA90/hope™ with Hewlett-Packard's HFSS and Ansoft's Maxwell® Eminence 3D full-wave simulators (1996)

EmpipeExpress™ and ***empath***™ connections to Sonnet Software's ***em***™ field simulator (1996)

Space Mapping™ optimization with finite element (FEM) and mode matching (MM) EM simulators (1997)



Yield interpretation in the parameter space

Selected Users of OSA Technology

Alcatel
AMTEL
Alenia
BNR
Boeing
British Telecom
ComDev
Compact Software
COMSAT
CRC (Canada)
Daimler Benz
Eesof
France Telecom
GE
Hughes
IMST (Germany)
Loral
M/A-COM
MIT Lincoln Labs
Micronet
NAWC
Nortel
Philips
Raytheon
Rockwell
Schrack Aerospace
Siemens
Sumitomo
Texas Instruments
Telettra
TRIO
TRW
Watkins-Johnson

University Users of OSA Technology

Austria	Belgium
Canada	Denmark
Germany	Hong Kong
Italy	Korea
Mexico	Netherlands
Spain	Switzerland
UK	USA

OSA90/hope™ Version 4.0

general nonlinear circuit simulation and optimization

comprehensive optimization/nonlinear modeling

statistical analysis and design

automated Space Mapping optimization

3D visualization, global optimization

Datapipe connection to user's in-house simulators

JWB-97-14

HarPE™
Version 2.0

device characterization, simulation and optimization

FET, bipolar, HEMT, HBT, thermal modeling

parameter extraction, statistical modeling

cold and hot measurements

Huber optimization, Monte Carlo analysis

can be invoked from OSA90™ as a child process

Empipe™ Version 4.0

merges OSA90™ and Sonnet's em™ for direct EM optimization

integrates EM analysis into circuit-level optimization

captures and optimizes arbitrary geometries

a library of built-in microstrip elements

intelligent and efficient interpolation and database

JWB-97-16

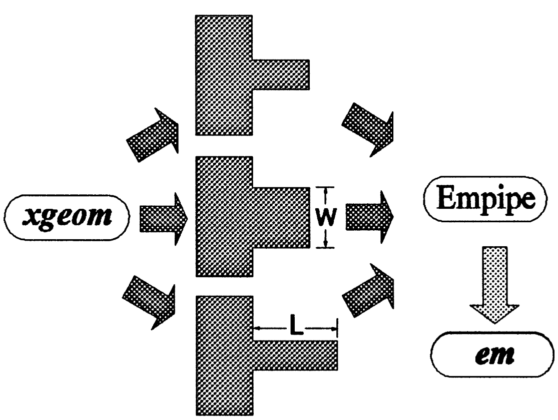
EmpipeExpress

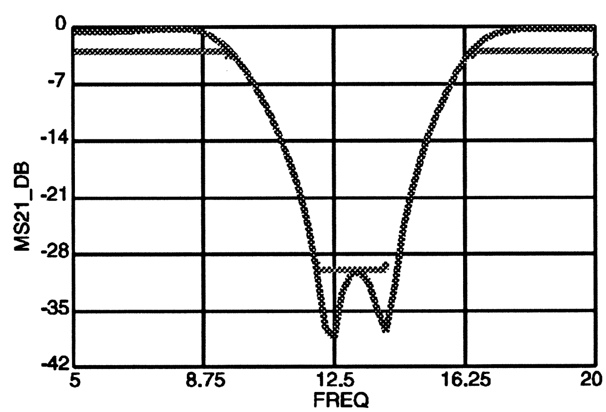
driving Sonnet's *em*

consolidated optimization features

concise, intuitive user interface

Geometry Capture





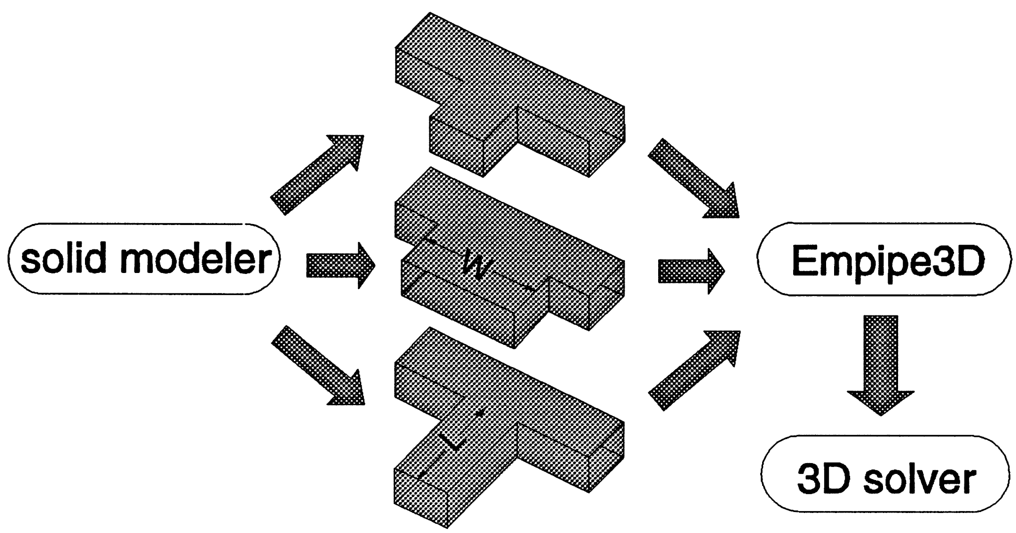
JWB-97-17

Empipe3D

driving Maxwell Eminence of ANSOFT and HFSS from hp

automated, efficient optimization

parameterization of arbitrary 3D structures by Geometry Capture



Overview of Presentation

design centering; yield optimization; cost-driven design

integration through Datapipe™

EM optimization

parameterization through Geometry Capture™

parallel computation

Space Mapping™ optimization

Physics-Based Yield Optimization of MMICs

random variations in manufacturing process may lead to some circuits failing to meet design specifications

production tuning of MMICs is restricted

component replacement is not possible

circuits are manufactured in batches rather than individually

the cost is directly affected by yield

the ability to predict and enhance production yield is critical

accurate EM simulations of passive elements and physical simulations of active devices enhanced by Space Mapping optimization

Yield Optimization of a Three-Stage MMIC Amplifier (*Bandler, Biernacki, Cai, Chen, Ye and Zhang, 1992*)

the three-stage X-band MMIC amplifier is based on the circuit topology and fabrication layout originally designed by Thomson-Semiconductors *(Kermarrec and Rumelhard, 1988)*

intended as a gain block for phased-array antennas

the amplifier contains three GaAs MESFETs using an interdigitated structure with two gate fingers of dimensions 150 μm × 1.0 μm

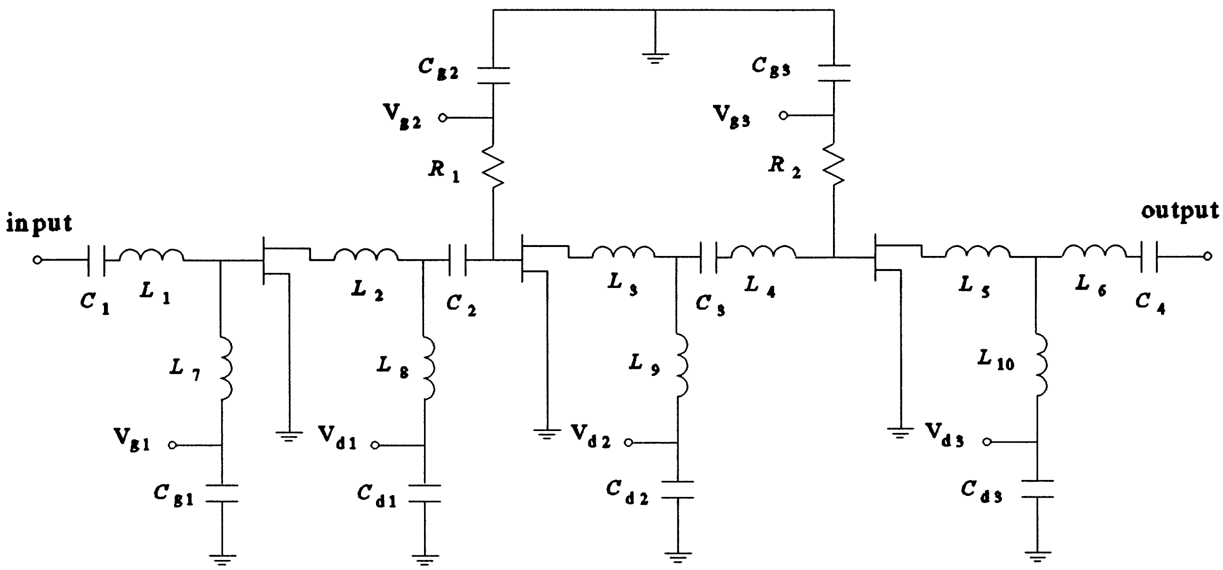
all passive elements are realized using lumped MMIC elements: spiral inductors, MIM capacitors and bulk resistors

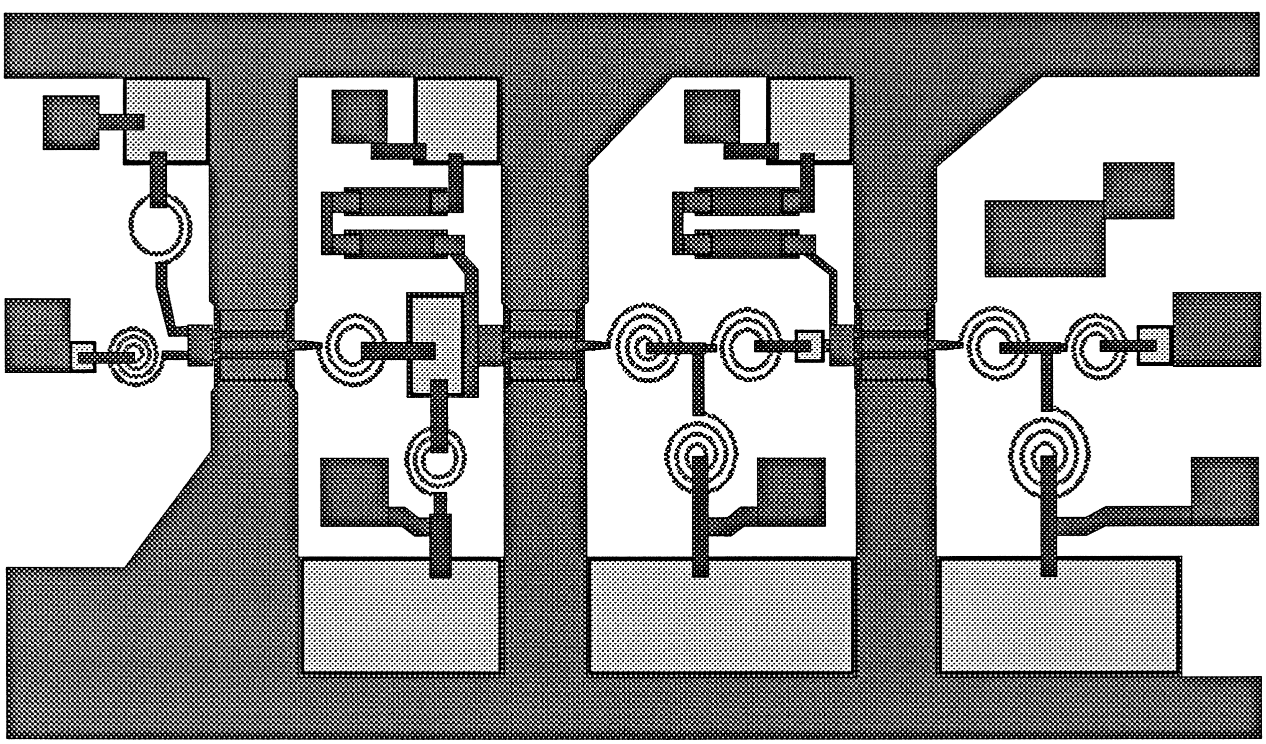
37 statistical variables with correlations and 16 design variables

yield optimization carried out by OSA90/hope

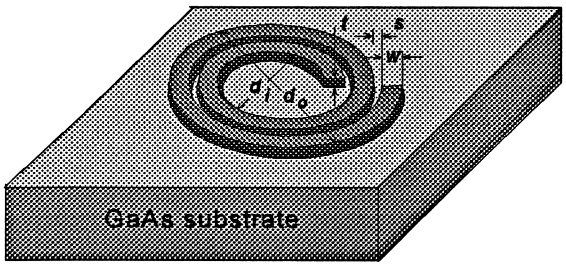
yield is improved from 26% at the nominal design to 69% after optimization

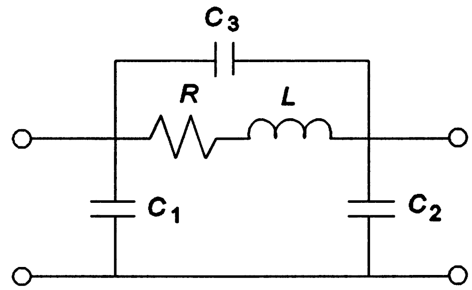
Circuit Schematic and Layout of the Three-Stage Amplifier

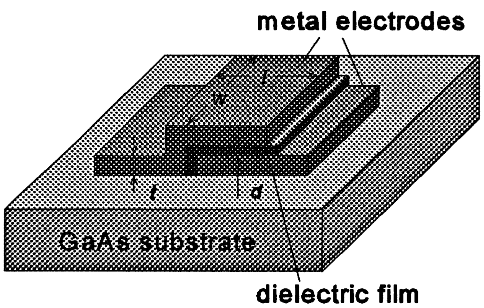


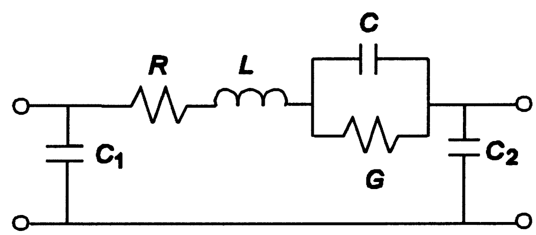


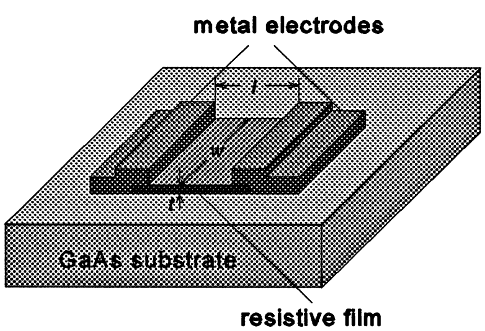
Passive Elements

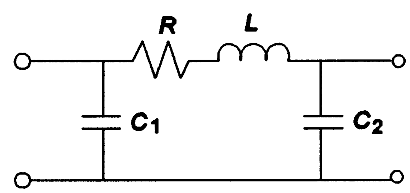












the expressions for the equivalent circuit components are derived from (simplified) device physics

Predictable Yield-Driven Circuit Optimization
(*Bandler, Ye, Cai, Biernacki and Chen, 1992*)

usefulness of yield-driven design depends on the accuracy of yield estimated using the statistical model

yield predicted by Monte Carlo simulation using the model should be consistent with the yield predicted directly from the device measurement data

the advantage of a statistical model over the measurement data is that the model provides for convenient interpolation

the selection of device parameters for yield optimization can be assisted by yield sensitivity analyses

the yield can be significantly increased by simultaneous circuit-device optimization

design of a small-signal broadband amplifier is investigated using OSA90/hope with the KTL model w.r.t. a number of specifications

the predicted yield is verified using the device data

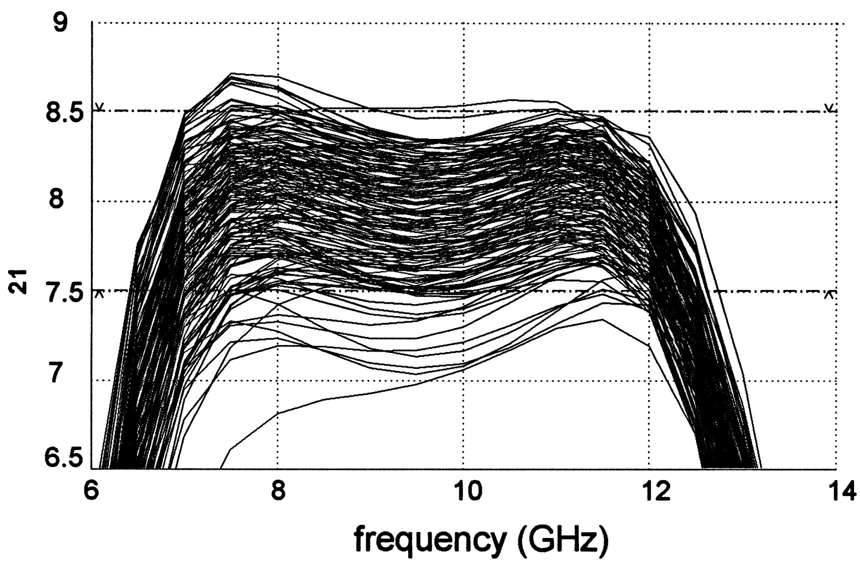
YIELD VERIFICATIONS

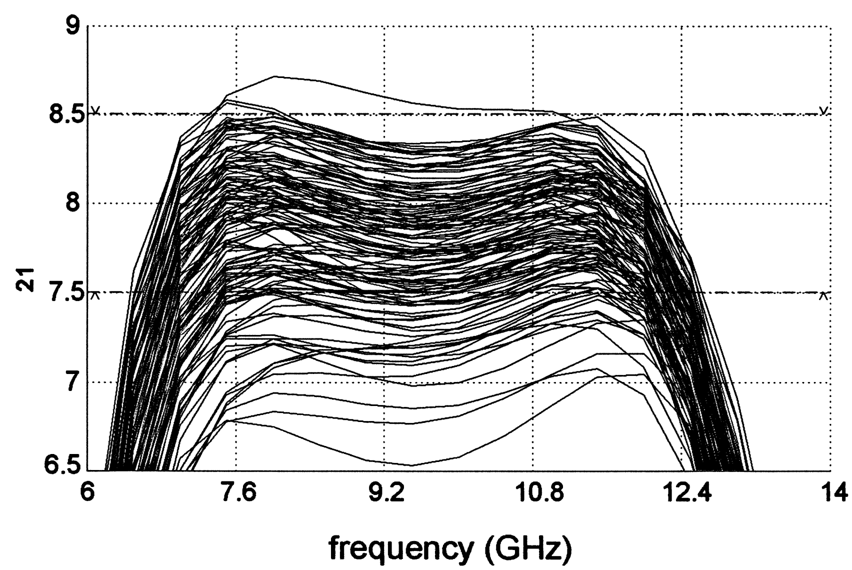
	Before Yield Optimization		After Yield Optimization	
	Predicted Yield (%)	Verified Yield (%)	Predicted Yield (%)	Verified Yield (%)
Spec. 1	17.5	15.7	67	57.9
Spec. 2	21	20	83	75.7
Spec. 3	44	37.1	98	93.6

Spec. 1: $7.5\text{dB} < |S_{21}| < 8.5\text{dB}$, $|S_{11}| < 0.5$, $|S_{22}| < 0.5$.
Spec. 2: $6.5\text{dB} < |S_{21}| < 7.5\text{dB}$, $|S_{11}| < 0.5$, $|S_{22}| < 0.5$.
Spec. 3: $6.0\text{dB} < |S_{21}| < 8.0\text{dB}$, $|S_{11}| < 0.5$, $|S_{22}| < 0.5$.

200 Monte Carlo outcomes are used for predicted yield, 140 for verified yield.

Gain After Optimization from Model and from Data





Physics-Based Cost-Driven Design
(*Bandler, Biernacki, Cai and Chen, 1995*)

yield optimization maximizes the yield by adjusting the nominal values of the design variables keeping tolerances fixed

the cost for obtaining small tolerances may be very high

there is a trade-off between the yield and the cost

cost-driven design minimizes the cost while maintaining the required yield

cost-driven optimization

$$\underset{\boldsymbol{x}}{\text{minimize}} \quad C(\boldsymbol{x})$$

$$\text{subject to } \; Y \geq Y_S$$

$\boldsymbol{x}$ vector of parameter tolerances
Y design yield
Y_S specified yield
$C(\boldsymbol{x})$ cost function, e.g.,

$$C(\boldsymbol{x}) = \sum_{i=1}^{m} \frac{c_i}{x_i}$$

OSA's Datapipe™

encapsulating simulators as black-box executables with alphanumeric inputs and outputs

built-in support for network and parallel computing

preprocessing and postprocessing of data

preprocessing of ***x1, x2****, ...*;

FILE="*simulator*"

INPUT=(*text,* ***x1, x2****,* ...)

OUTPUT=(***y1****,* ***y2****,* ...);

postprocessing of ***y1, y2****, ...*;

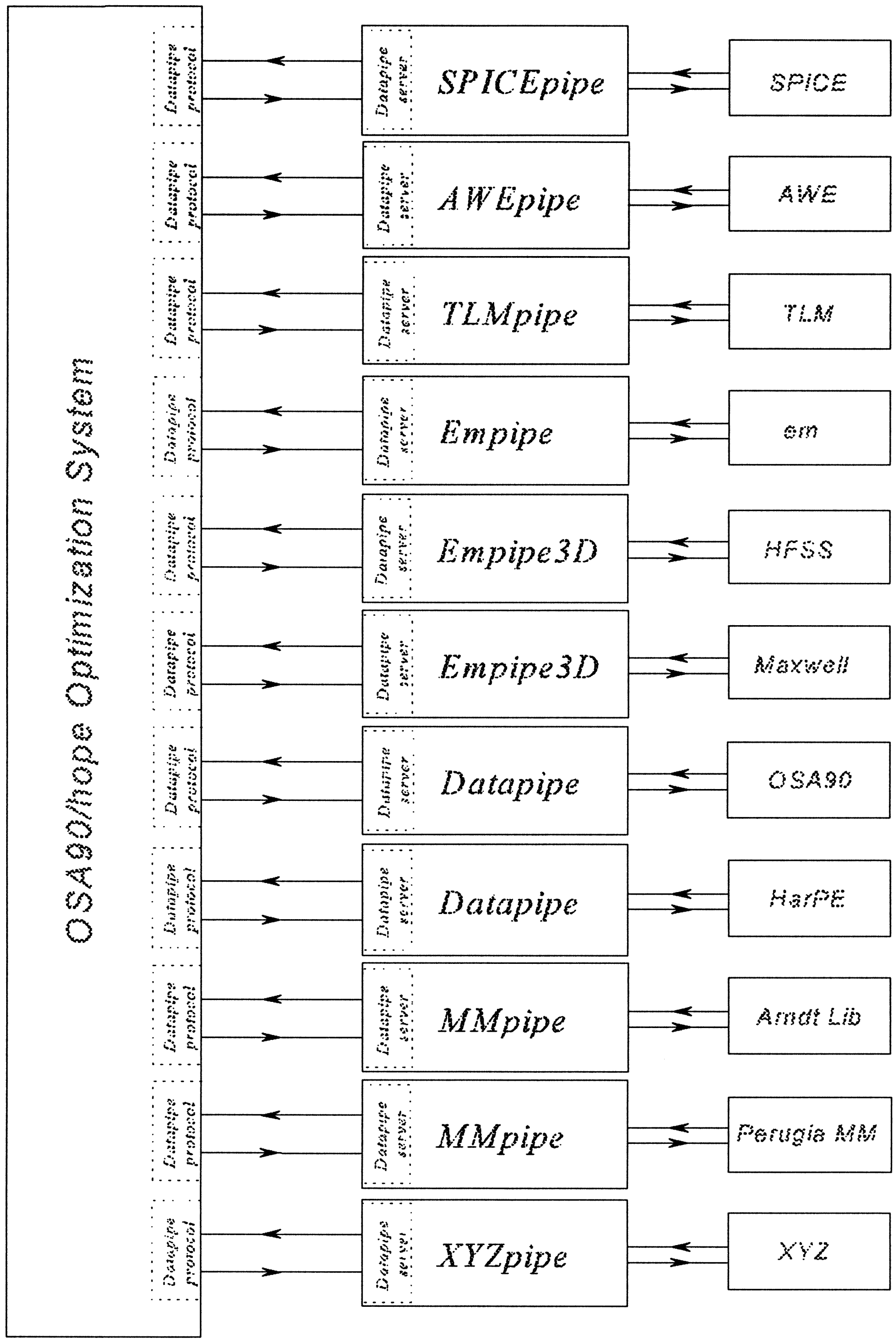
hierarchy of variables

multiple simulators can be combined (serial and parallel)

simultaneous specifications in different domains

symbolic algebra and gradients

OSA's Datapipe™ System



Challenges of Automated EM Optimization
(*Bandler et al., 1993, 1994*)

drastically increased analysis time

discrete nature of some EM solvers

continuity of optimization variables

gradient information

interpolation and modeling

integrated data bases

Geometry Capture™
(*OSA, 1994*)

EM simulators deal directly with the layout representation of circuits in terms of absolute coordinates

geometrical coordinates are not directly related to designable parameters

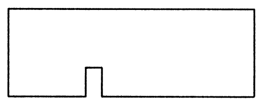
geometrical parameterization is needed for every new structure

using a graphical layout editing tool the user marks the evolution of the structure as the designable parameters change

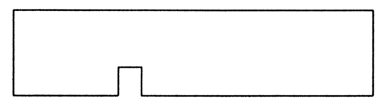
processed by OSA's Empipe to extract the relevant information

a mapping between the geometrical coordinates and the designable parameter values is established

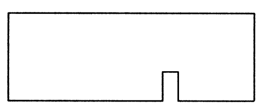
Various Object Evolutions



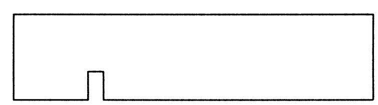
(a)



(b)



(c)



(d)

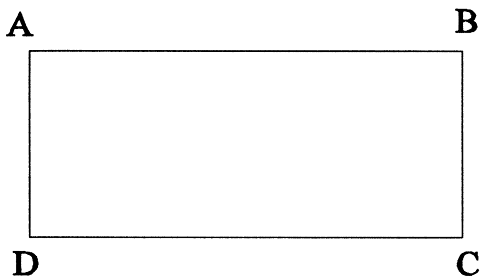
(a) initial geometry

(b) proportional expansion of the whole structure along the x axis

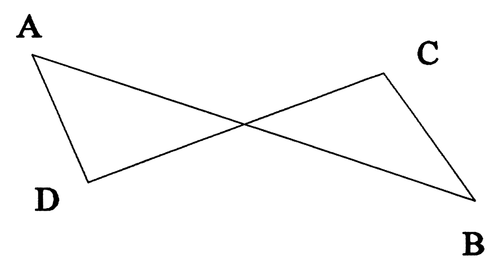
(c) only the location of the slit in the fixed line is allowed to change

(d) only the segment to the right of the slit is allowed to expand

Possible Pitfalls of Arbitrary Movement of Vertices



(a)

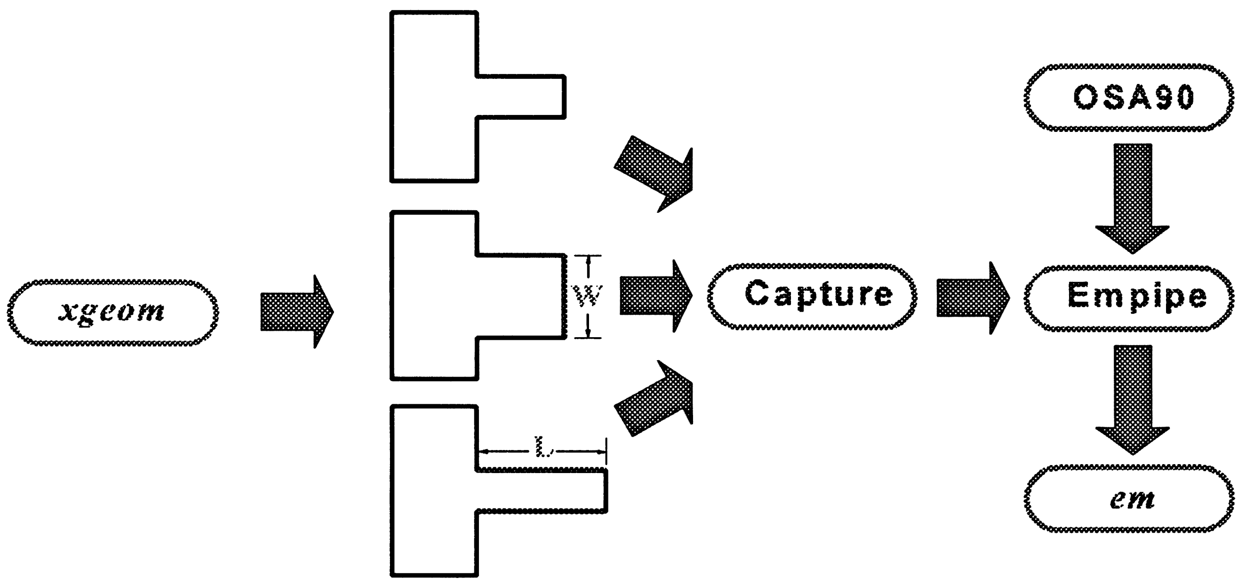


(b)

(a) initial geometry

(b) an unwanted result due to an arbitrary and independent movement of vertices

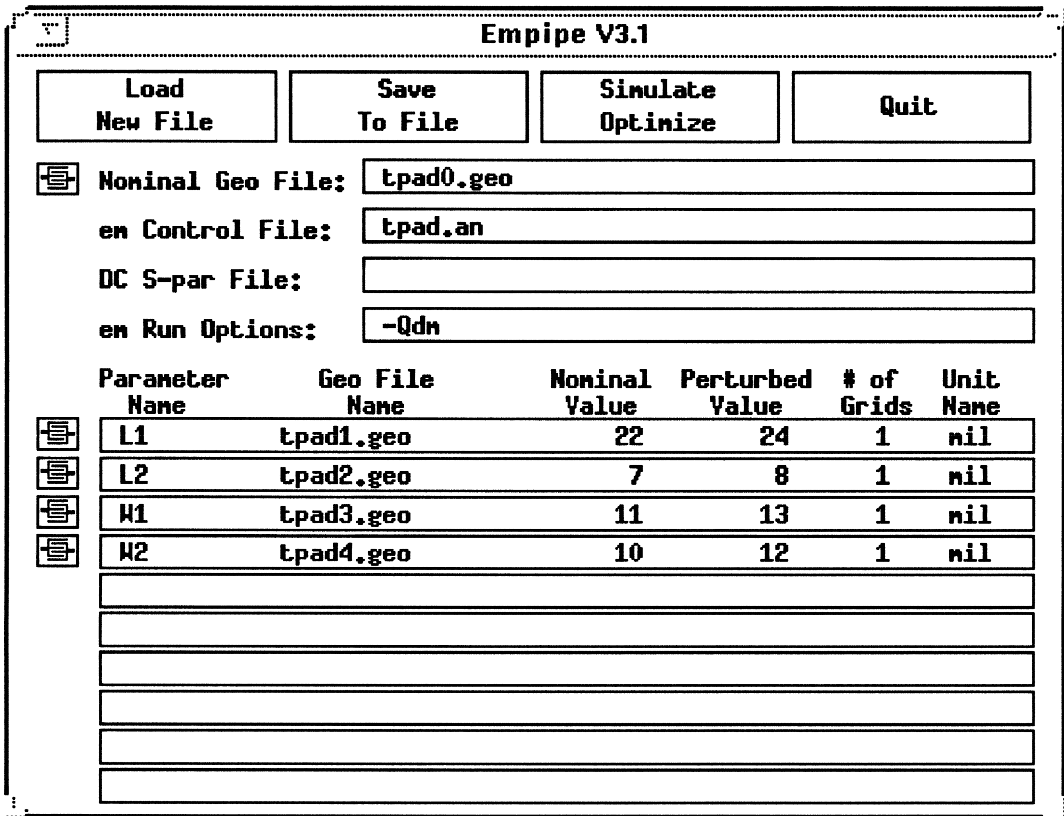
Implementation of Geometry Capture™



employs a sophisticated algorithm in a manner completely transparent to the user

extremely easy to use

Empipe Geometry Capture™ Form Editor


Empipe V3.1

Load New File | Save To File | Simulate Optimize | Quit

Nominal Geo File: tpad0.geo

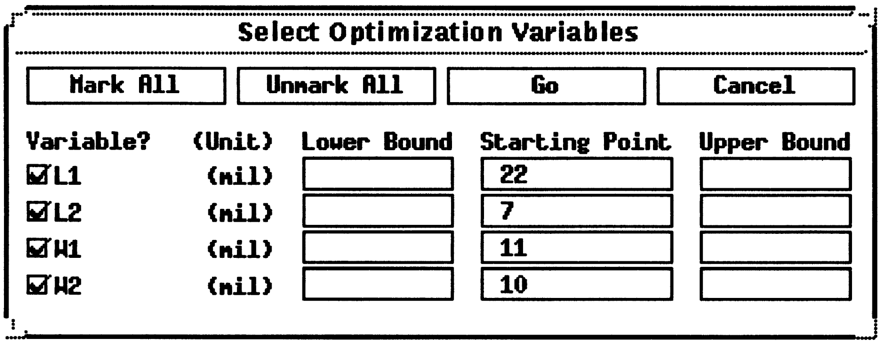
em Control File: tpad.an

DC S-par File:

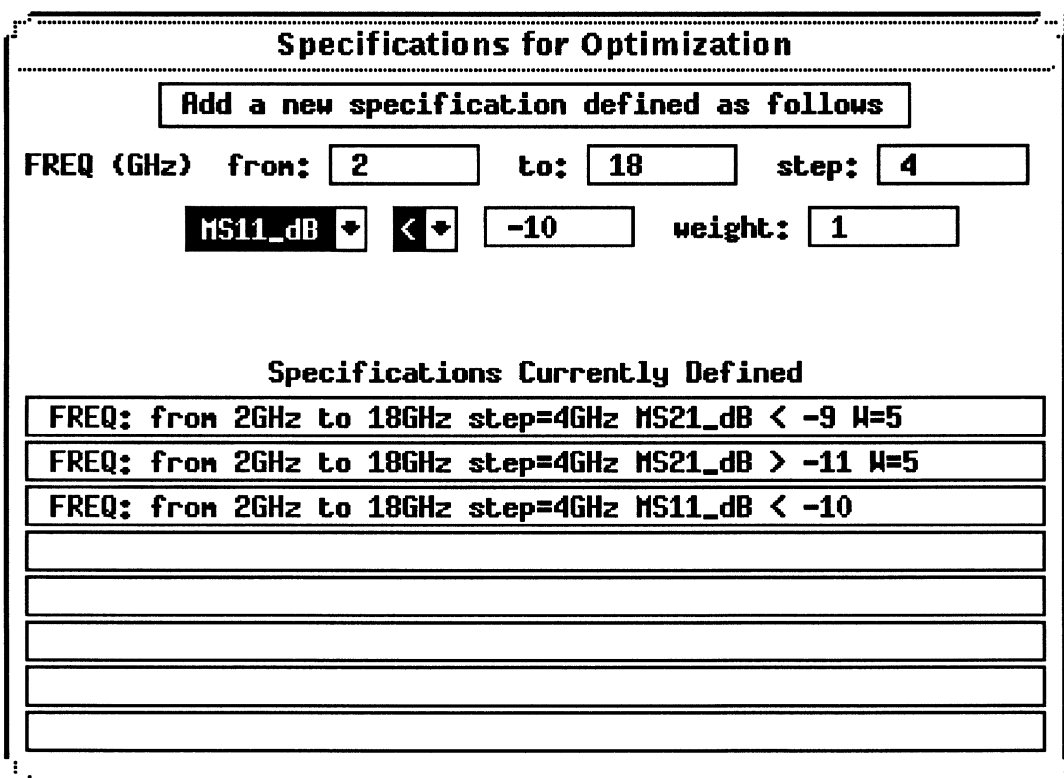
em Run Options: -Qdm

Parameter Name	Geo File Name	Nominal Value	Perturbed Value	# of Grids	Unit Name
L1	tpad1.geo	22	24	1	mil
L2	tpad2.geo	7	8	1	mil
W1	tpad3.geo	11	13	1	mil
W2	tpad4.geo	10	12	1	mil

Select Optimization Variables Windows

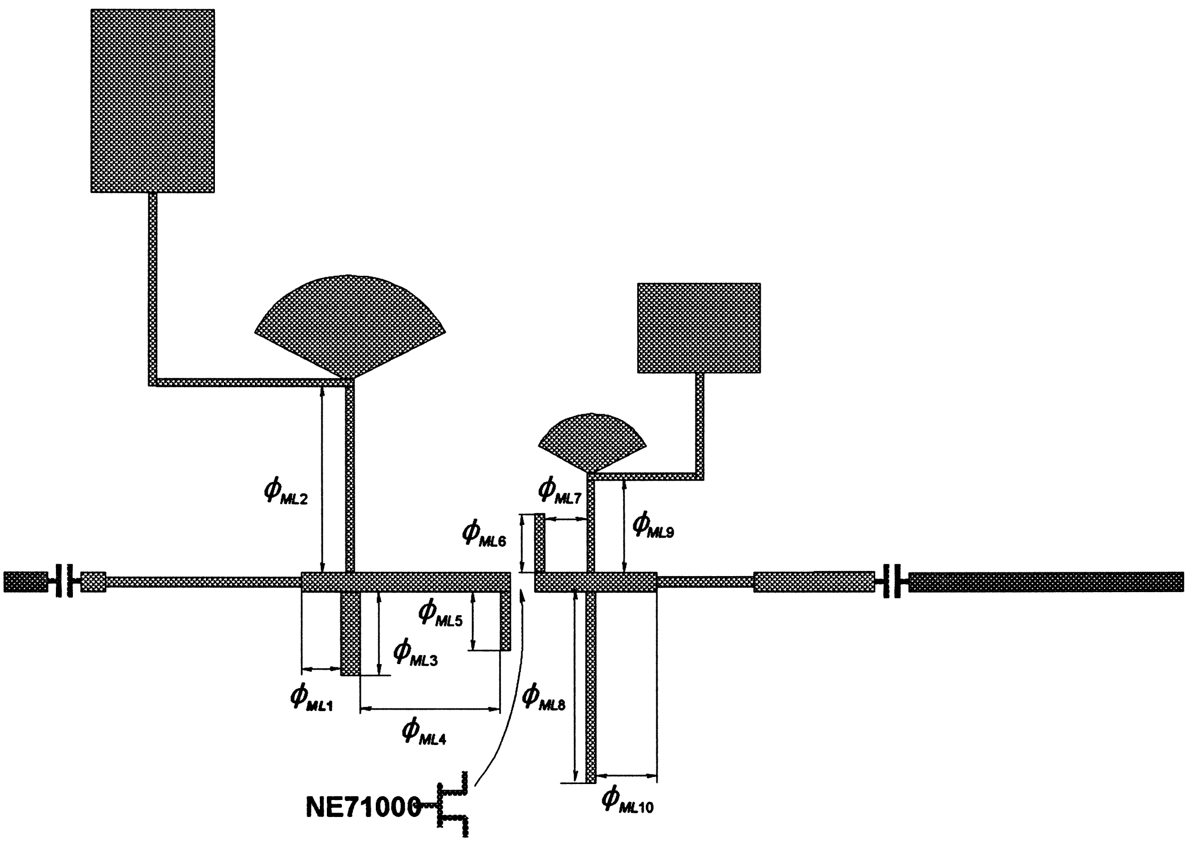


Specifications for Optimization Windows



Nonlinear FET Class B Frequency Doubler

(Microwave Engineering Europe, 1994)



using Geometry Capture™, the linear subcircuit is defined as one optimizable structure with 10 variables

Direct EM Optimization of the Frequency Doubler
(*Bandler, Biernacki, Cai, Chen and Grobelny, 1995*)

Geometry Capture for optimization of arbitrary planar structures is used

Empipe handles direct optimization with Sonnet's ***em***

the complete structure between the two capacitors is considered as a whole and simulated by Sonnet's ***em***

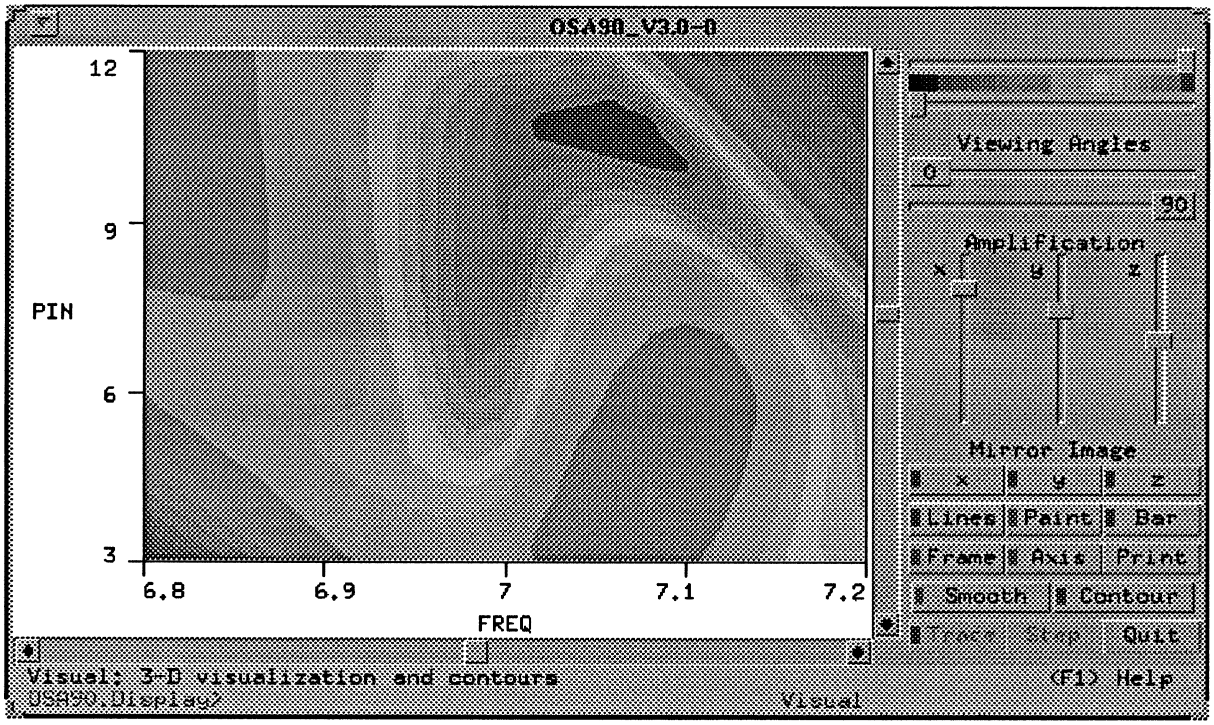
the circuit is directly optimized by OSA90/hope™ through Empipe with 10 optimization variables

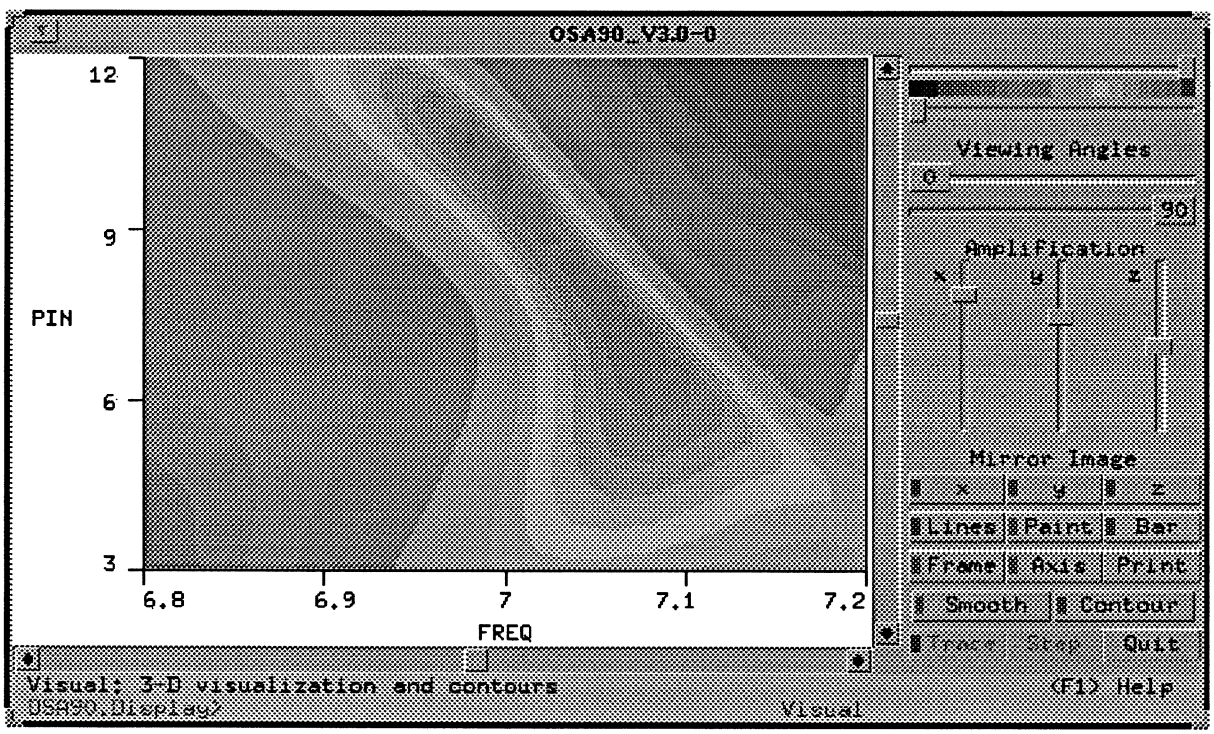
design specification:

conversion gain > 3 dB
spectral purity > 20 dB

at 7 GHz and 10 dBm input power

Spectral Purity Before and After Optimization





Parallel Computing Options

multiprocessor computers and specialized compilers vs. distributing EM analyses over a computer network

the overhead of parallelization is negligible as compared to the CPU-intensive EM analyses

splitting at the component/subcircuit level

suitable when several EM simulation results are needed simultaneously

- off-grid interpolation
- numerical gradient estimation
- multiple outcomes in statistical analysis

suits best the operational flow of interpolation, optimization and statistical analysis

Organization of Parallel Computing

organized by Empipe from one of the networked computers (master host)

using standard UNIX protocols (remote shell and equivalent hosts) an EM analysis is started on each of the available hosts

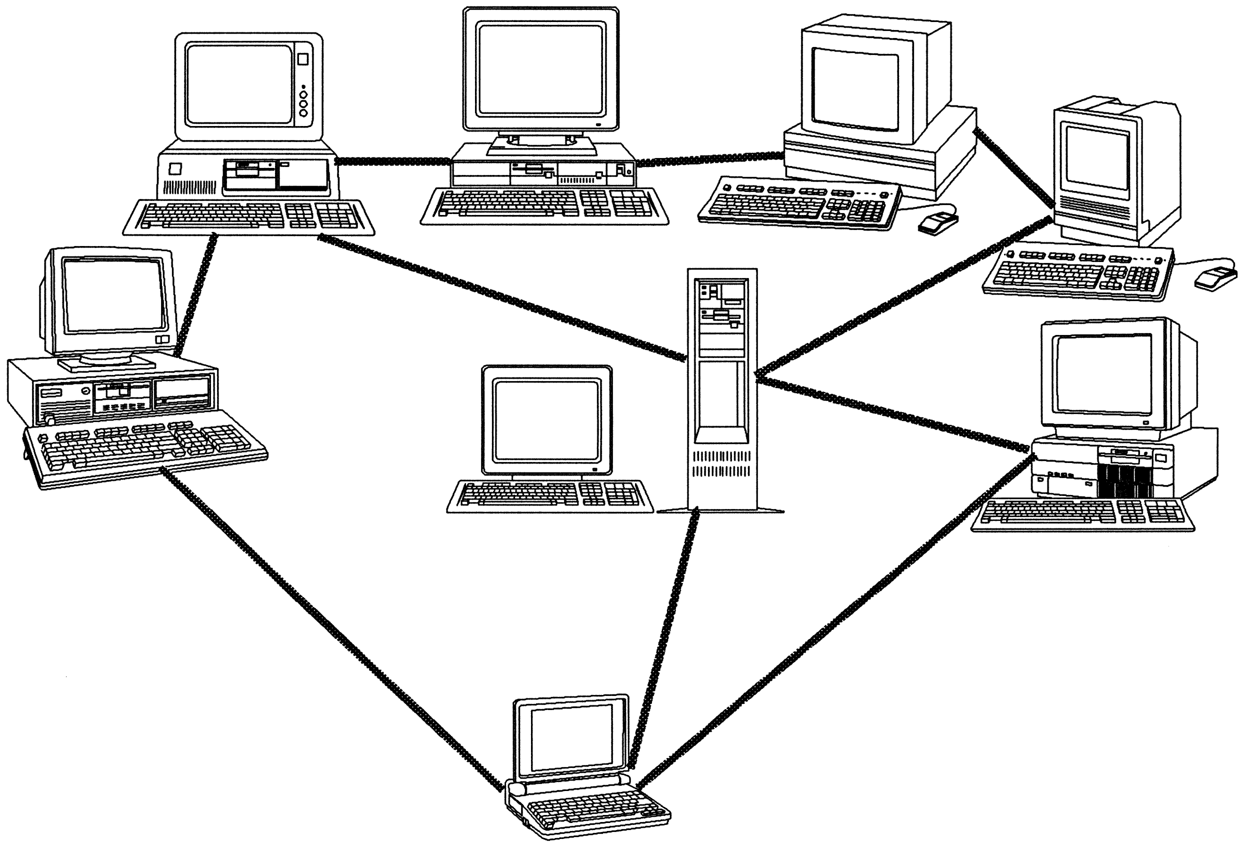
when the analysis is finished on a host, the next job, if any, is dispatched to that host

EM simulation results are gathered from all the hosts and stored in a data base created on the master host

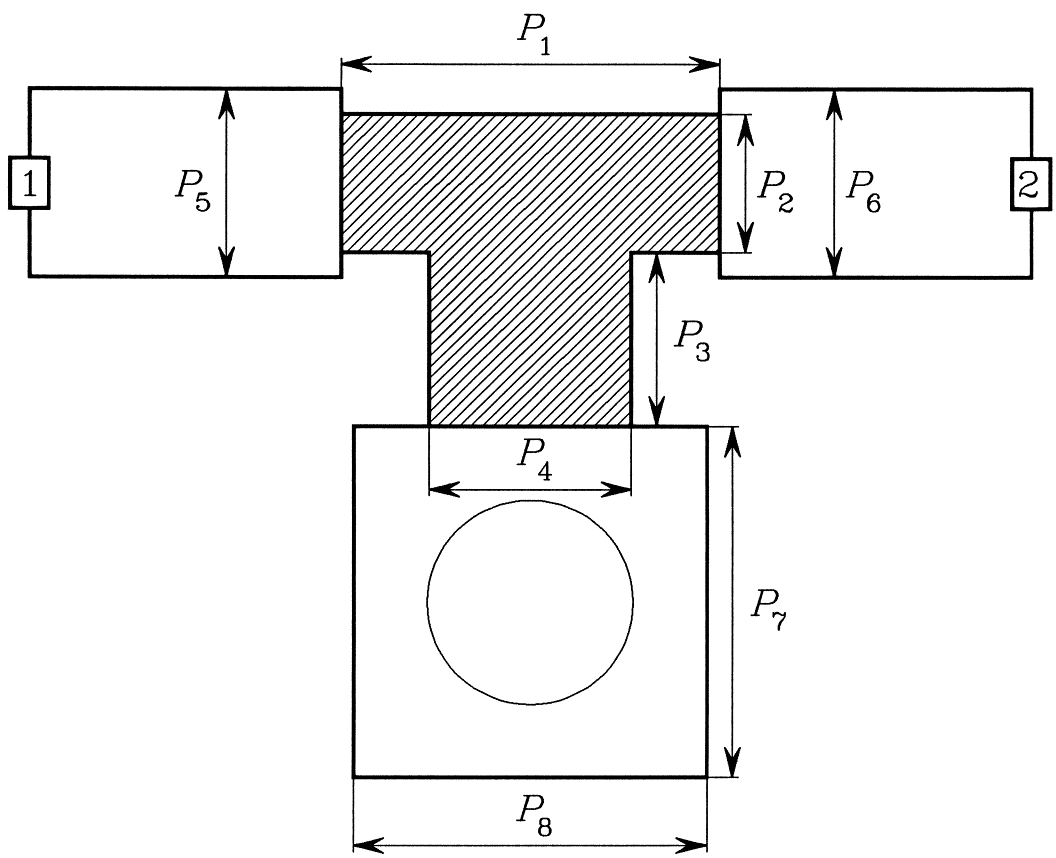
no platform specific mechanisms

applicable to both local and wide area networks of heterogeneous workstations

Heterogeneous Network of Computers



10 dB Distributed Attenuator



built on a 15 mil thick substrate with relative dielectric constant of 9.8

metallization of a high resistivity (50 Ω/sq)

the feed lines and the grounding pad are assumed lossless

Statistical Design of the Attenuator

design specifications (from 2 GHz to 18 GHz)

$9.5\ \text{dB} \leq$ insertion loss $\leq 10.5\ \text{dB}$

return loss $\geq 10\ \text{dB}$

the structure, treated as a whole, is described by 8 geometrical parameters

designable: 4 parameters describing the resistive area

statistical variables: all 8 parameters (with a standard deviation of 0.25 mil)

em simulation at a single frequency requires about 7 CPU minutes on a Sun SPARCstation 1+

Parallel Computing in Nominal Design of the Attenuator

30 ***em*** analyses

an average of 3.8 analyses run in parallel

about 168 minutes on the network of Sun SPARCstations 1+

time is reduced by 75%

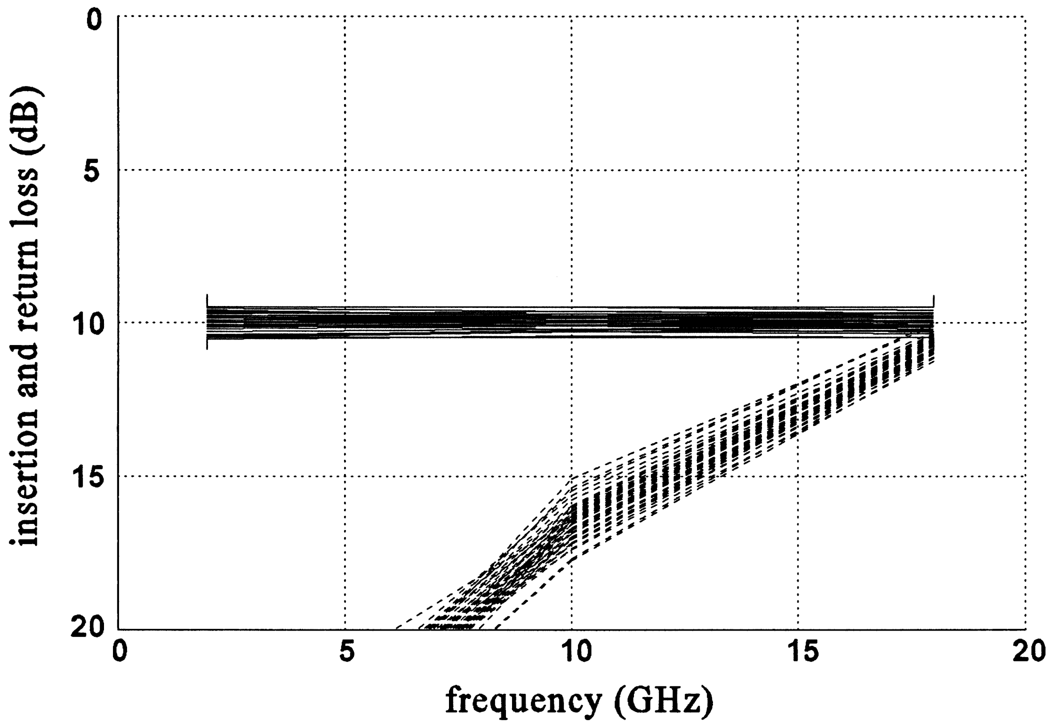
Parallel Computing in Statistical Design of the Attenuator

additional 113 ***em*** analyses

an average of 2.5 analyses run in parallel

time is reduced by 60%

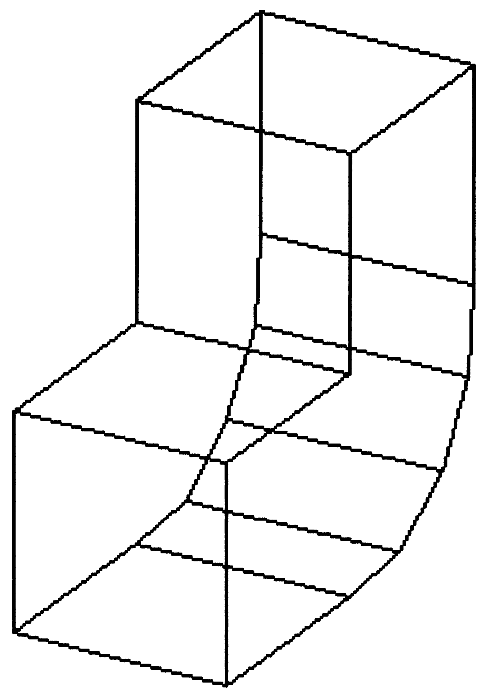
Monte Carlo Sweeps of the Attenuator Responses



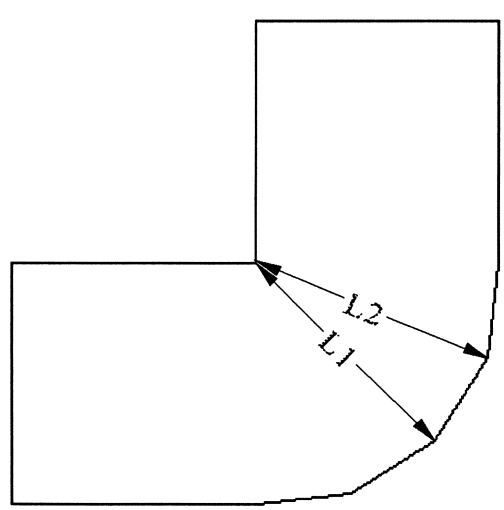
yield (estimated from 250 Monte Carlo outcomes) is increased from 82% to 97%

WR-75 Waveguide Bend

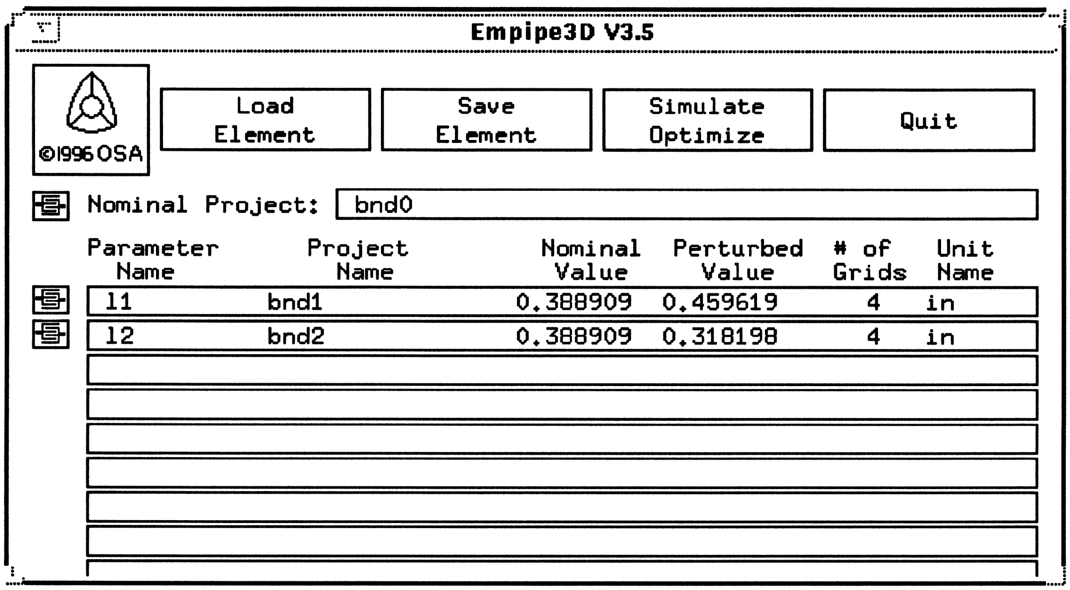
(only half of the structure is shown due to symmetry)



Two Design Variables

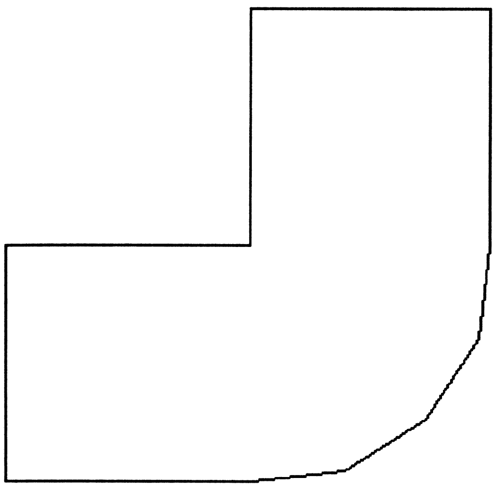


Empipe3D Geometry Capture

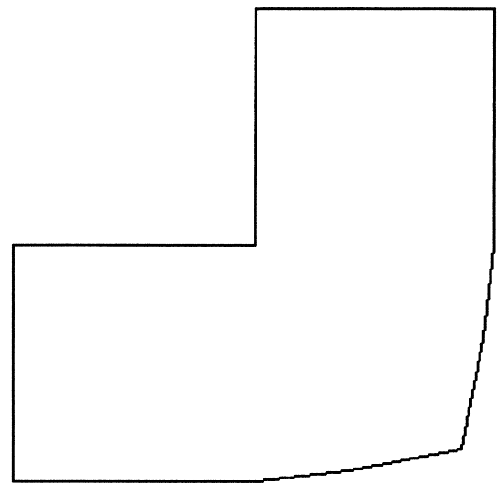


gateway to HFSS and Maxwell® Eminence

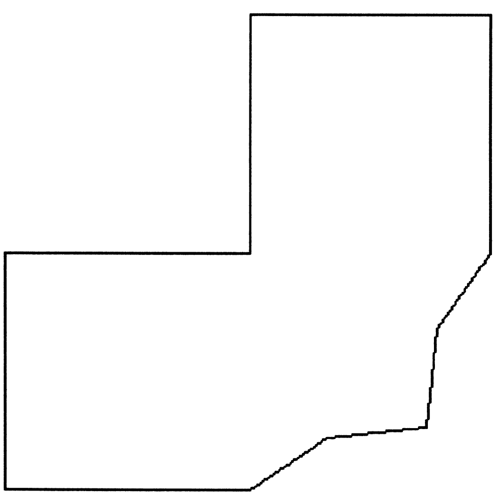
Geometries Representing the Parameters "L1" and "L2"



L1 = 0.3889 inch
L2 = 0.3889 inch

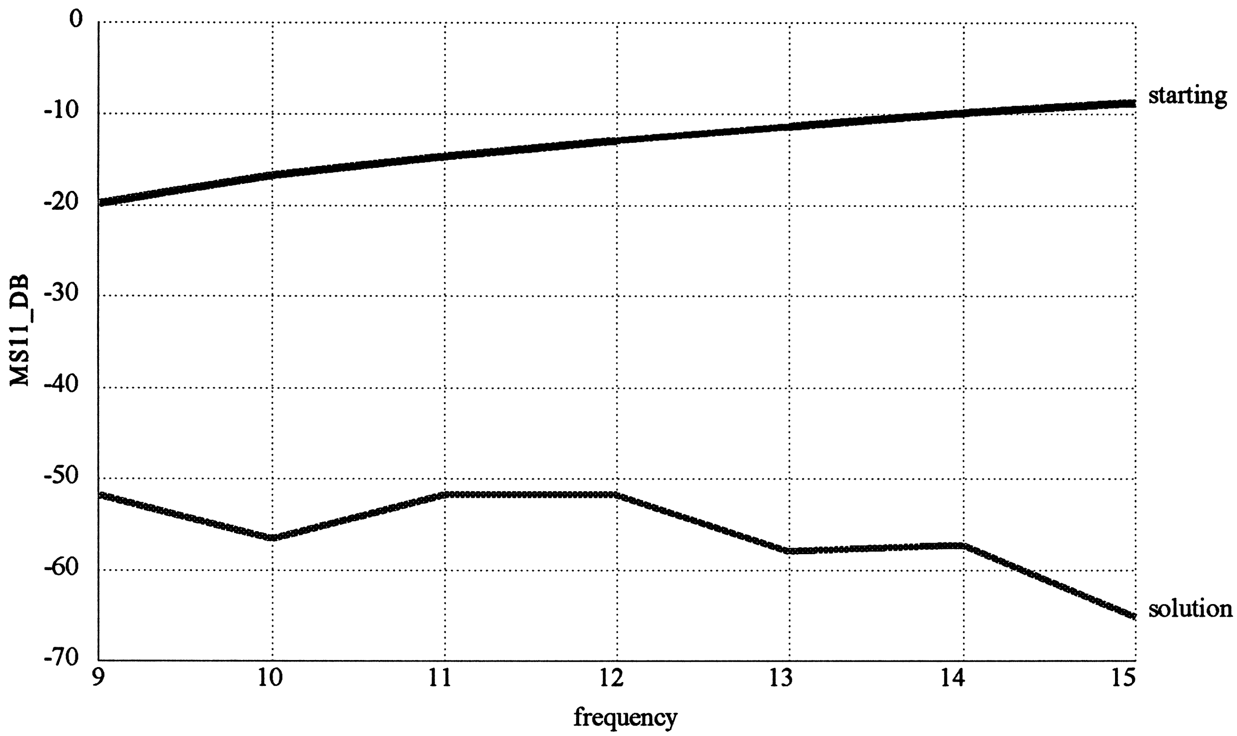


L1 = 0.4596 inch
L2 = 0.3889 inch



L1 = 0.3889 inch
L2 = 0.3182 inch

Automated Minimax Optimization

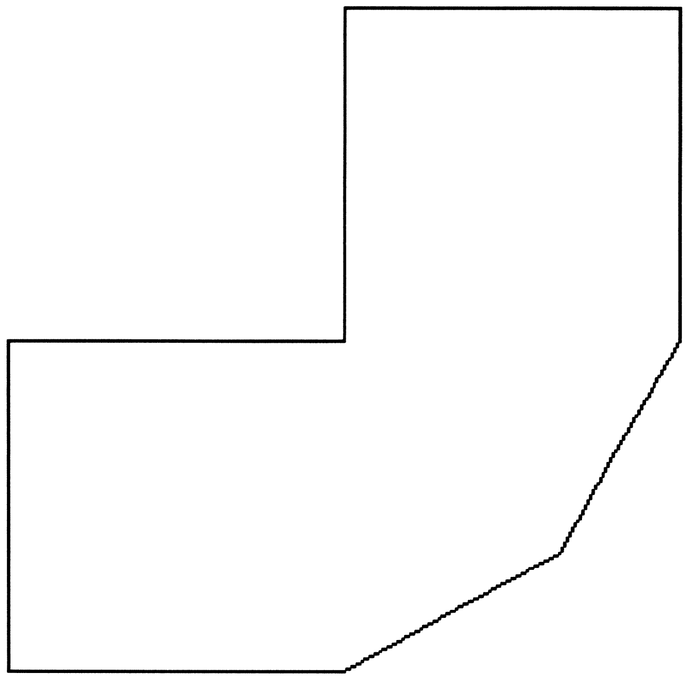


specification: return loss ≥ 40 dB from 9 to 15 GHz

starting point: $L1$ = 0.3889 inch
$L2$ = 0.3889 inch
solution: $L1$ = 0.343185 inch
$L2$ = 0.330018 inch

12 minimax iterations, 18 simulations by Maxwell Eminence

The Optimized Bend



this solution is virtually identical to the two-face bend optimized solution

Optimization Systems Associates Inc.

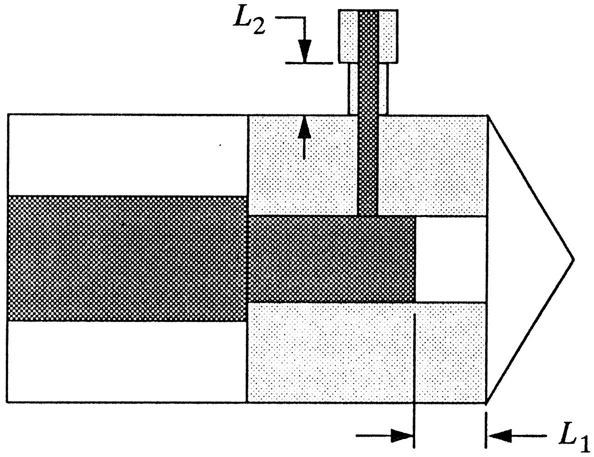
Extract From:
EM Field Simulators Made Practical
2 Day Short Course

Daniel G. Swanson, Jr.

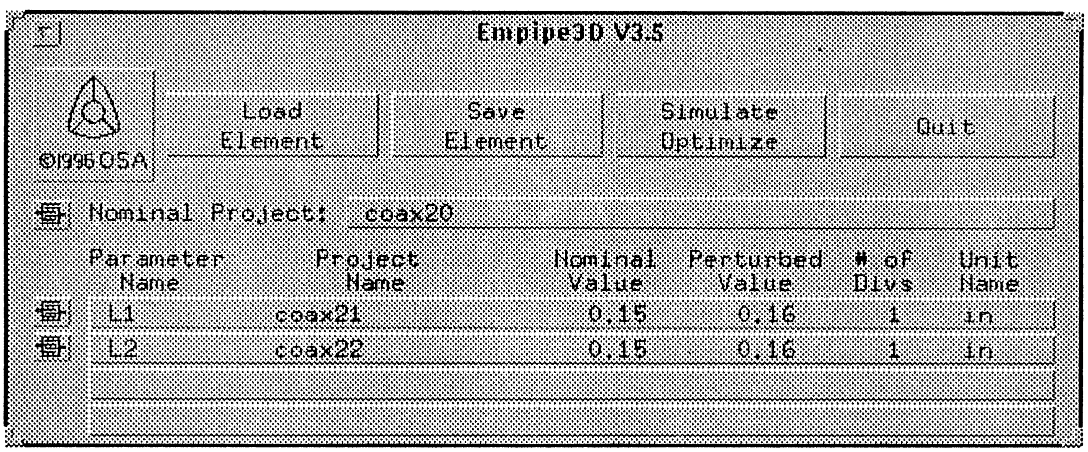
Besser Associates
4600 El Camino Real, suite 210
Los Altos, CA 94022
USA

PCS Band Coax-to-Coax Transition (cont.)

One way to create the additional capacitance we need near port two is to reduce the diameter of the output coaxial line for a short distance. Just for good measure we will also vary the length of the open stub.



Empipe3D was used in conjunction with *Maxwell Eminence* to optimize this structure. To set up the problem we first draw the base or reference structure. Then we draw one new structure for each of variables that have been defined. In the new models, small changes are made to the dimensions that correspond to the variables. We are not allowed to change the number or names of the objects in the model. Our "game plan" for drawing the model that was developed earlier comes in handy at this point. After we have drawn the models we need, a simple procedure captures the information for *Empipe3D*.



Notes:

PCS Band Coax-to-Coax Transition (cont.)

Another set of menus help us set up the optimization problem. The result is a circuit net list that we can easily interpret. Our 3D field-solver project becomes another circuit element and can be combined with other library elements if desired.

```
! Empipe3D user-defined structure COAX2

Model
#include "coax2_osa/coax2.inc";

   COAX2_L1: ?0.05 0.15 0.2?;
   COAX2_L2: ?0.05 0.15 0.3?;

   COAX2  1 2 0  model=7
      L1=(COAX2_L1 * 1in)  L2=(COAX2_L2 * 1in);

   PORTS 1 0 2 0;

   CIRCUIT;

   MS_DB[2,2] = if (MS > 0) (20 * log10(MS)) else (NAN);
   MS11_DB = MS_DB[1,1];
   MS22_DB = MS_DB[2,2];
end

Sweep
   AC: FREQ: from 1.8GHz to 2GHz step=0.1GHz MS22_dB MS11_dB
      {XSWEEP title="MS11_dB and Spec" X=FREQ Y=MS11_dB
       SPEC=(from 1.8GHz to 2GHz, < -40)};
end

Spec
   AC: FREQ: from 1.8GHz to 2GHz step=0.01GHz MS11_dB < -40;
end

Control
   Perturbation_Scale=1.0e-4;
   Optimizer=Minimax;
end
```

Notes:

PCS Band Coax-to-Coax Transition (cont.)

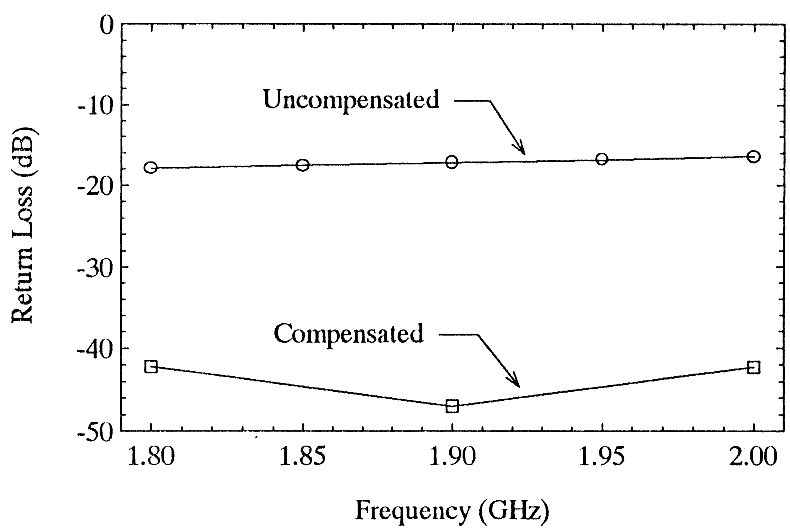
The optimization of this structure proceeded quite quickly; the total time was 1 hour, 48 minutes. The starting values and optimized values for both variables are shown below.

Variable	Start Point	End Point
L_1	.150	.137
L_2	.150	.139

A total of 10 field-solver solutions were computed. It is interesting to look at the "trajectory" of the field-solver solutions. We specified 10 mil steps in both variables for the field-solver solutions. Notice that the final solution falls off this "grid" of known solutions because the software can interpolate between known solutions.

Solution No.	1	2	3	4	5	6	7	8	9	10
L_1	.15	.16	.15	.14	.15	.14	.13	.12	.13	.14
L_2	.15	.15	.16	.14	.14	.15	.13	.13	.14	.13

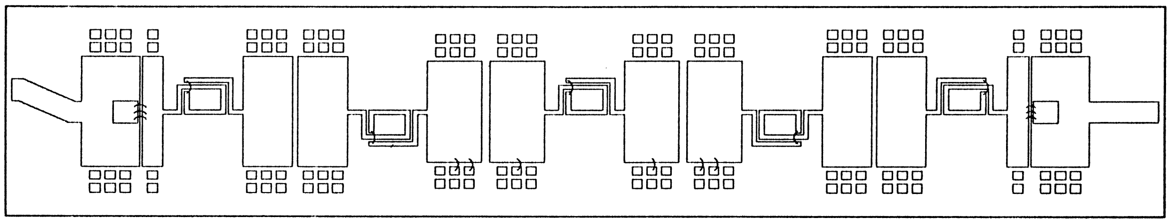
Below we have plotted the return loss of the original transition and the return loss of the compensated transition.



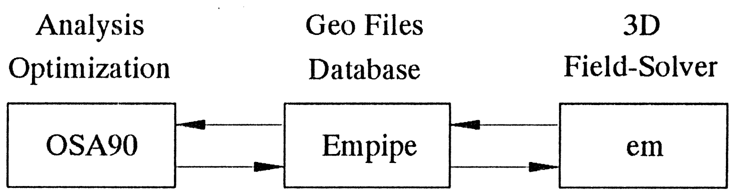
Notes:

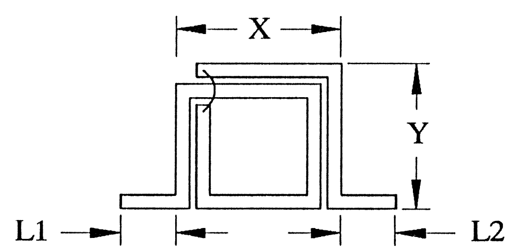
Pseudo-Lumped 3.7 GHz Bandpass Filter

This filter is a lower frequency version of the previous example. The two key parameters for this design were insertion loss and the width of the spurious free stopband. Printed spiral inductors were used to achieve the higher inductance values needed at this frequency. The final layout for this filter is shown below. The substrate is 20 mil thick alumina, 945 mil long by 190 mil wide. A more complete description of this filter can be found in [33].



This example demonstrates how the field-solver can now be used to optimize planar circuits. The filter was subdivided into three unique pi-network elements and one spiral inductor element. The analysis and optimization of these circuit elements were controlled by a linear simulator, *OSA/90*, with an auxiliary interface to the field-solver, *Empipe*.

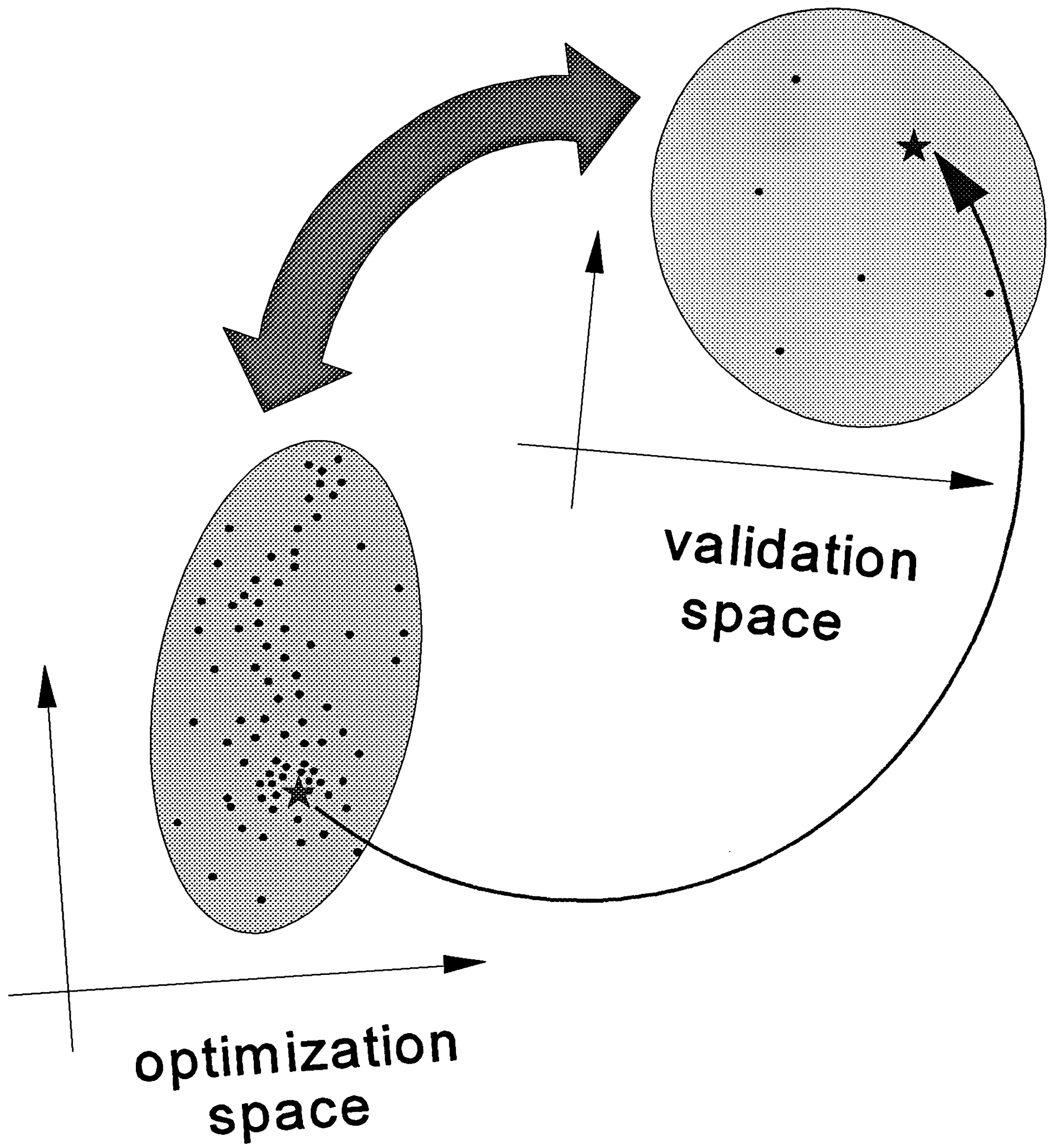




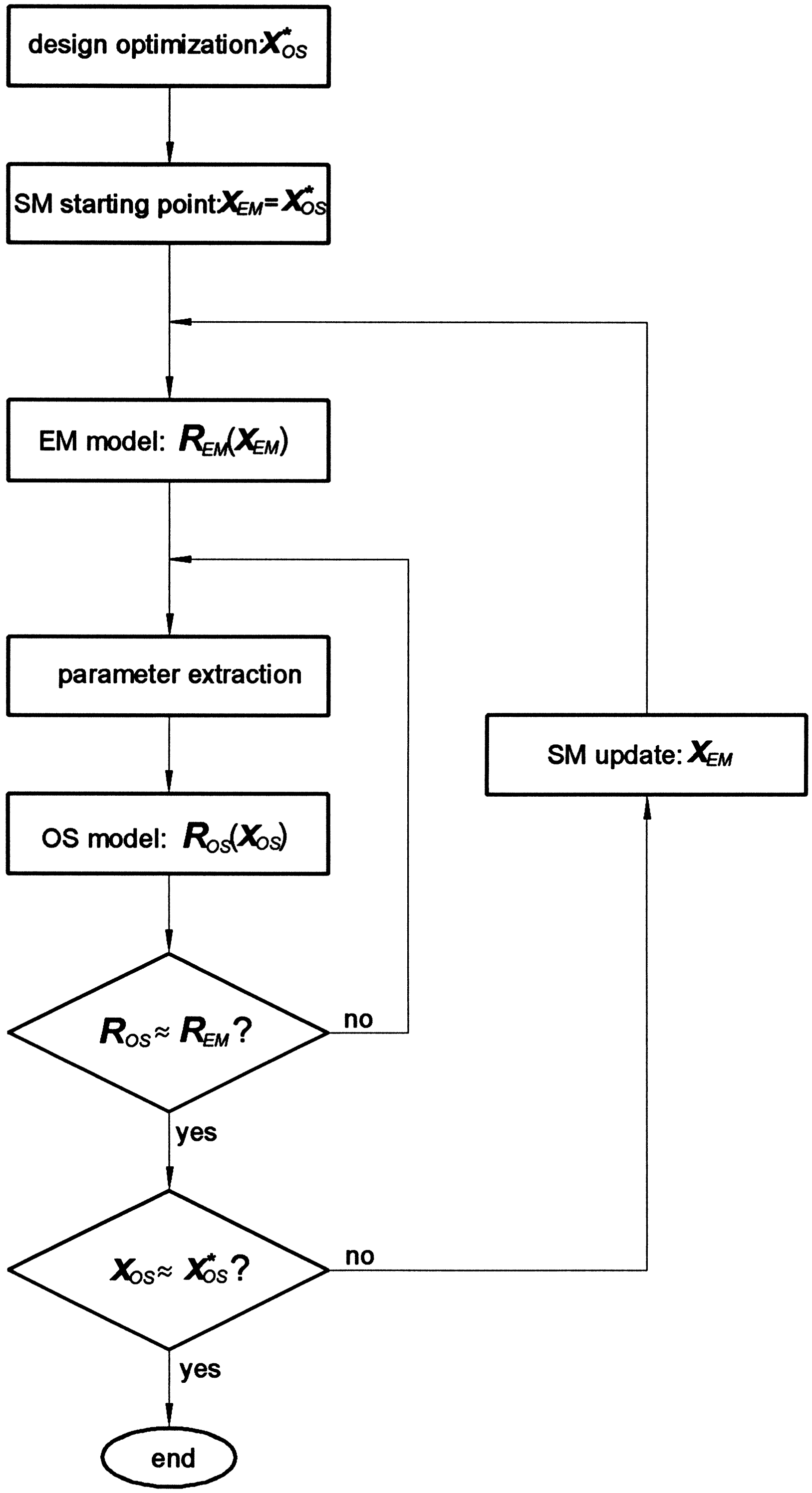
The analysis and optimization proceed by first building a database of field-solver solutions around the starting point and then interpolating in the existing database or adding new solutions to the database. One side benefit of this approach is that it frees the user from the fixed grid. That is, solutions can be found with dimensions that do not fall on the analysis grid. More details on direct driven em optimization can be found in [34],[35].

Notes:

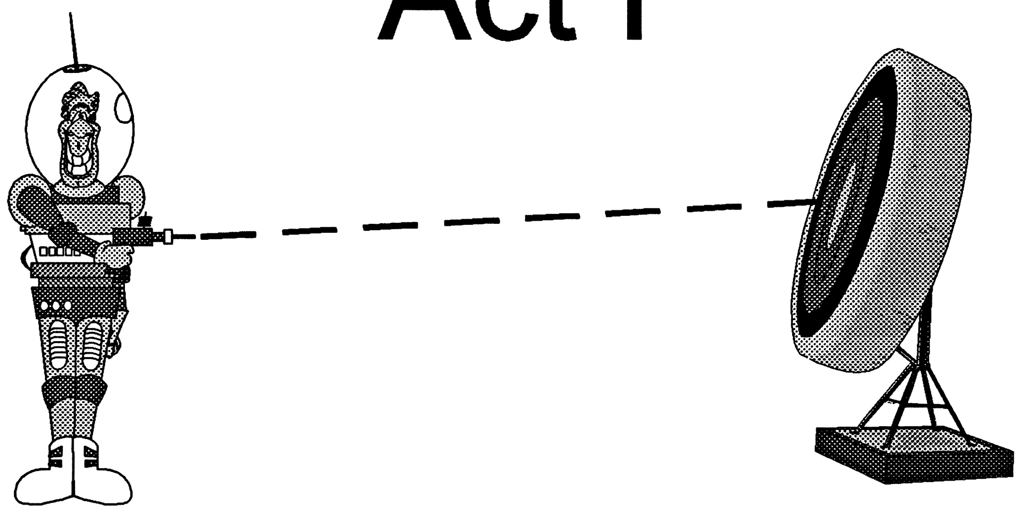
Space Mapping™
(Bandler et al., 1994)



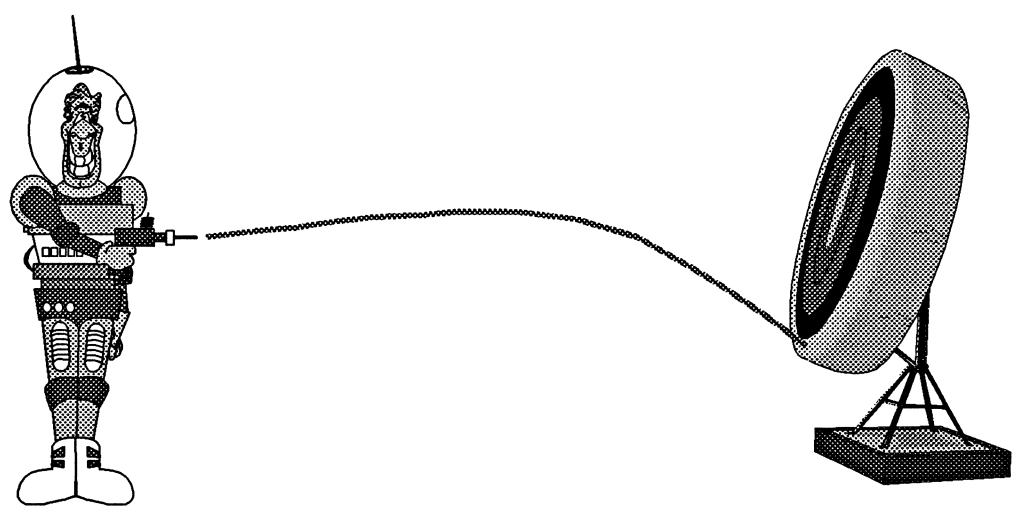
Automated Aggressive Space Mapping™



Space Mapping
Act I



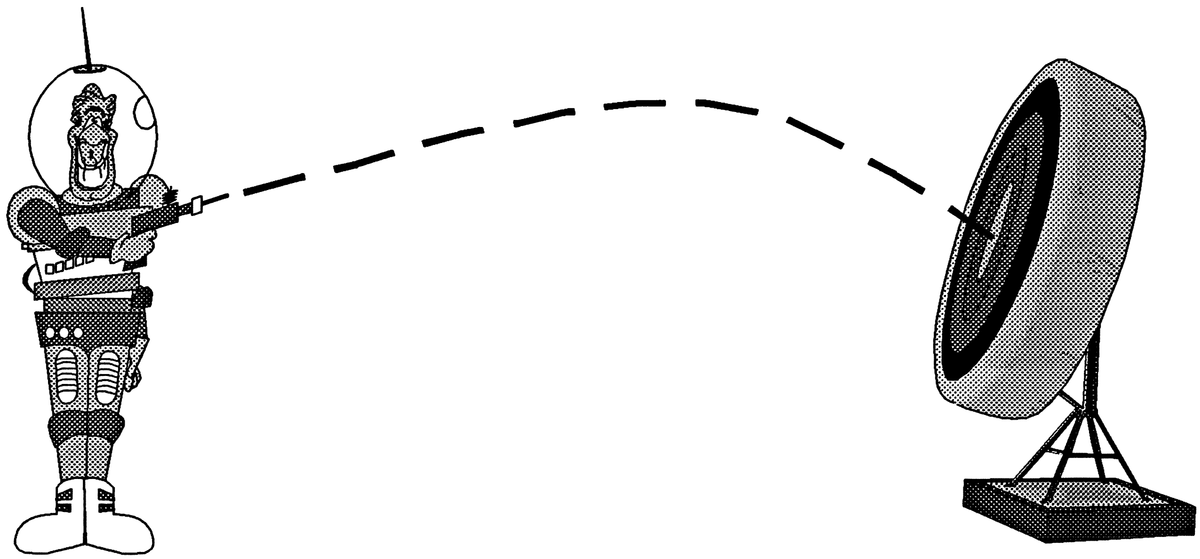
ideal aim



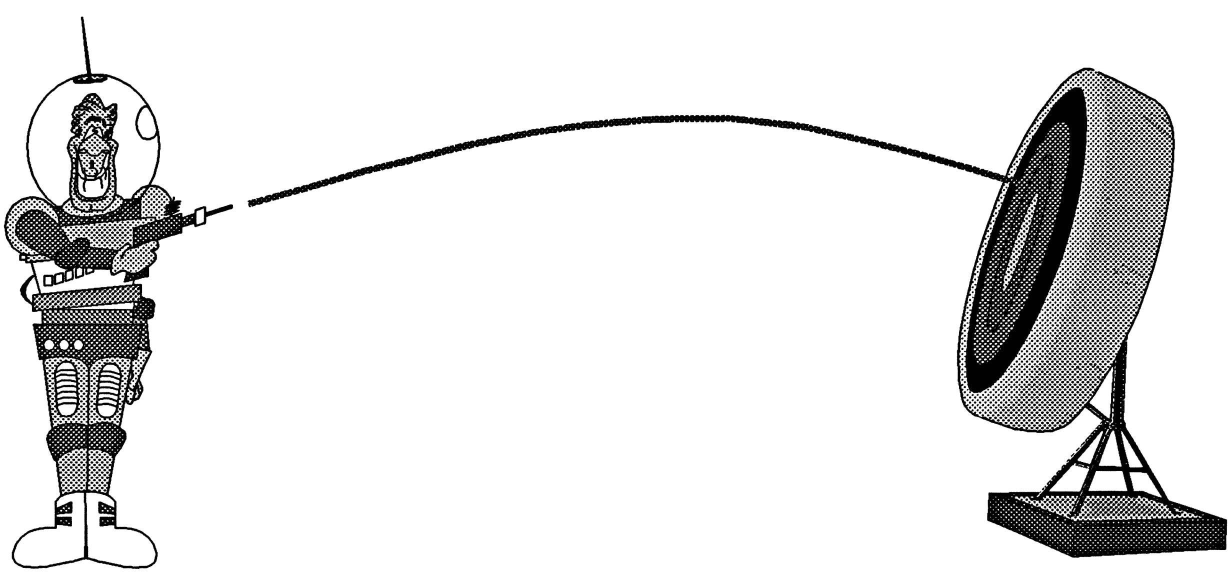
reality check ... oops

JWB-97-59

Space Mapping
Act II



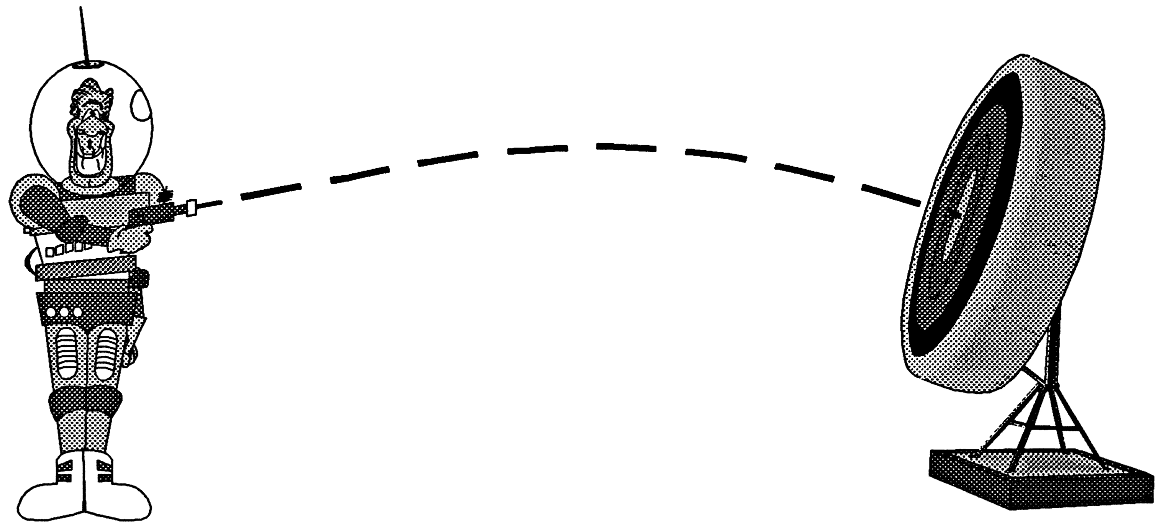
Broyden update



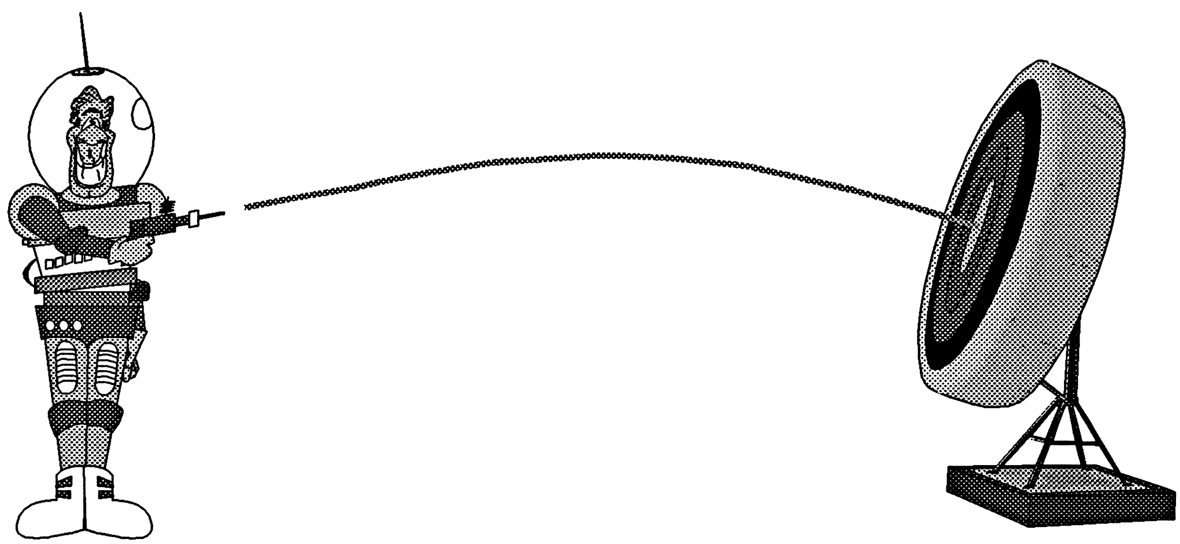
almost there

JWB-97-60

Space Mapping Act III



I licensed OSA



Hey, SM works!!

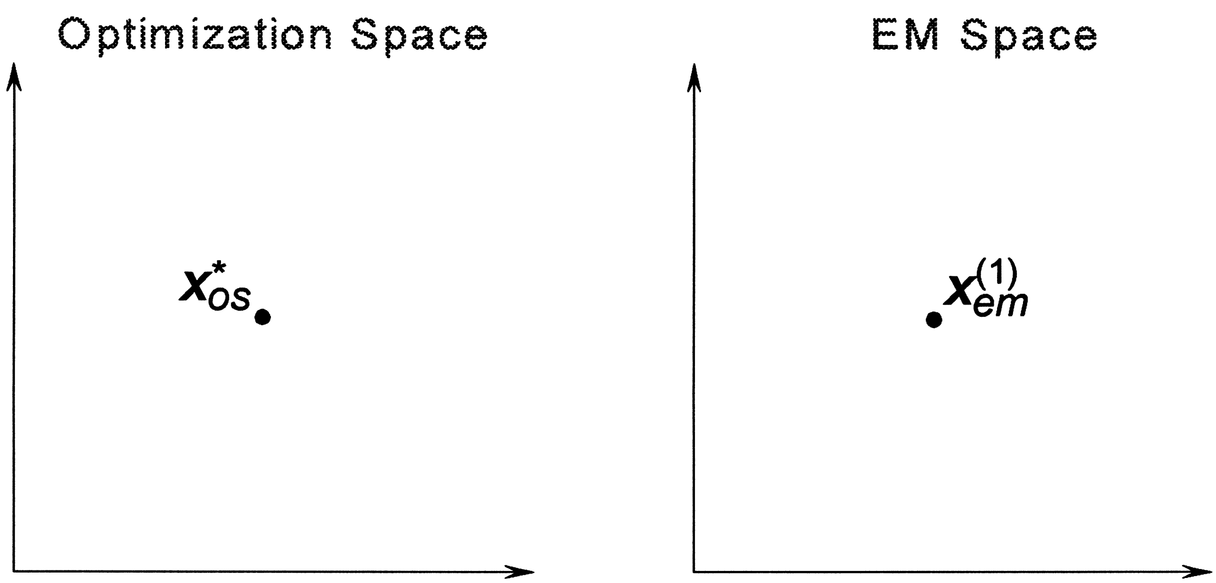
JWB-97-61

Illustration of Aggressive Space Mapping Optimization

Step 0

find the optimal design $\boldsymbol{x}_{os}^{*}$ in Optimization Space

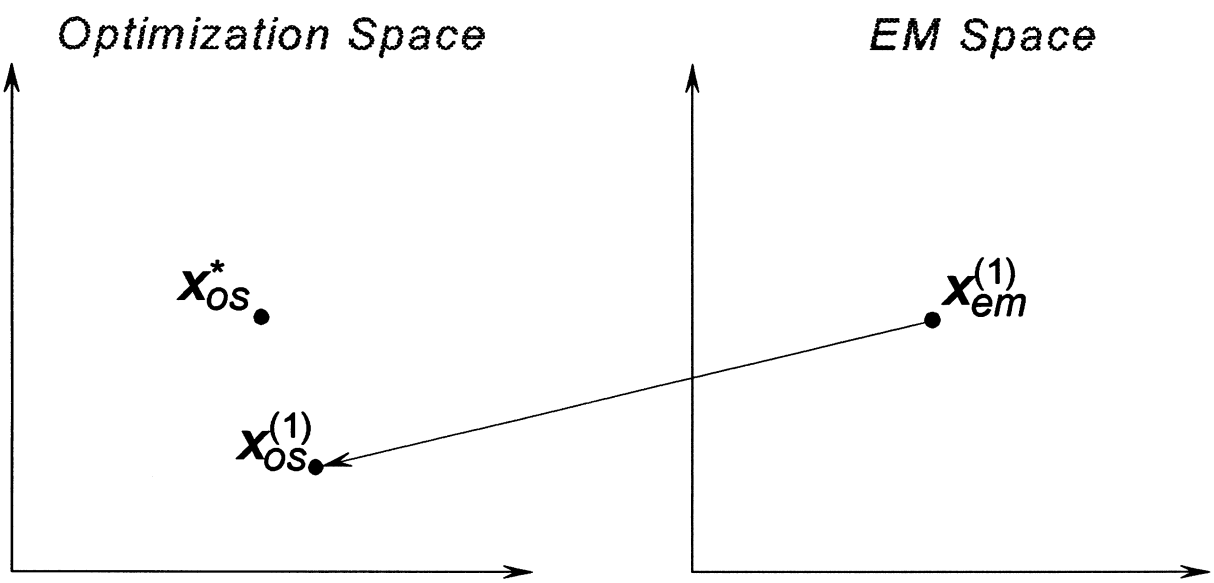
Step 1



set $\boldsymbol{x}_{em}^{(1)} = \boldsymbol{x}_{os}^{*}$ assuming $\boldsymbol{x}_{em}$ and $\boldsymbol{x}_{os}$ represent the same physical parameters

Illustration of Aggressive Space Mapping Optimization

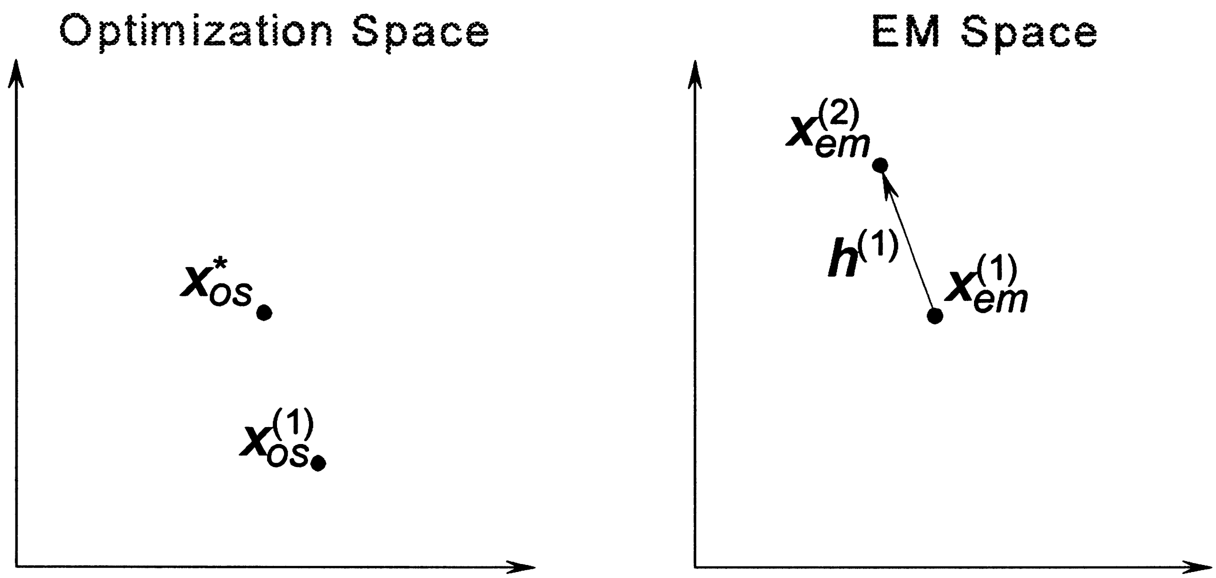
Step 2



perform X_{os}-space model parameter extraction

Illustration of Aggressive Space Mapping Optimization

Step 3



initialize Jacobian approximation $\boldsymbol{B}^{(1)} = \mathbf{1}$

obtain $\boldsymbol{x}_{em}^{(2)}$ by solving

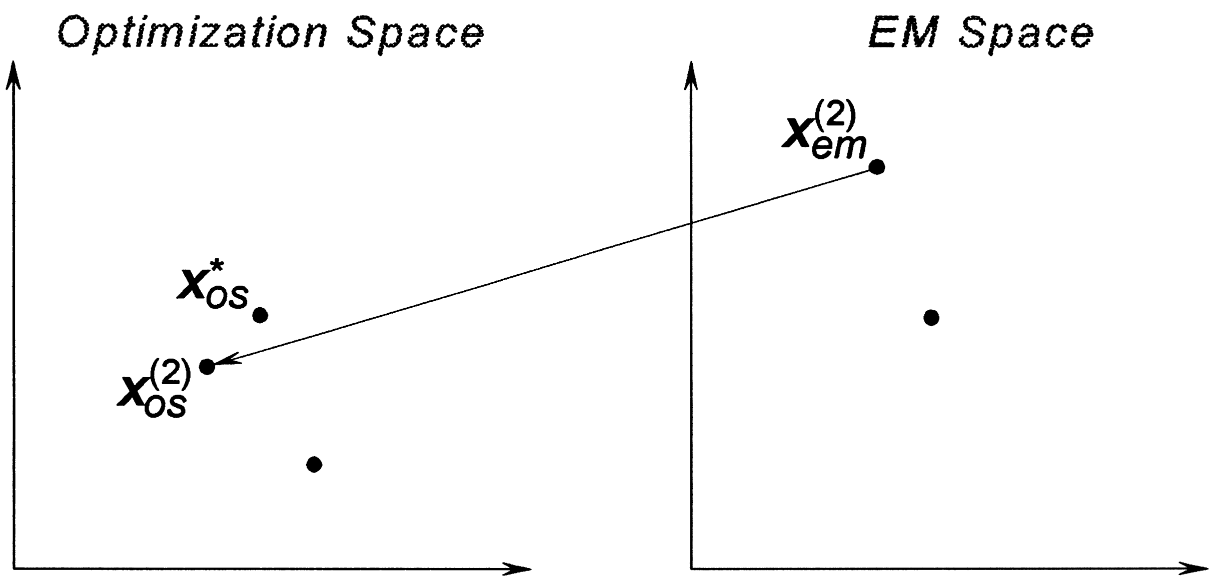
$$\boldsymbol{B}^{(1)}\boldsymbol{h}^{(1)} = -\boldsymbol{f}^{(1)}$$

where

$$\boldsymbol{f}^{(1)} = \boldsymbol{x}_{os}^{(1)} - \boldsymbol{x}_{os}^{*}$$

Illustration of Aggressive Space Mapping Optimization

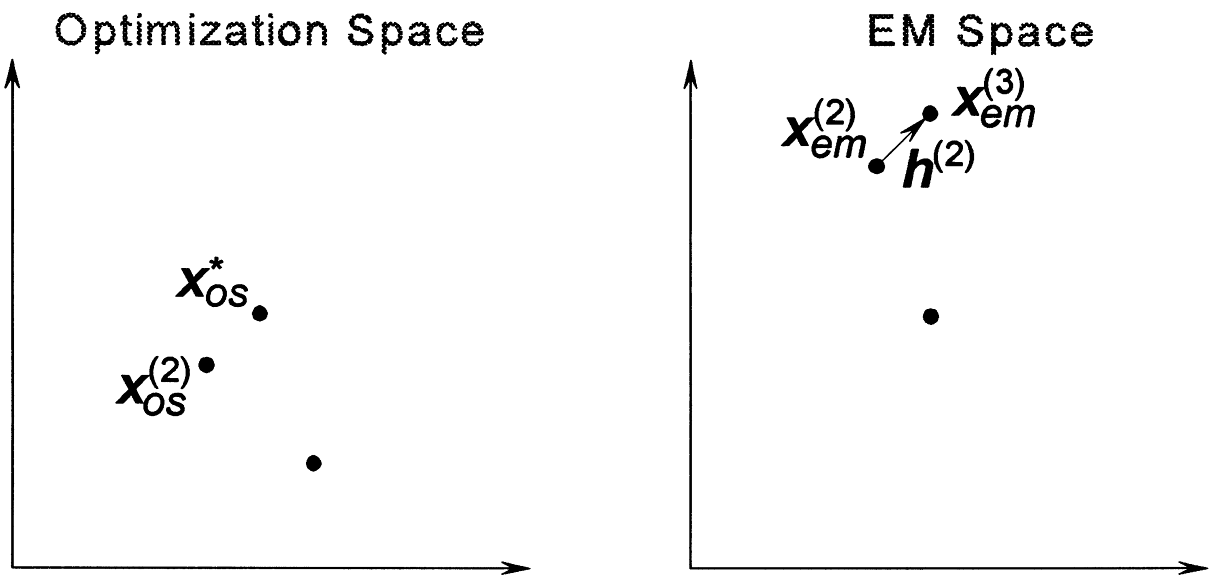
Step 4



perform X_{os}-space model parameter extraction

Illustration of Aggressive Space Mapping Optimization

Step 5



update Jacobian approximation from $\boldsymbol{B}^{(1)}$ to $\boldsymbol{B}^{(2)}$

obtain $\boldsymbol{x}_{em}^{(3)}$ by solving

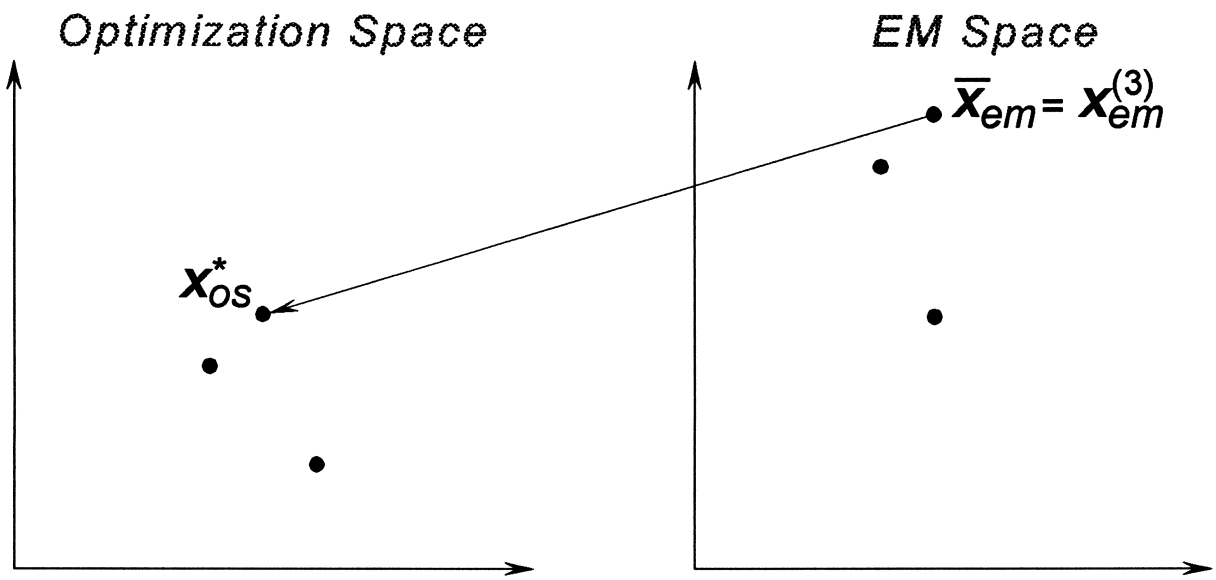
$$\boldsymbol{B}^{(2)}\boldsymbol{h}^{(2)} = -\boldsymbol{f}^{(2)}$$

where

$$\boldsymbol{f}^{(2)} = \boldsymbol{x}_{os}^{(2)} - \boldsymbol{x}_{os}^{*}$$

Illustration of Aggressive Space Mapping Optimization

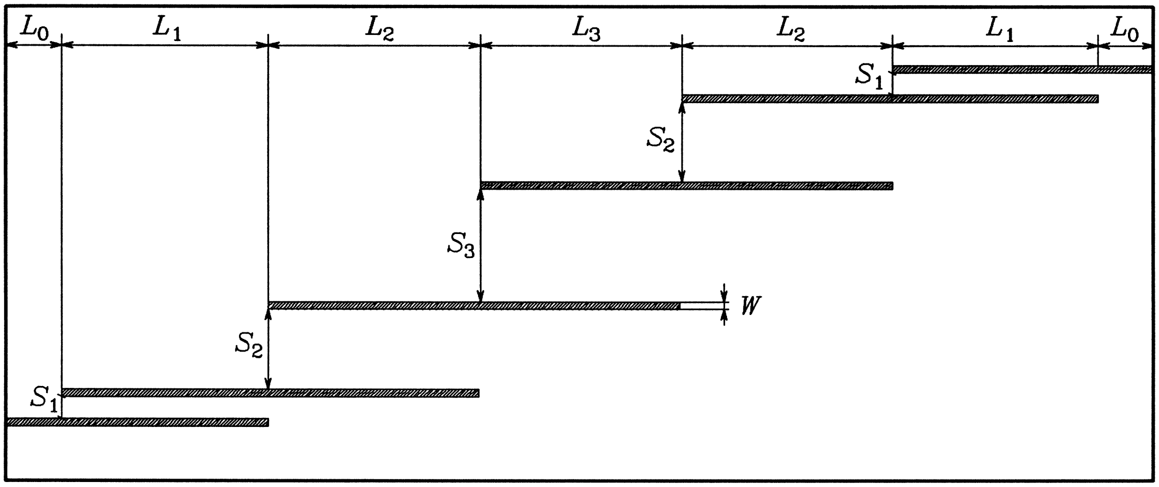
Step 6



perform X_{os}-space model parameter extraction

if $\| x_{os}^{(3)} - x_{os}^{*} \| \leq \epsilon$ then $\bar{x}_{em} = x_{em}^{(3)}$ is considered as the SM solution

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

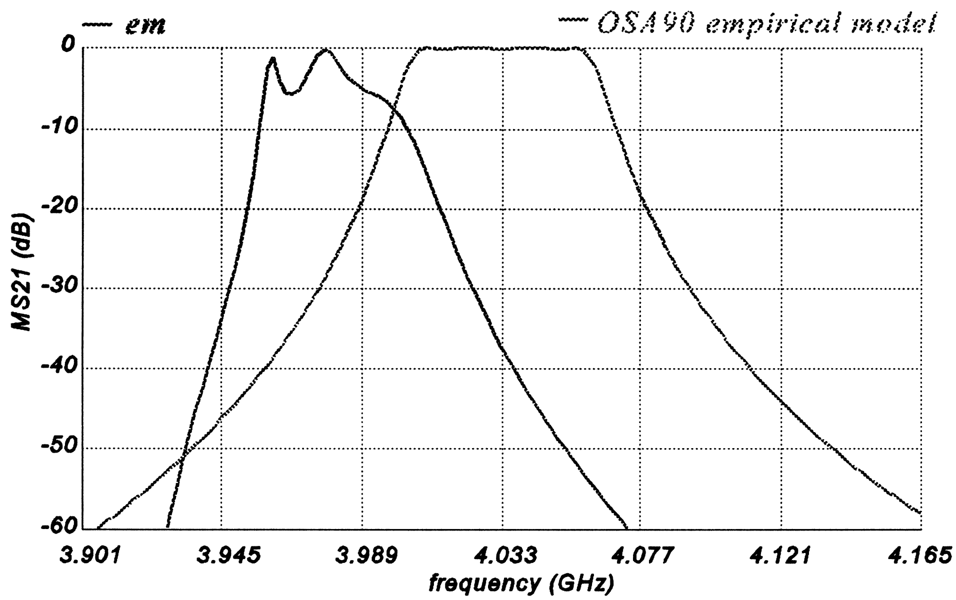
100 elapsed minutes are needed for ***em*** analysis at a single frequency on a Sun SPARCstation 10

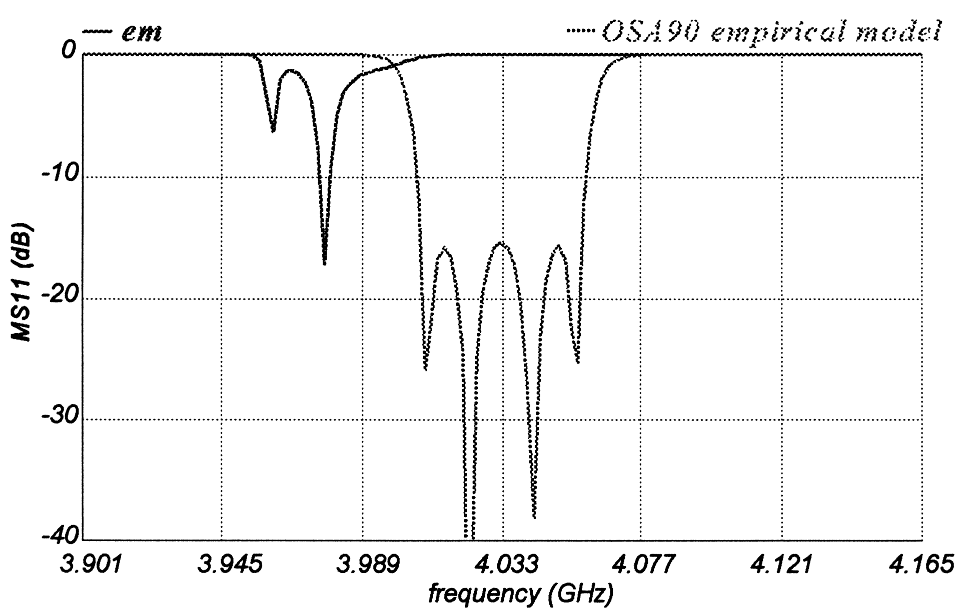
design specifications

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

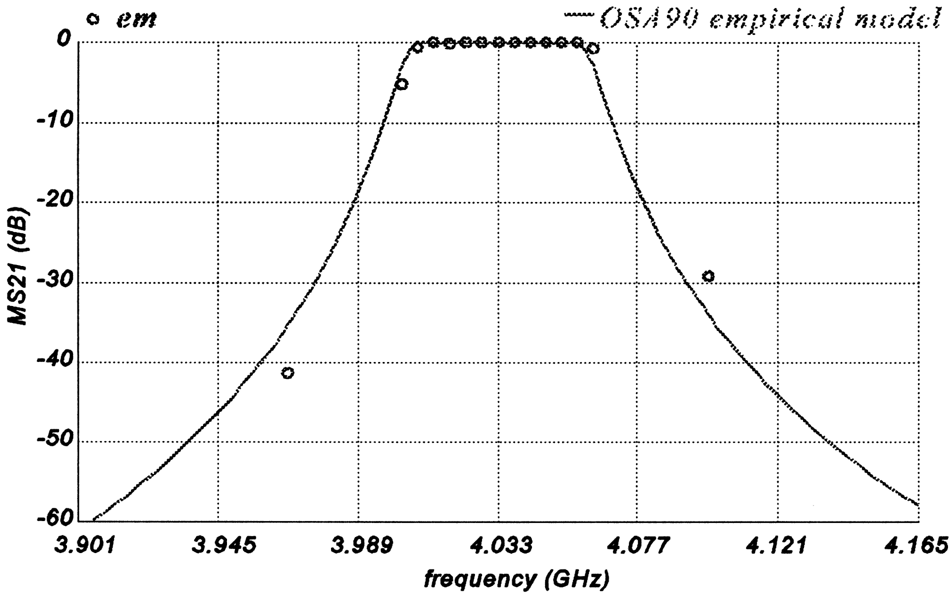
$|S_{21}| > 0.95$ for 4.008 GHz $< f < 4.058$ GHz

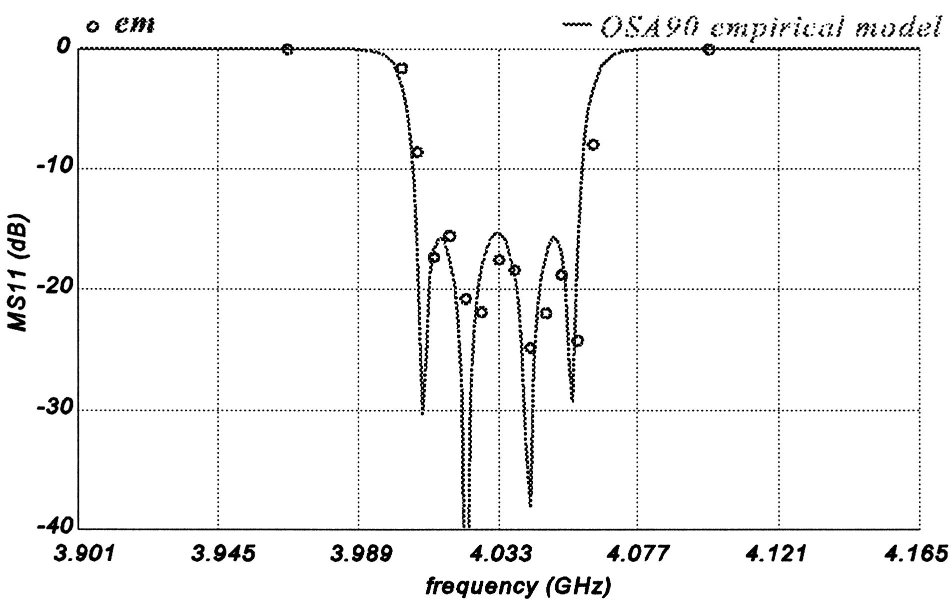
Starting Point of EM Optimization: Design Using Empirical Circuit Model



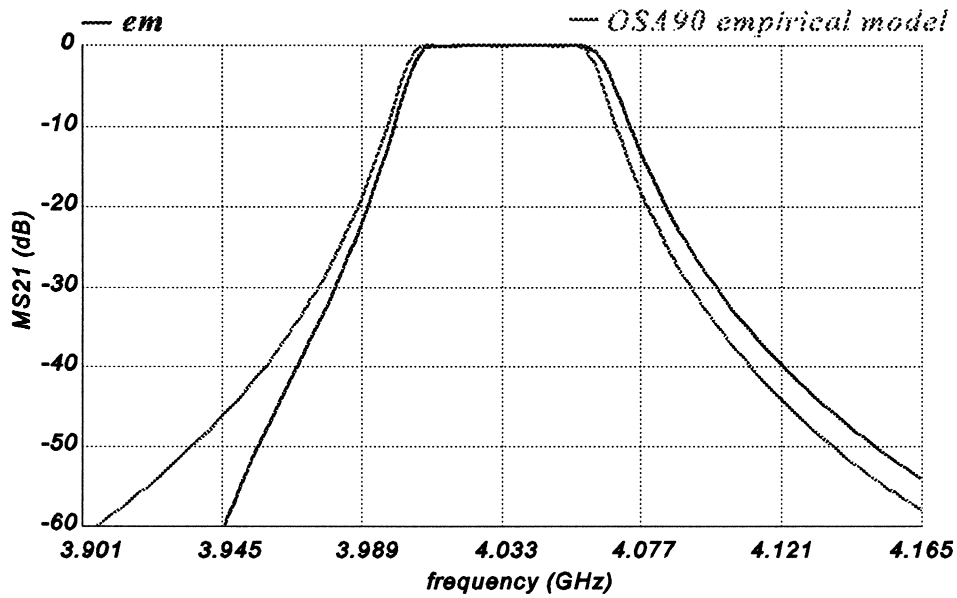


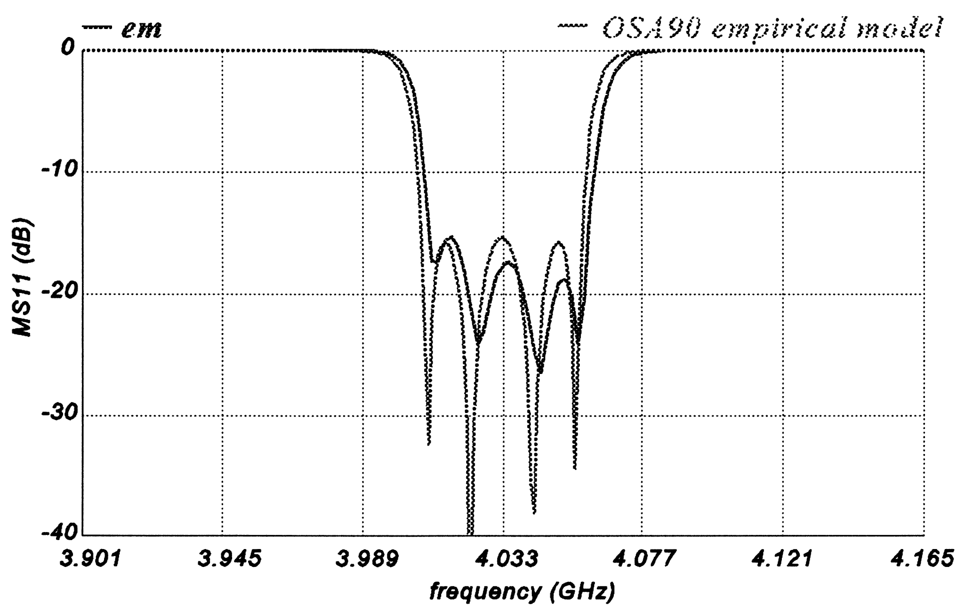
Solution by Aggressive Space Mapping After 3 Iterations



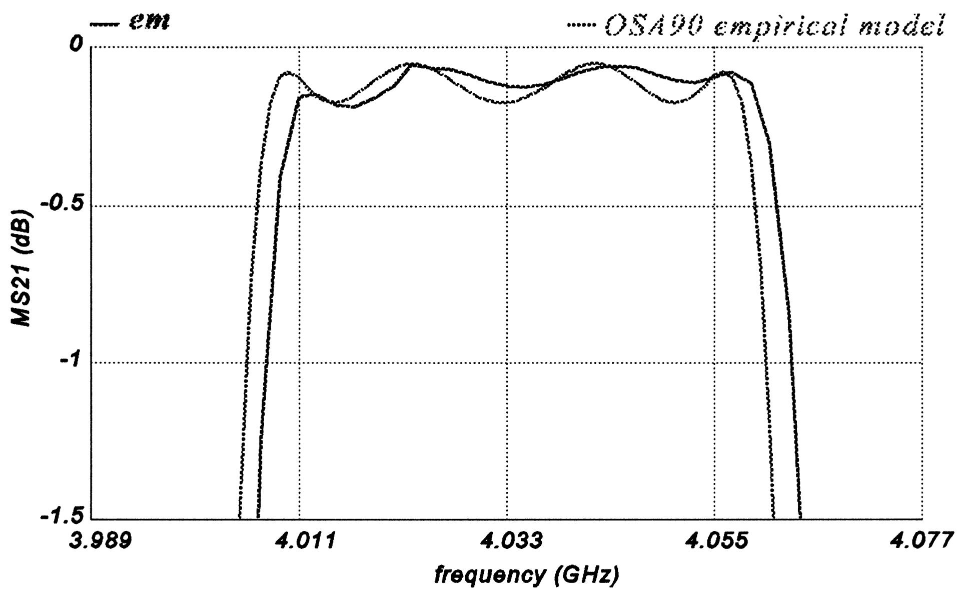


Solution by Aggressive Space Mapping
Fine Frequency Sweep

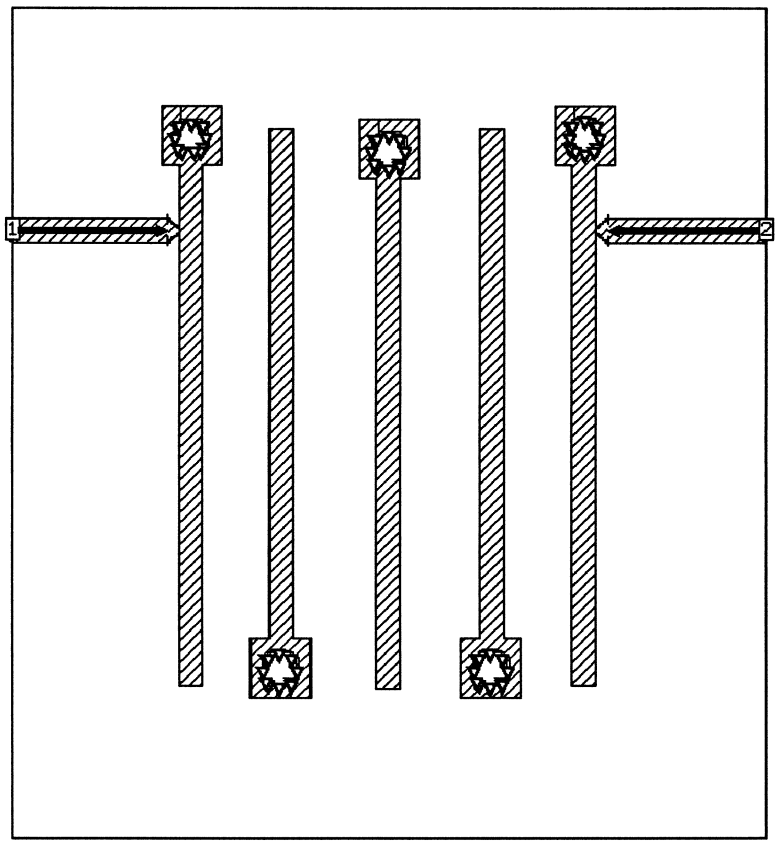




Solution by Aggressive Space Mapping
Detail of the Passband with Fine Frequency Sweep



A Five-Pole C-Band Interdigital Filter



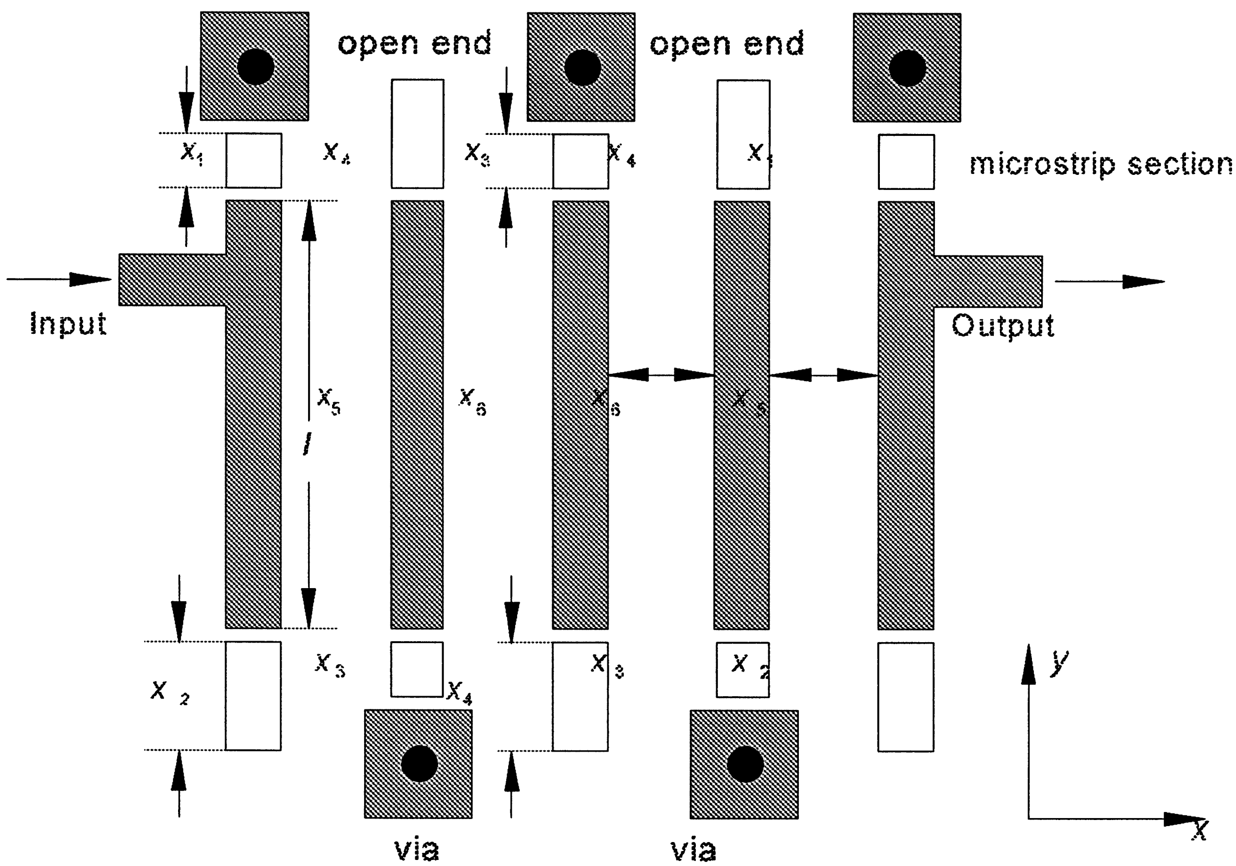
15 mil thick alumina substrate with $\varepsilon_r = 9.8$.

the width of each microstrip is chosen to be 10 mil

quarter wavelength resonators

Decomposition of the Interdigital Filter

the coarse model is constructed using decomposition



the substructures are analyzed separately using either EM models with a coarse grid or empirical models

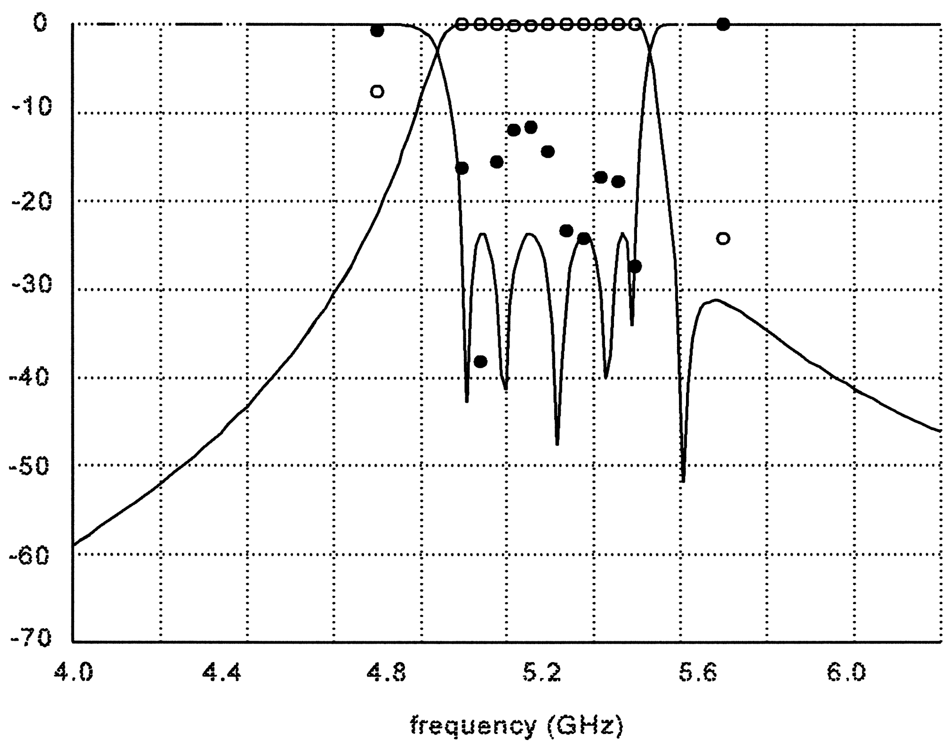
the partial results are then combined through circuit theory to obtain the response of the overall filter

Design Procedure

first, we optimize the filter using the coarse model

minimax solution x_{os}^* is obtained

we check this coarse model solution using the fine model at a few selected frequencies



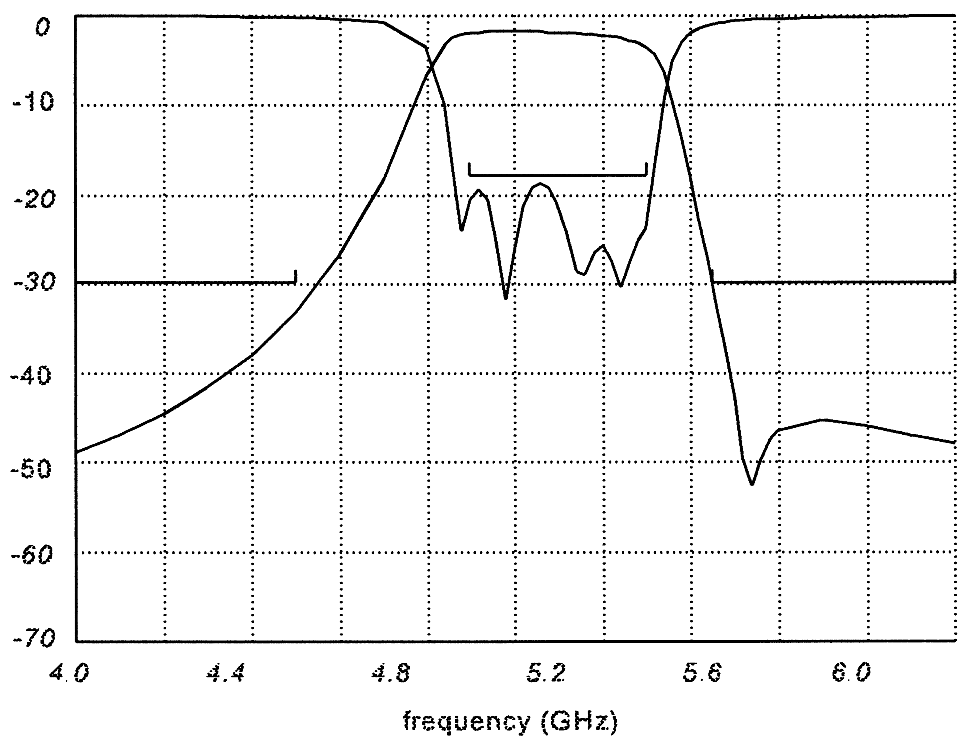
solid curves	optimized $\lvert S_{11}\rvert$ and $\lvert S_{21}\rvert$ responses of the coarse model at the optimal point x_{os}^*
circles	fine model responses at x_{os}^*

Final EM Validation

a dense frequency sweep is desired

here, simulation includes the conductor and dielectric losses

the fine model responses at $\boldsymbol{x}_{em}^{(3)}$



the passband return loss is better than 18.5 dB

Space Mapping (SM)

to avoid direct optimization of computationally intensive models

automatic alignment of two distinct models

two different EM simulators are used here

optimization space (OS) model - the RWGMM library of waveguide MM models (Fritz Arndt) connected by network theory

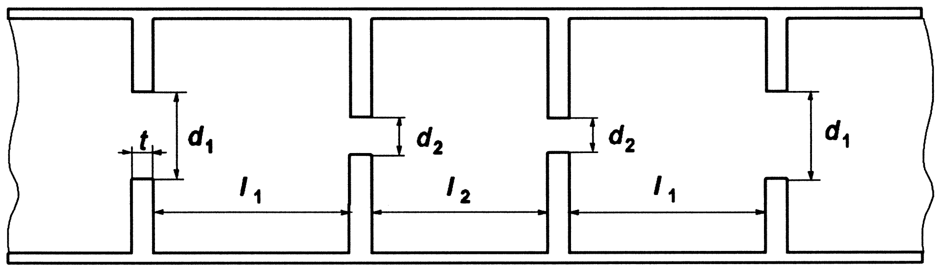
- computationally efficient
- accurately treats a variety of predefined geometries
- ideally suited for modeling complex waveguide structures decomposable into available library building blocks

EM space or "fine" model - Maxwell Eminence 3D FEM-based field simulator

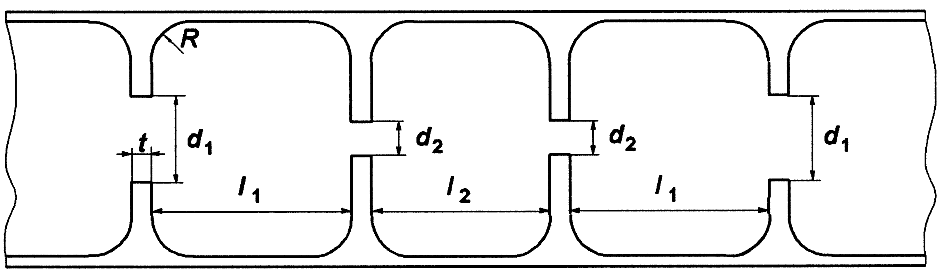
- capable of analyzing arbitrary shapes
- computationally very intensive

Optimization of the H-Plane Resonator Filter

OS model, for hybrid MM/network theory simulation



fine model, for analysis by FEM



the waveguide cross-section is 15.8 × 7.9 mm

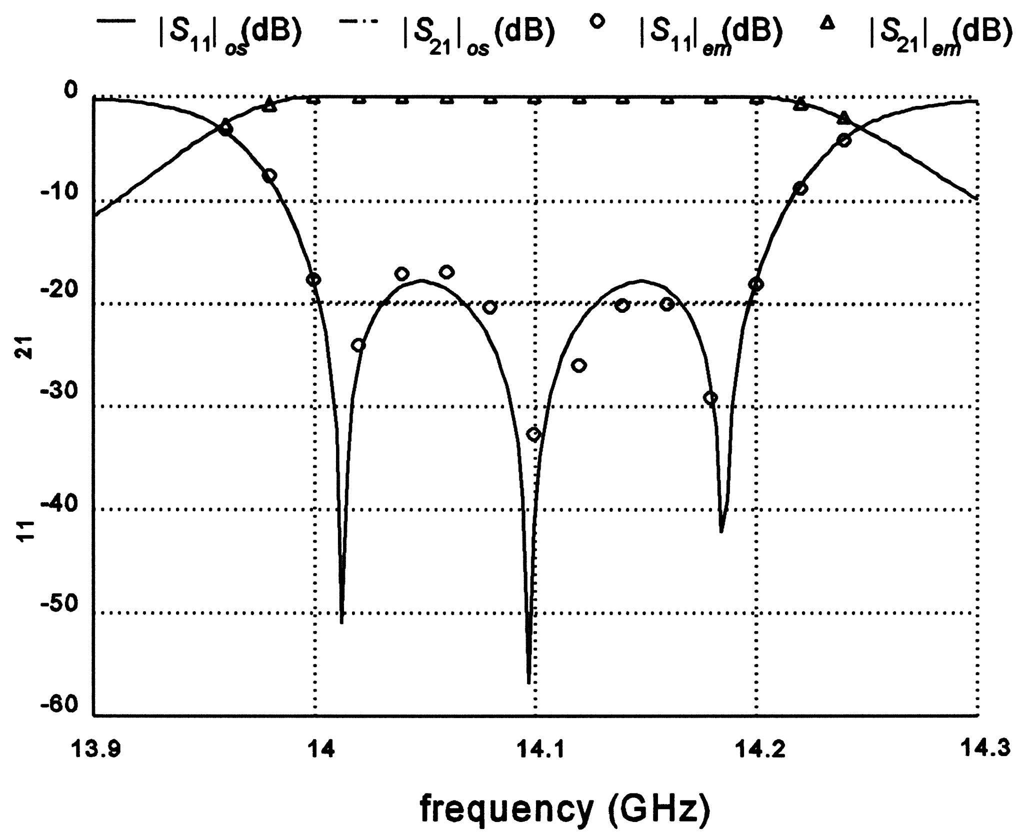
$t = 0.4$ mm, $R = 1$ mm

optimization variables: d_1, d_2, l_1 and l_2

design specifications

$$|S_{21}|\ (\text{dB}) < -35 \quad \text{for } 13.5 \le f \le 13.6 \text{ GHz}$$
$$|S_{11}|\ (\text{dB}) < -20 \quad \text{for } 14.0 \le f \le 14.2 \text{ GHz}$$
$$|S_{21}|\ (\text{dB}) < -35 \quad \text{for } 14.6 \le f \le 14.8 \text{ GHz}$$

SM Optimized FEM Response



only 4 Maxwell Eminence simulations lead to the optimal solution

$d_1 = 6.17557$, $d_2 = 3.29058$, $l_1 = 13.0282$ and $l_2 = 13.8841$

direct optimization using Empipe3D confirms that the SM solution is optimal

Tolerance Simulation Using SM

first, the mapping is established during nominal SM optimization

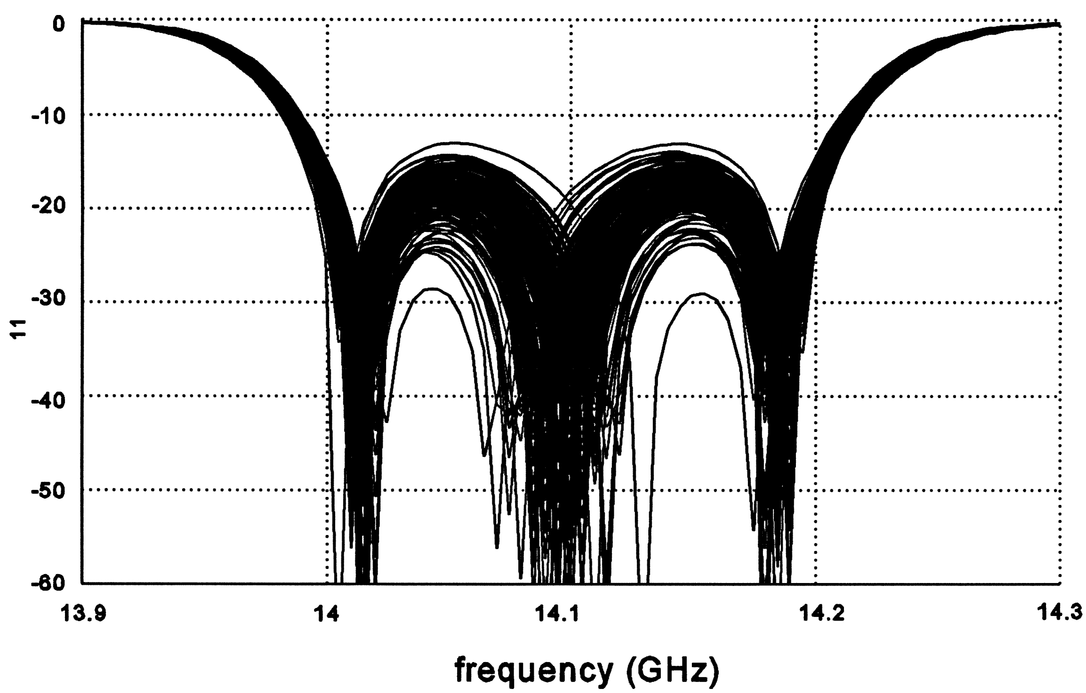
statistical outcomes in the EM space are mapped to the corresponding points in the OS space

we are able to rapidly estimate the effects of manufacturing tolerances, benefitting from

- the accuracy of the FEM model
- the speed of the hybrid MM/network theory simulations

the CPU time required for the Monte Carlo analysis is comparable to just a single full FEM simulation

Monte Carlo Analysis of the H-Plane Filter



the statistical outcomes were randomly generated from normal distribution with a standard deviation of 0.0333%

the yield estimated from 200 outcomes is 88.5% w.r.t. the specification of $|S_{11}| < -15$ dB in the passband

increasing the standard deviation to 0.1% results in yield dropping to 19% for 200 outcomes

Conclusions

cost-effective yield-driven design technology is indispensable

integrated EM and physical simulation and optimization capable of handling arbitrary structures is the future

Space Mapping promises the accuracy of EM and physical simulation and the speed of circuit-level optimization

heterogeneous parallel CAD over a local or wide area network significantly increases design power

integration of EM simulators from various vendors into automated design using OSA's optimizers

Geometry Capture allows analysis and optimization of complicated structures as a whole

EM optimization of arbitrary geometries exerts a massive demand on resources, particularly for yield-driven design

parallel computation speed up CPU intensive optimization

integrating parallel computation with interpolation, response function modeling and data base techniques will immensely reduce the overall design time

References

J.W. Bandler and R.H. Jansen, Eds., *IEEE Trans. Microwave Theory Tech.,* Special Issue on Process-Oriented Microwave CAD and Modeling, vol. 40, 1992, pp. 1329-1594.

J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, S. Ye and Q.J. Zhang, "Integrated physics-oriented statistical modeling, simulation and optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 40, 1992, pp. 1374-1400.

J.W. Bandler, S. Ye, Q. Cai, R.M. Biernacki and S.H. Chen, "Predictable yield-driven circuit optimization," *IEEE MTT-S Int. Microwave Symp. Dig.* (Albuquerque, NM), 1992, pp. 837-840.

"CAD review: the 7GHz doubler circuit," *Microwave Engineering Europe,* May 1994, pp. 43-53.

J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "Cost-driven physics-based large-signal simultaneous device and circuit design," *IEEE MTT-S Int. Microwave Symp. Dig.* (Orlando, FL), 1995, pp. 1443-1446.

J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Integrated harmonic balance and electromagnetic optimization with Geometry Capture," *IEEE MTT-S Int. Microwave Symp. Dig.* (Orlando, FL), 1995, pp. 793-796.

J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, P.A. Grobelny and D.G. Swanson, Jr., "Heterogeneous parallel yield-driven electromagnetic CAD," *IEEE MTT-S Int. Microwave Symp. Dig.* (Orlando, FL), 1995, pp. 1085-1088.

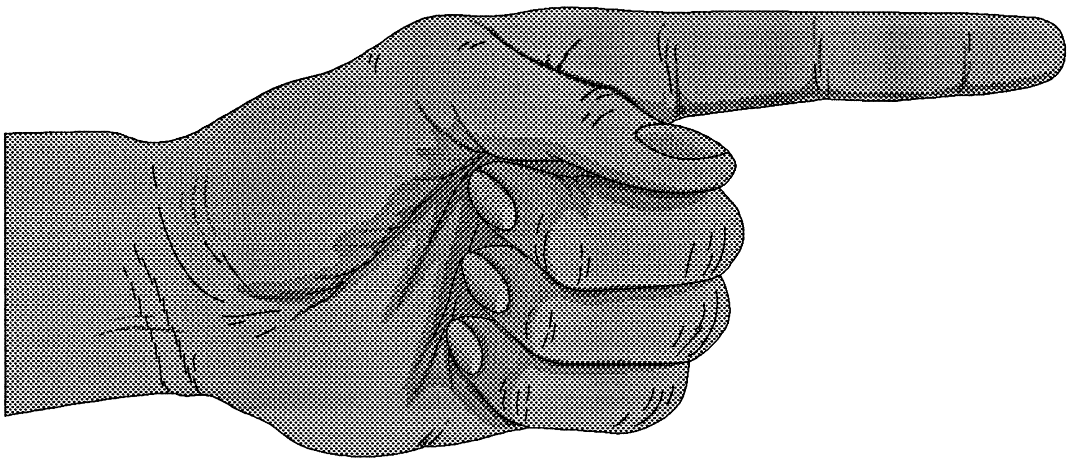
J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," *IEEE Trans. Microwave Theory Tech.*, vol. 43, 1995, pp. 2874-2882.

J.W. Bandler, R.M. Biernacki and S.H. Chen, "Fully automated space mapping optimization of 3D structures," *IEEE MTT-S Int. Microwave Symp. Dig.* (San Francisco, CA), 1996, pp. 753-756.

J.W. Bandler, R.M. Biernacki and S.H. Chen, "Parameterization of arbitrary geometrical structures for automated electromagnetic optimization," *IEEE MTT-S Int. Microwave Symp. Dig.* (San Francisco, CA), 1996, pp. 1059-1062.

J.W. Bandler, R.M. Biernacki, S.H. Chen and Y.F. Huang, "Design optimization of interdigital filters using aggressive space mapping and decomposition," *IEEE Trans. Microwave Theory Tech.*, vol. 45, May 1997.

J.W. Bandler, R.M. Biernacki, S.H. Chen and D. Omeragić, "Space mapping optimization of waveguide filters using finite element and mode-matching electromagnetic simulators," *IEEE MTT-S Int. Microwave Symp. Dig.* (Denver, CO), June 1997.



visit OSA's

website

www.osacad.com

JWB-97-85