AUTOMATED ELECTROMAGNETIC OPTIMIZATION OF RF AND MICROWAVE CIRCUITS

J.W. Bandler

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presented at

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presented at

ICASE/LaRC Workshop on Computational Electromagnetics and its Applications
Newport News, VA, May 29-31, 1996

Overview of the Presentation

OSA's technology

benchmark EM design problems

- double folded stub filter
- attenuator
- HTS filter
- interdigital filter
- frequency doubler
- waveguide transformers
- waveguide bend

Geometry Capture™ for user-defined parameterization of arbitrary structures

parallel computing

Space Mapping™

EM optimization of 3D structures

Optimization Systems Associates Inc.

PIONEERS IN

yield and tolerance optimization

circuit performance optimization

parametric design centering

statistical device modeling

robust parameter extraction

harmonic balance simulation

physics based design

EM based design

large-scale optimization

benchmark CAD technology

software architecture for IC design

Areas of Expertise

RF/microwave circuit simulation, design and optimization

harmonic balance simulation techniques

robust and statistical modeling of active and passive devices

device modeling, statistical estimation of production yield

powerful performance and yield optimization algorithms

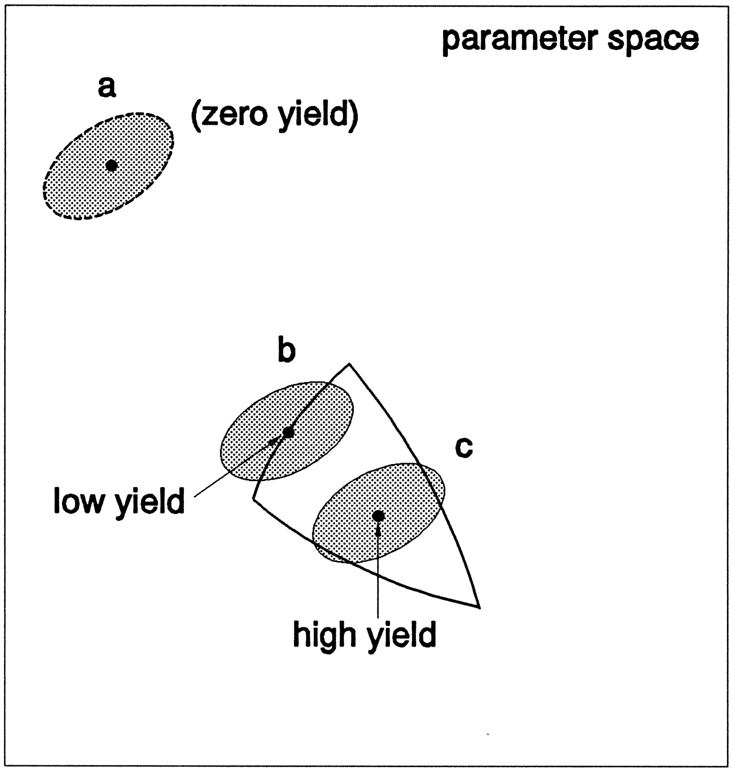
manufacturing tolerance assignment and cost minimization

algorithms for automated production alignment and tuning

customized optimizers for large-scale problems

software architectures for integrated approach to design

electromagnetic optimization



Yield interpretation in the parameter space

OSA90/hope™ Version 3.1

general nonlinear circuit simulation and optimization
analytically unified DC, small-signal and large-signal
    harmonic balance analysis
statistical analysis and yield optimization
comprehensive optimization/nonlinear modeling
interconnects external simulators
    Empipe™ merges *em*™, even for arbitrary geometry!
    Spicepipe™ merges SPICE
Space Mapping™ breakthrough in EM optimization
3D visualization

HarPE™ Version 2.0

device characterization, simulation and optimization
FET, bipolar, HEMT, HBT, thermal modeling
parameter extraction
cold measurement processing
statistical modeling, Monte Carlo analysis
Huber optimization
cumulative probability distribution fitting
can be invoked from OSA90/hope™ as a child process

Empipe™ Version 3.1

powerful and friendly software system for automated EM design optimization

- driving Sonnet's *em*™ field simulator
- employing the sophisticated optimizers of OSA90™
- breakthrough Geometry Capture™ allows you to designate geometrical and material parameters as variables for optimization
- any arbitrary structures that can be simulated by *em*™ can be optimized using Empipe™
- automatic off-grid interpolation integrated with intelligent database management
- intuitive and extremely user-friendly

a significant step towards the required integrated approach for interprocessing circuit/field/measurement data

OSA90/hope™ Optimization

state-of-the-art gradient-based optimizers with a proven track record in electrical circuit and system optimization

L1
L2 (least squares)
Huber
minimax
quasi-Newton
conjugate gradient
simplex
random
simulated annealing
yield (design centering)

exact or approximate gradient

specification and goal definition

quadratic modeling of functions and gradients

sensitivity displays help the user to select the most crucial variables for optimization

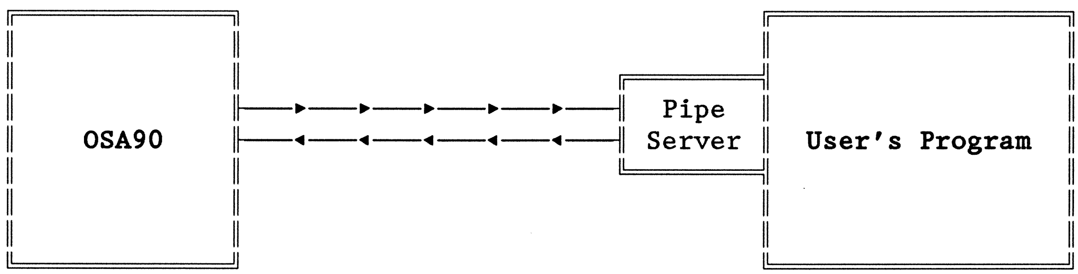
Space Mapping™ for CPU intensive optimization

automated Aggressive Space Mapping™

OSA90/hope™ Datapipe™

Datapipe™: predefined protocols for UNIX pipes

ready-to-use to facilitate high-speed data connections to and from the user's software; over networks

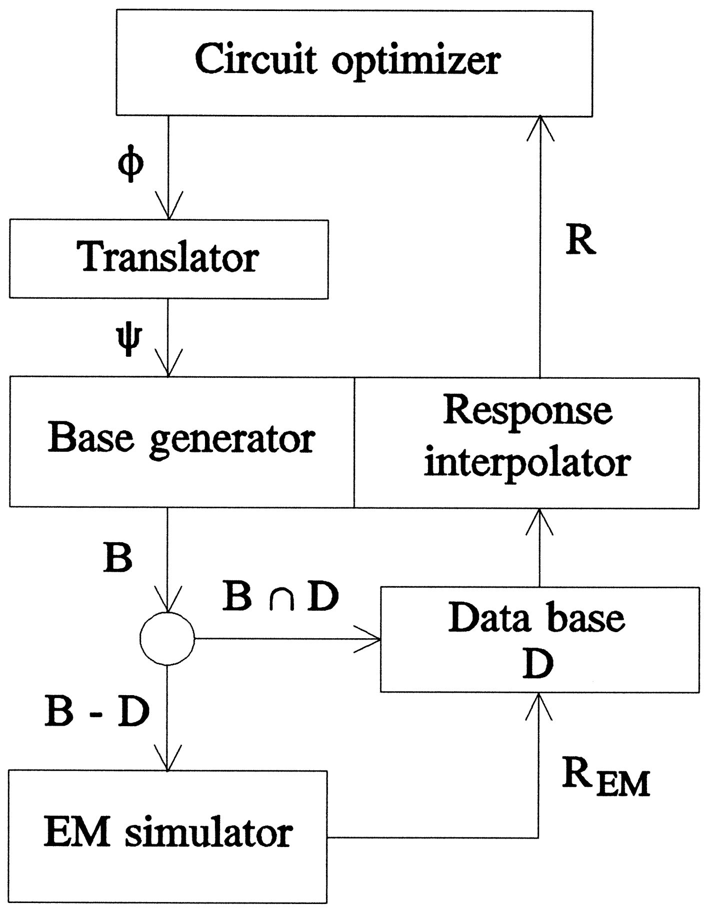


typical READ and WRITE statements are used to receive and send data

a small pipe server establishes the protocols

maintains complete security of user's software: OSA does not need access to the user's source code

Interconnection Between a Circuit Optimizer and a Numerical EM Simulator



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

drastically increased analysis time

discrete nature of some EM solvers

continuity of optimization variables

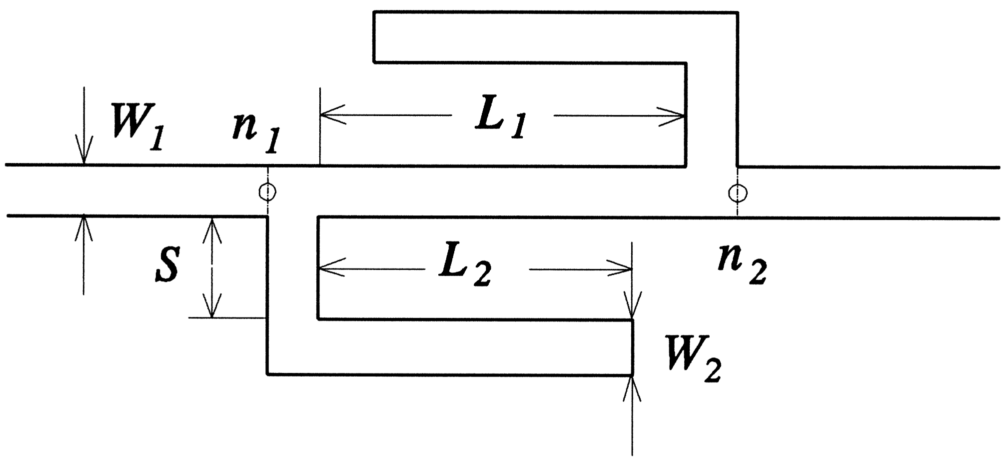
gradient information

interpolation and modeling

integrated data bases

original Space Mapping™ algorithm

Benchmark EM Design Problems
A Double Folded Stub Filter
(*Jim Rautio, Sonnet Software*)

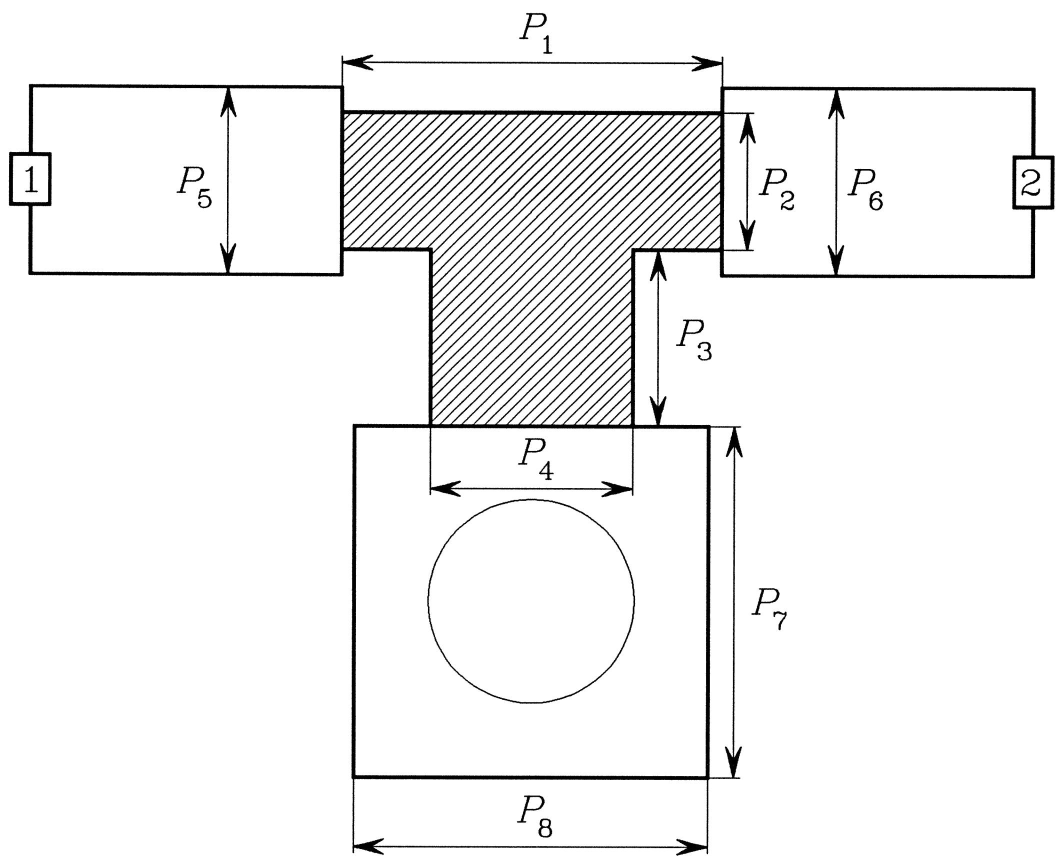


for bandstop filter applications

substantially reduced filter area w.r.t. the conventional double stub structure

substrate thickness is 5 mil and the relative dielectric constant is assumed to be 9.9

Benchmark EM Design Problems
A 10 dB Distributed Attenuator
(*Dan Swanson, Watkins-Johnson*)

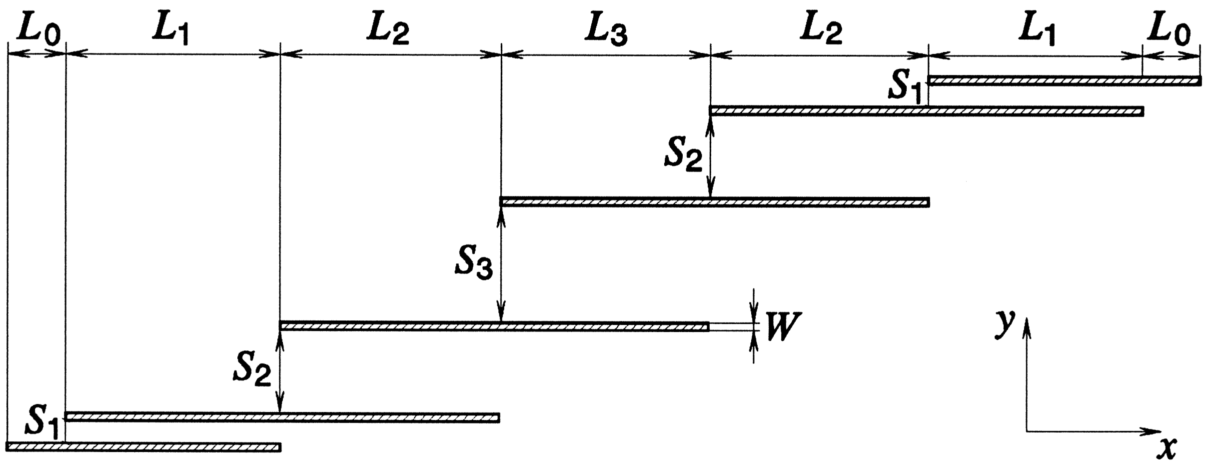


built on a 15 mil thick substrate with relative dielectric constant of 9.8

metallization of a high resistivity (50 Ω/sq)

the feed lines and the grounding pad are assumed lossless

Benchmark EM Design Problems
An HTS Filter
(*Chuck Moskowitz and Salvador Talisa, Westinghouse*)

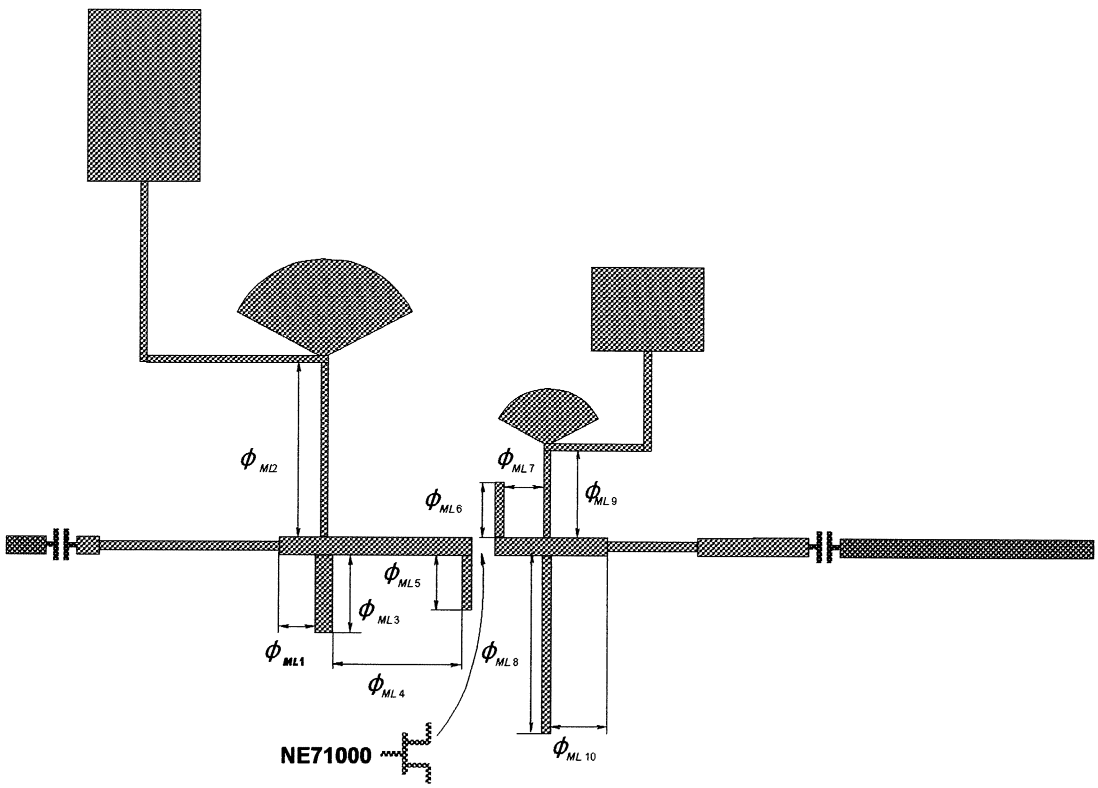


high-temperature superconducting four pole quarter-wave parallel coupled-line microstrip filter

high relative dielectric constant (more than 23) of the substrate material (lanthanum aluminate)

narrow bandwidth (1.25%)

Benchmark EM Design Problems
A Nonlinear FET Class B Frequency Doubler
(Microwave Engineering Europe, 1994)



the linear subcircuit is defined as one optimizable structure with 10 variables

requires integration of large-signal harmonic balance of nonlinear circuits with active devices into EM-based optimization

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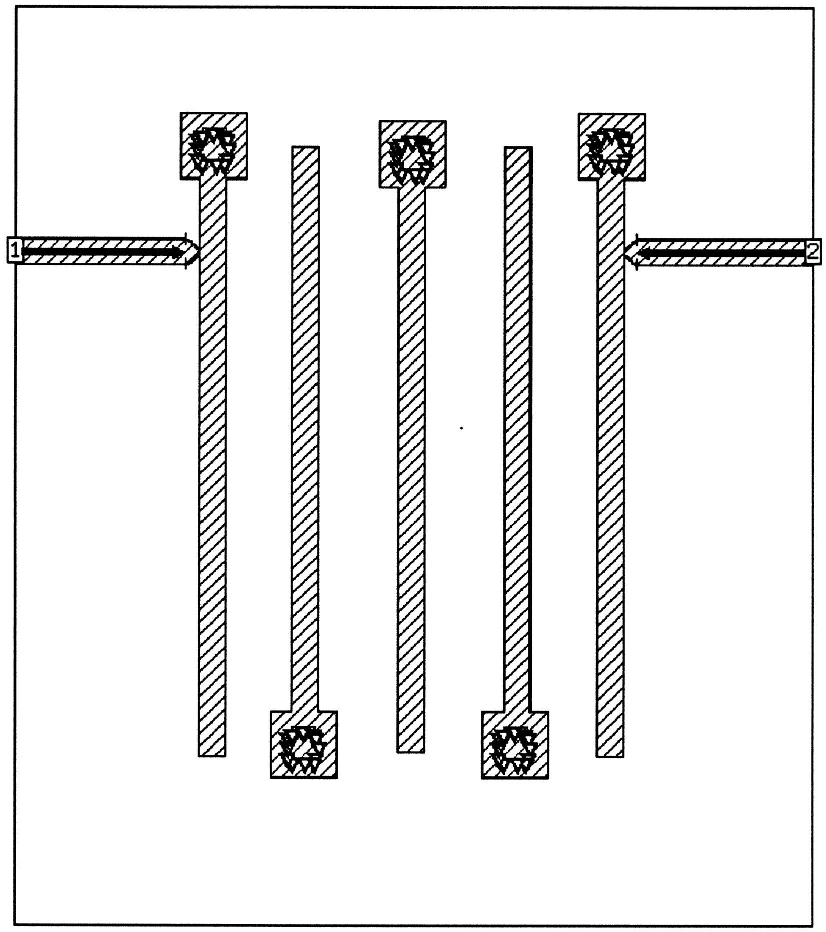
Benchmark EM Design Problems
An Interdigital C-Band Filter
(*Dan Swanson, Watkins-Johnson*)



a five-pole interdigital filter with tapped lines

drawn using *xgeom* of Sonnet Software

96-9-15

Geometry Capture™

to optimize shapes and dimensions of geometrical objects by automatically adjusting the user-defined parameters subject to implicit geometrical constraints

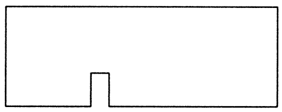
work includes development of theory and algorithms employing concepts from analytic geometry, supported by graphical interfacing

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

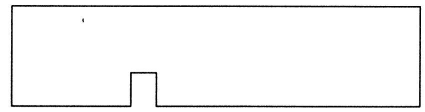
geometrical coordinates are implicitly related to designable parameters

geometrical parameterization is needed for every new structure

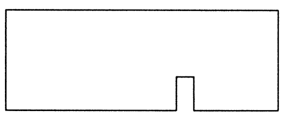
Various Object Evolutions



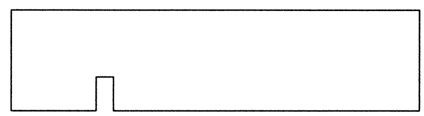
(a)



(b)



(c)



(d)

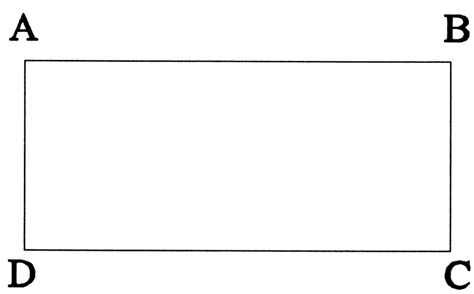
(a) initial geometry

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

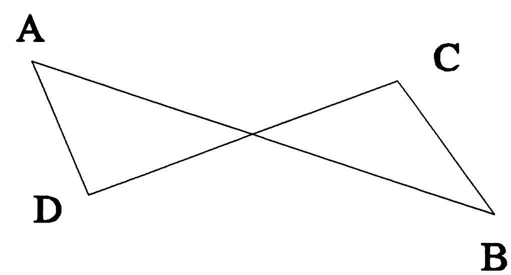
(c) only the location of the slit in the fixed line is allowed to change

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

Possible Pitfalls of Arbitrary Movement of Vertices



(a)

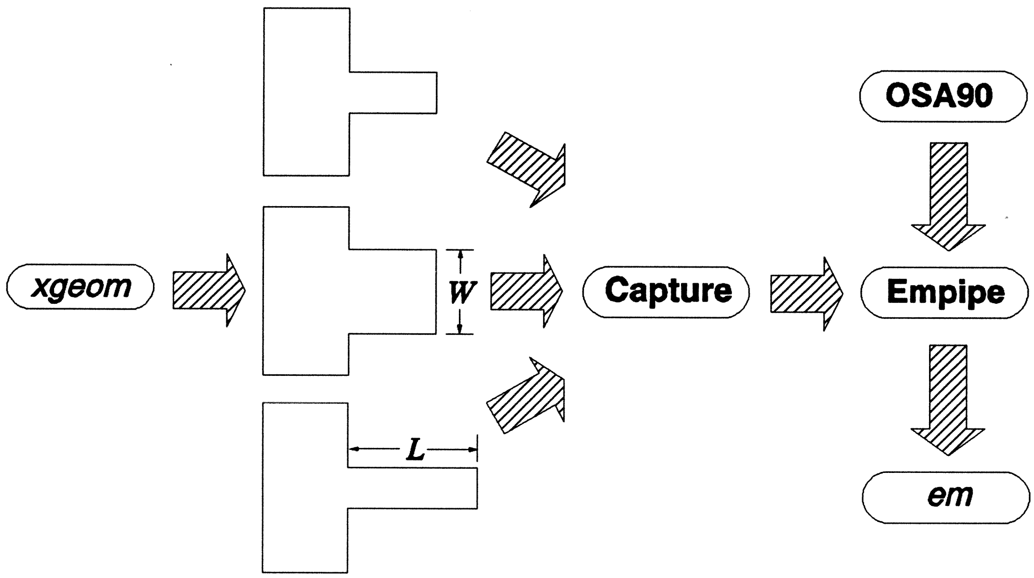


(b)

(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

processed by Empipe™ to extract the relevant information

extremely easy to use

Direct EM Optimization of the Frequency Doubler
(*Bandler et al., 1995*)

involves optimization of an arbitrary planar structure

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

Empipe™ links ***em***™ simulations to the optimizer

the performance of the overall circuit is directly optimized with 10 optimization variables

design specification:

conversion gain > 3 dB
spectral purity > 20 dB

at 7 GHz and 10 dBm input power

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

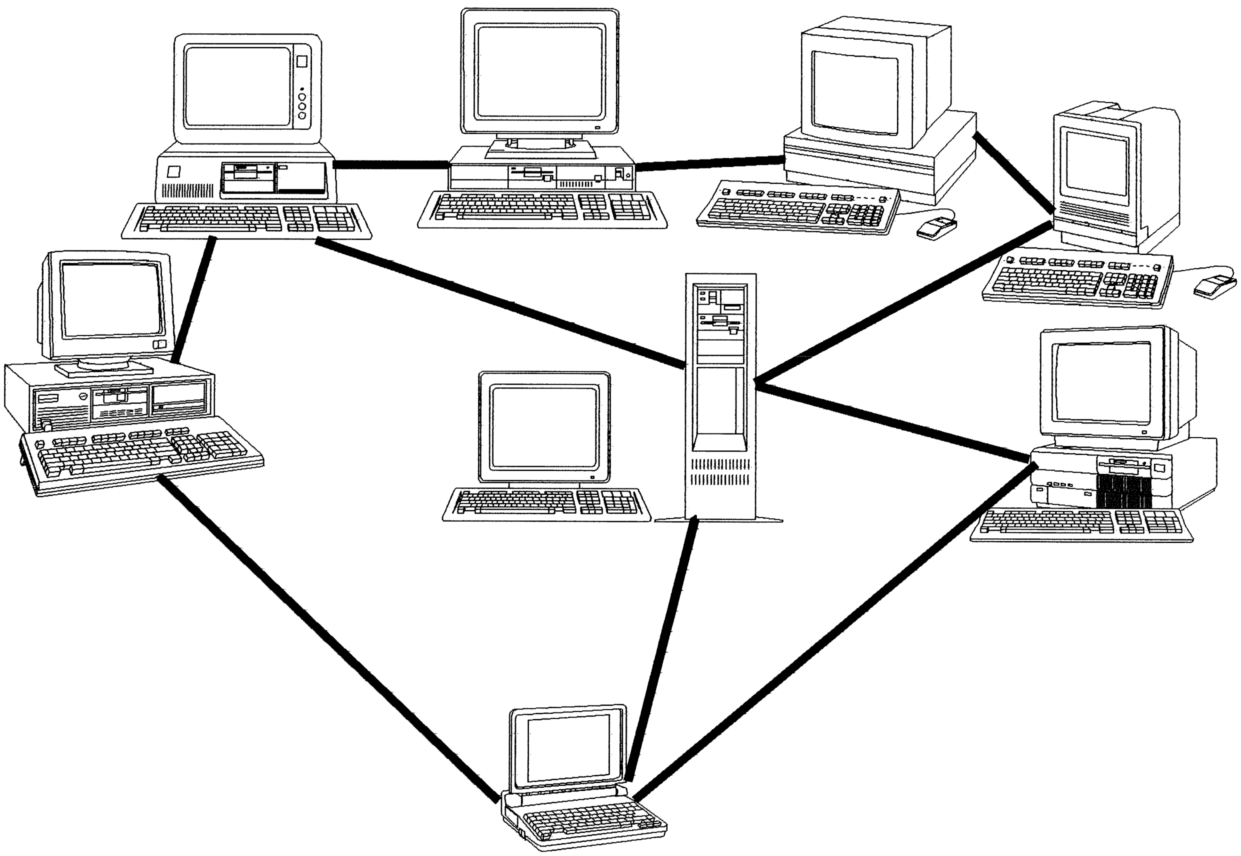
when the analysis is finished on a host, the next job, if any, is dispatched to that host

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



Statistical Design of the Attenuator

design specifications (from 2 GHz to 18 GHz)

9.5 dB ≤ insertion loss ≤ 10.5 dB

return loss ≥ 10 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%

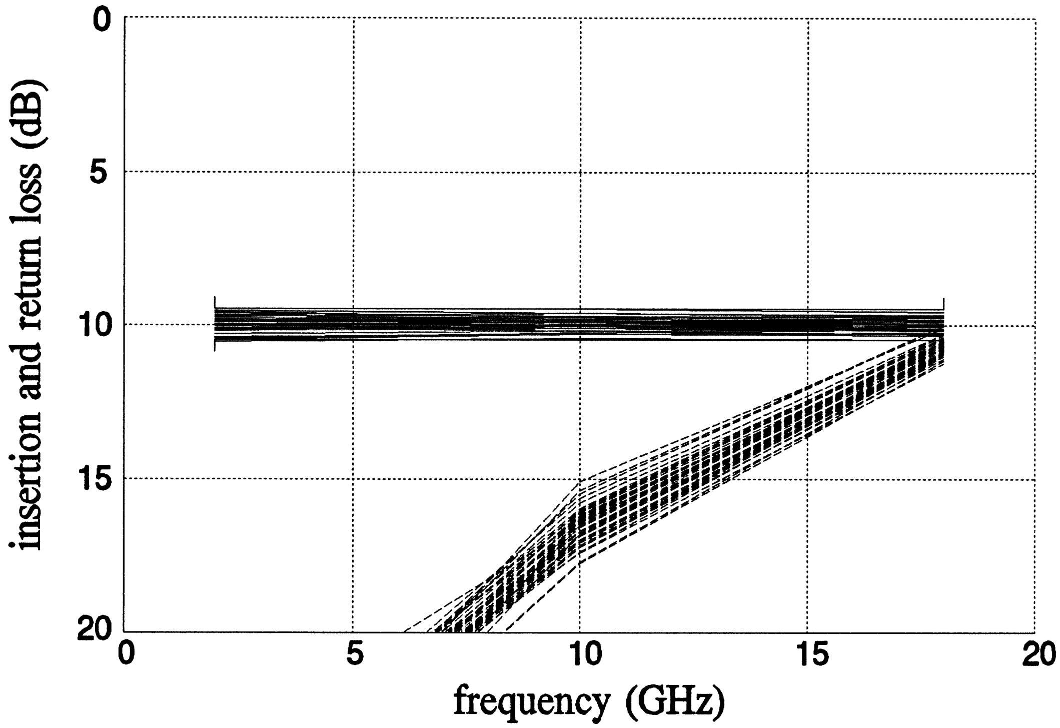
Parallel Computing in Statistical Design of the Attenuator

additional 113 ***em***™ analyses

an average of 2.5 analyses run in parallel

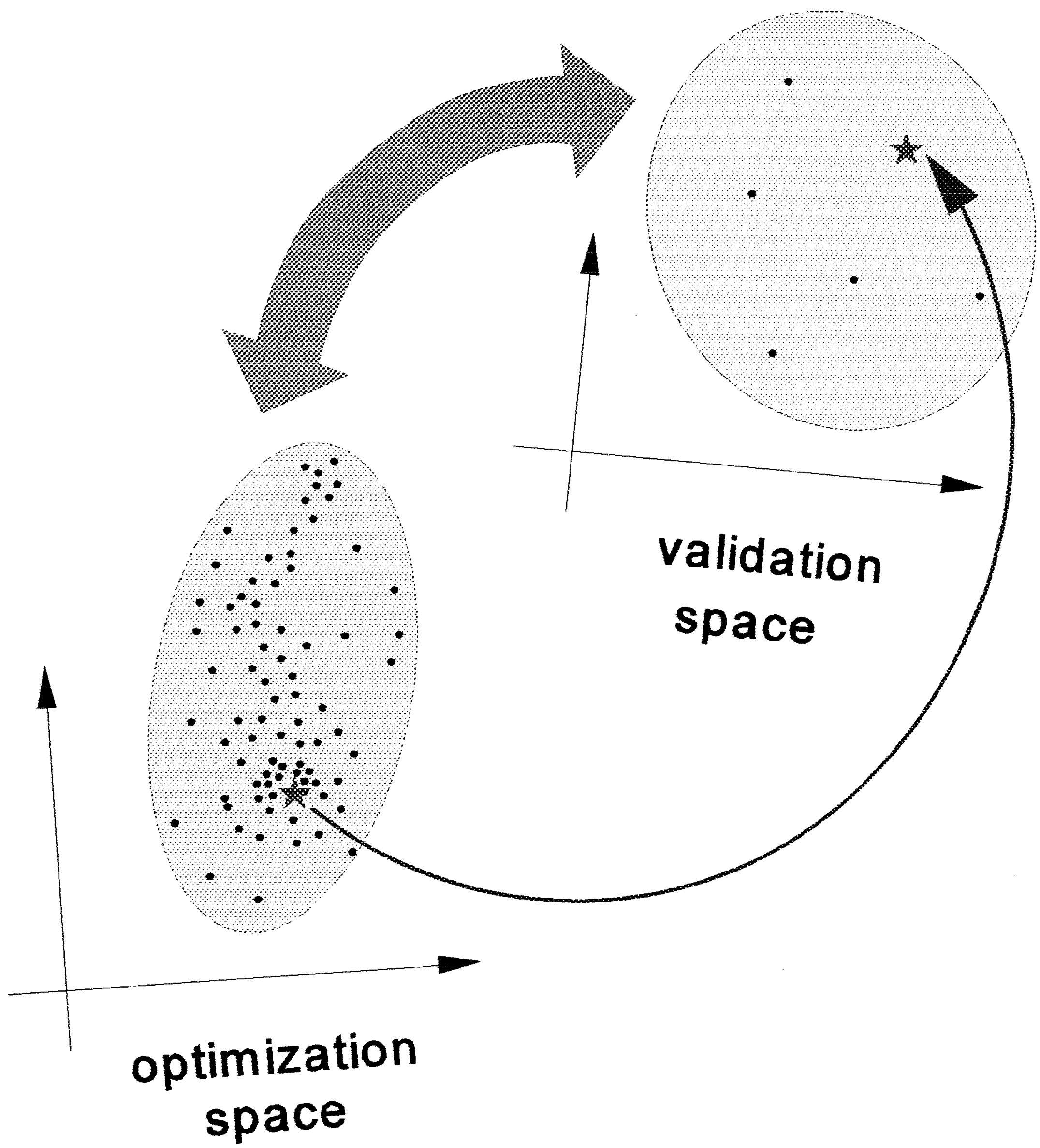
time is reduced by 60%

Monte Carlo Sweeps of the Attenuator Responses



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

Space Mapping™
(Bandler et al., 1994)



Work on Space Mapping™

develop theory and corresponding algorithms for parameter Space Mapping™

to allow CPU intensive models to be automatically replaced during optimization by slower but also less accurate models

consider hierarchical family of models: equivalent circuit, empirical, or even decomposed or coarse grid numerical EM models, particularly for arbitrary geometries

aggressive strategy for Space Mapping™

automation issues for Space Mapping™

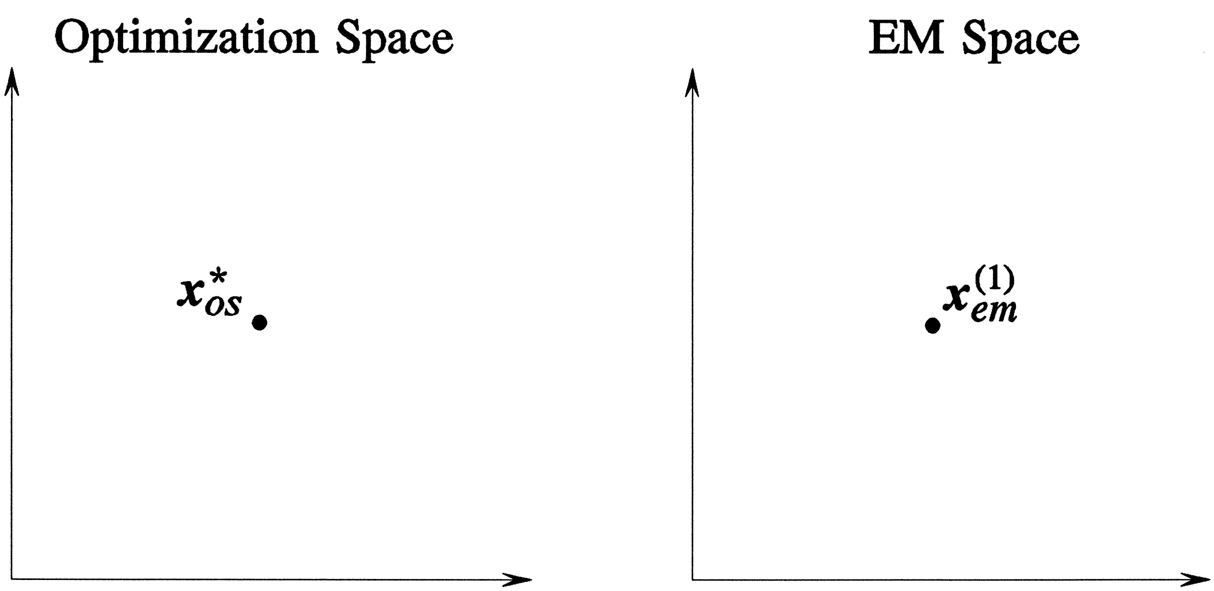
expected cornerstone for successful EM optimization

Illustration of Aggressive Space Mapping™ Optimization

Step 0

find the optimal design x_{os}^* in Optimization Space

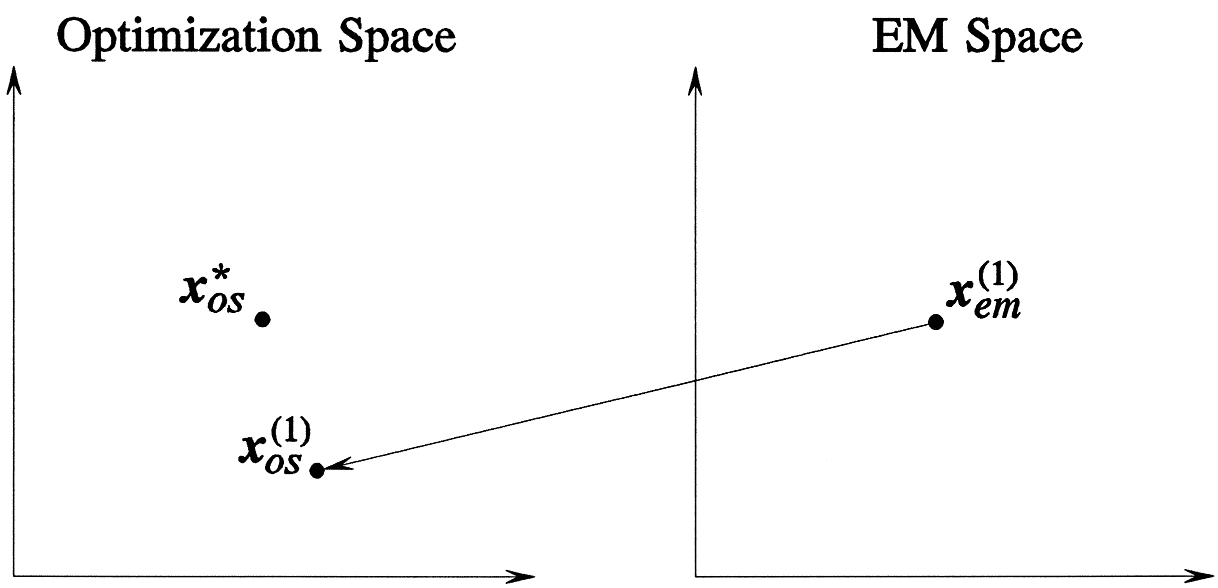
Step 1



set $x_{em}^{(1)} = x_{os}^*$ assuming x_{em} and x_{os} represent the same physical parameters

Illustration of Aggressive Space Mapping™ Optimization

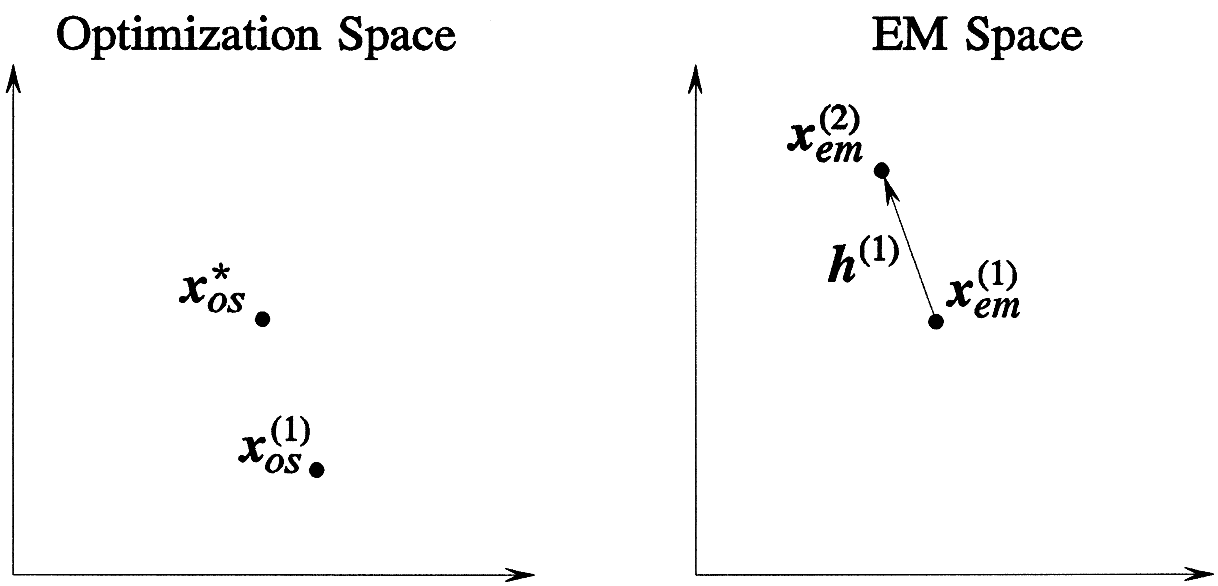
Step 2



perform X_{os}-space model parameter extraction

Illustration of Aggressive Space Mapping™ Optimization

Step 3



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

obtain $x_{em}^{(2)}$ by solving

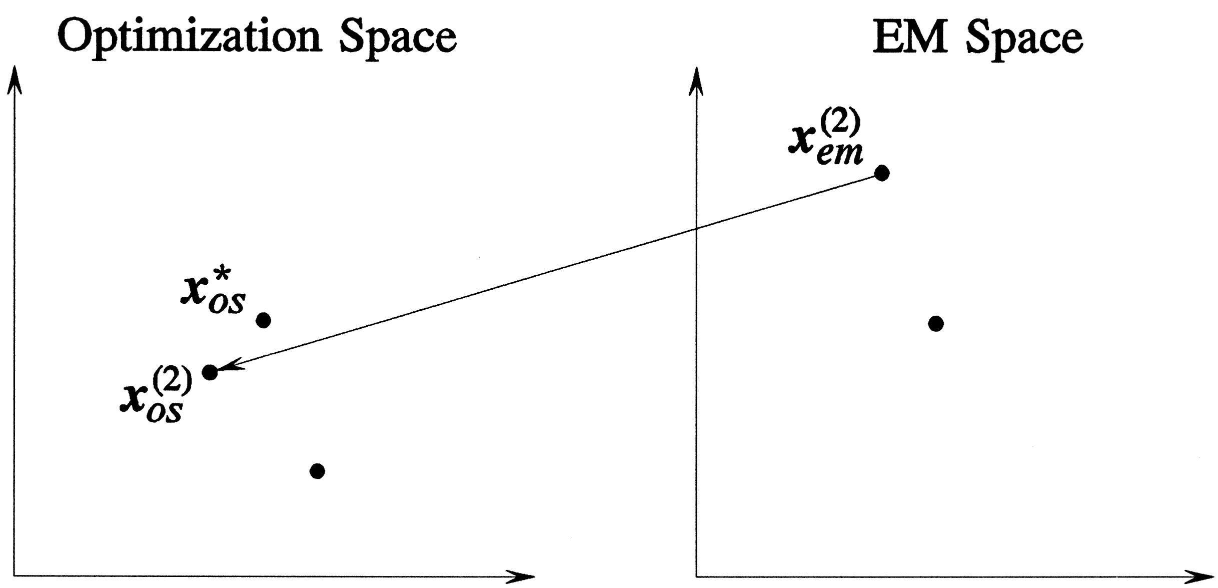
$$B^{(1)} h^{(1)} = -f^{(1)}$$

where

$$f^{(1)} = x_{os}^{(1)} - x_{os}^{*}$$

Illustration of Aggressive Space Mapping™ Optimization

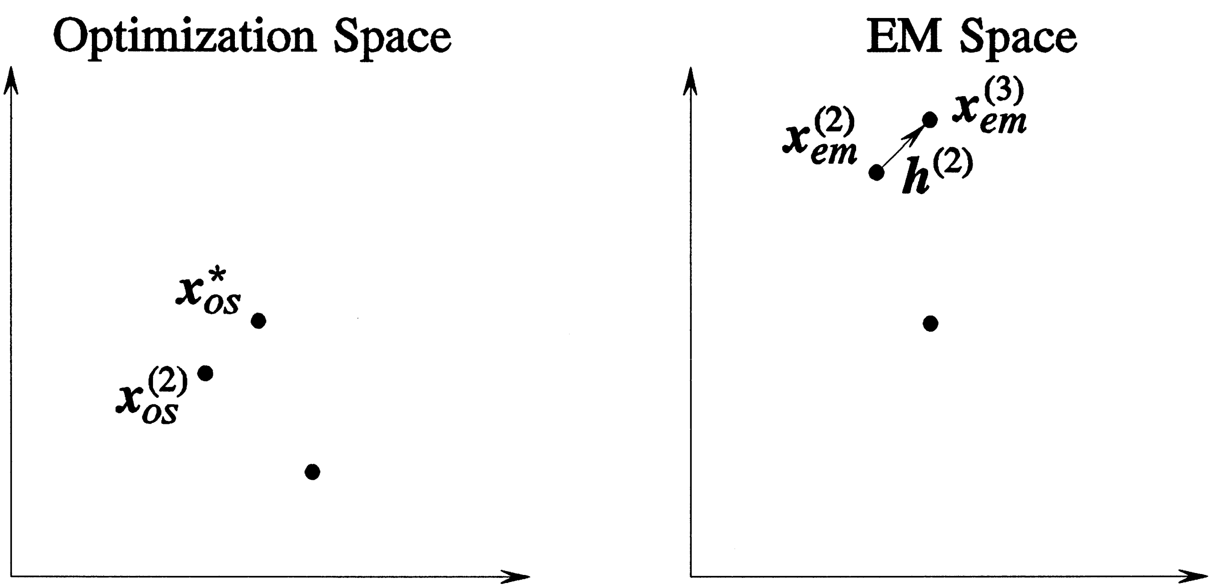
Step 4



perform X_{os}-space model parameter extraction

Illustration of Aggressive Space Mapping™ Optimization

Step 5



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

obtain $x_{em}^{(3)}$ by solving

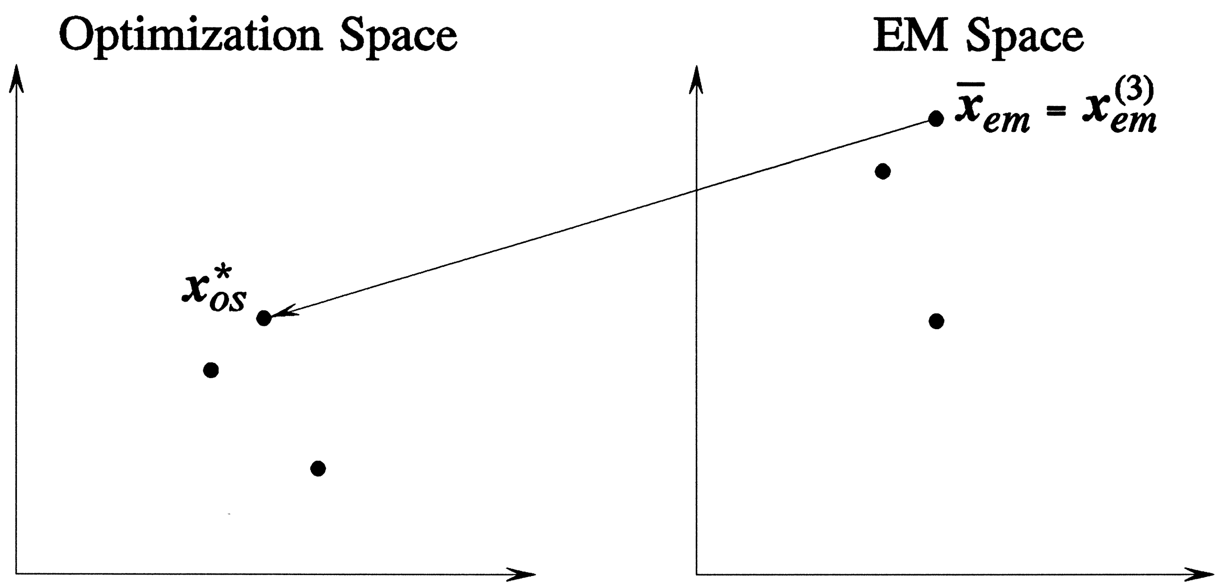
$$B^{(2)} h^{(2)} = -f^{(2)}$$

where

$$f^{(2)} = x_{os}^{(2)} - x_{os}^{*}$$

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

Automated Aggressive Space Mapping™

automating the aggressive SM strategy using a two-level Datapipe™ architecture

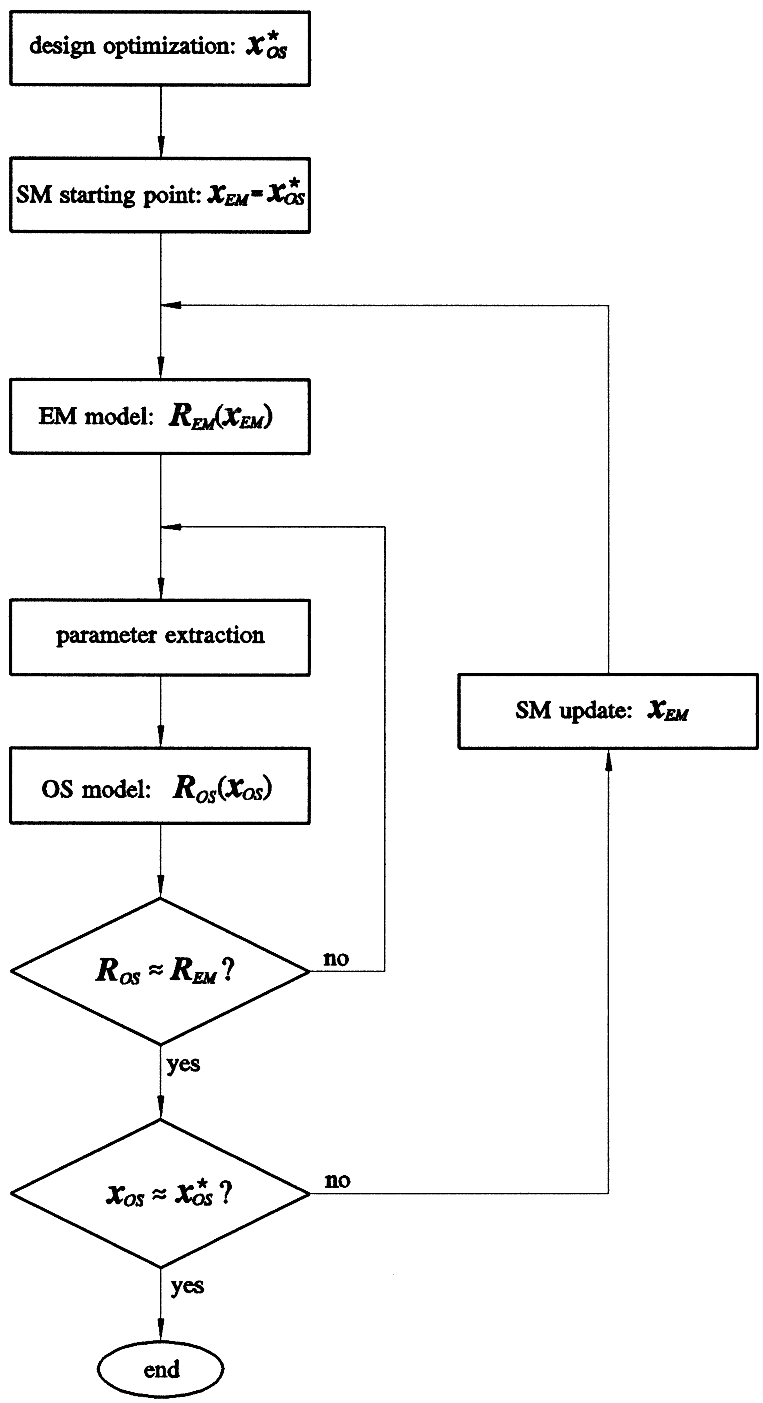
- outer level automates a generic aggressive SM loop including a Broyden update

- inner level implements parameter extraction for specific models

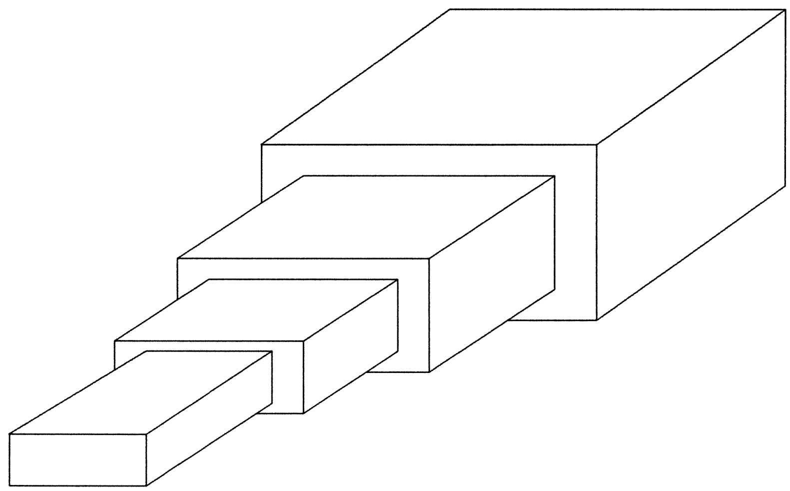
parameter extraction is crucial to SM optimization

the impact of uniqueness on the convergence of the aggressive SM strategy

Implementation of Aggressive Space Mapping™



Benchmark EM Design Problems
Waveguide Transformers



a two-section waveguide transformer

two cases of Space Mapping™ used to align

(a) an ideal empirical model and a non-ideal empirical model

(b) an empirical model and HFSS simulations

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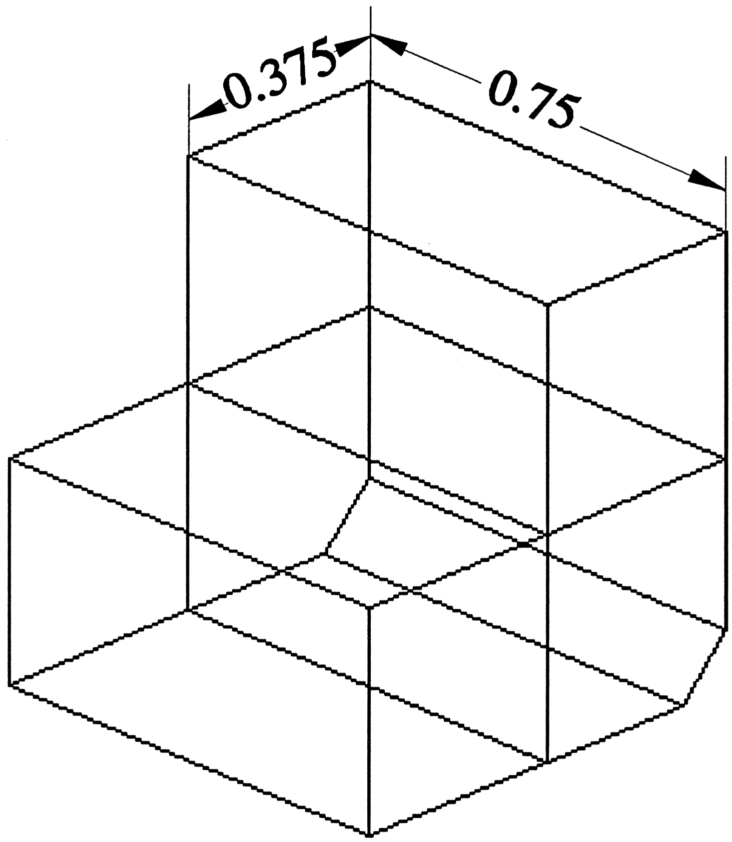
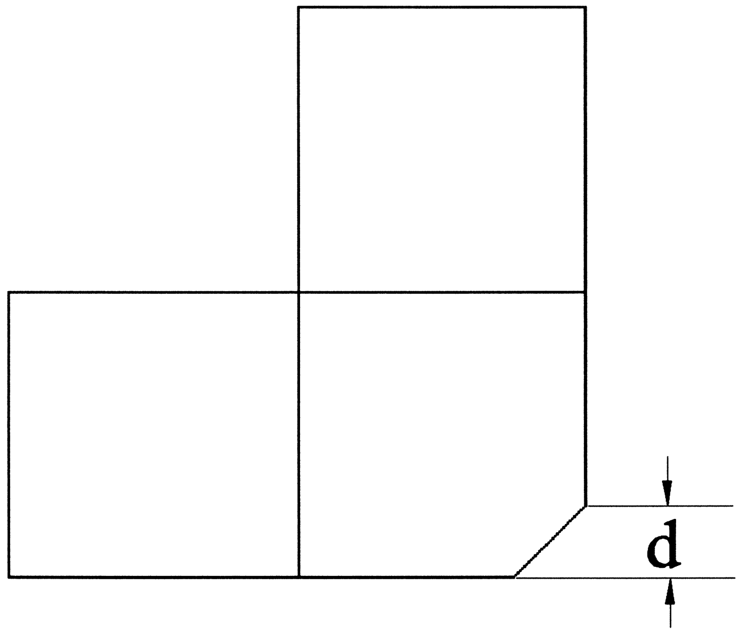
Benchmark EM Design Problems
WR-75 Mitered Waveguide Bend



Single Section Mitered Bend



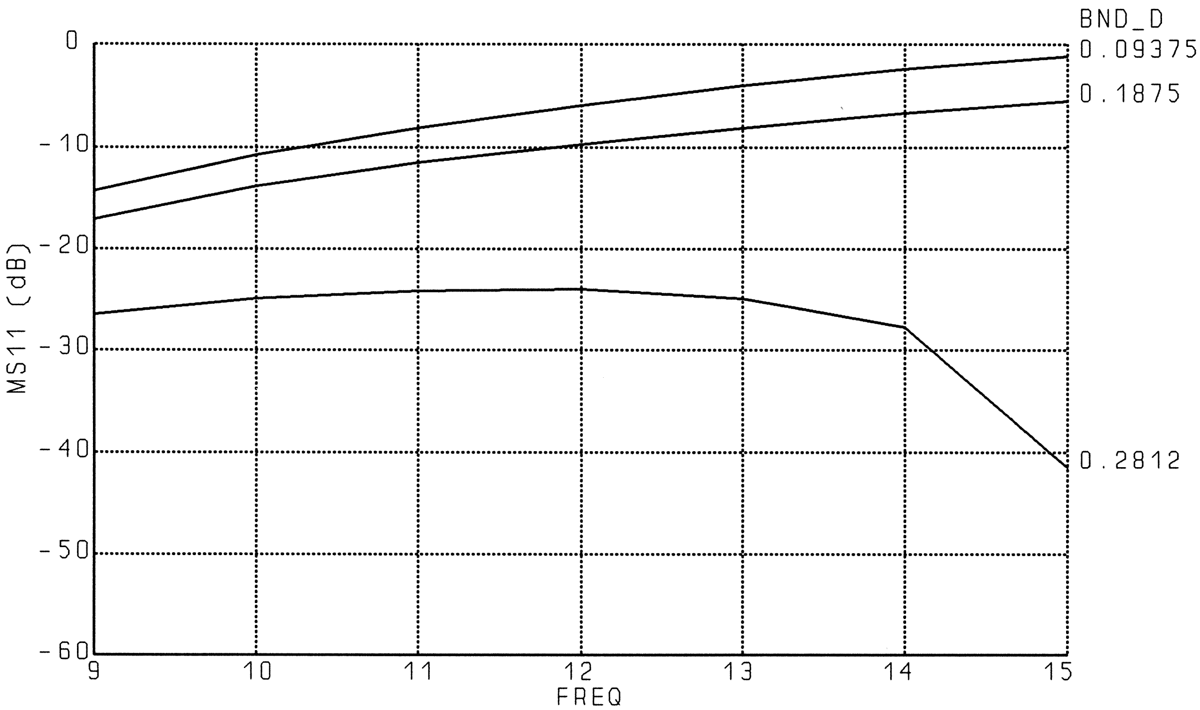
specification in the frequency range from 9.84 to 15 GHz

return loss $\geq$ 40 dB

one variable only: the position of the miter d, bounded as

$0 \leq d \leq 0.375$ inch

Sweep of the Miter Position

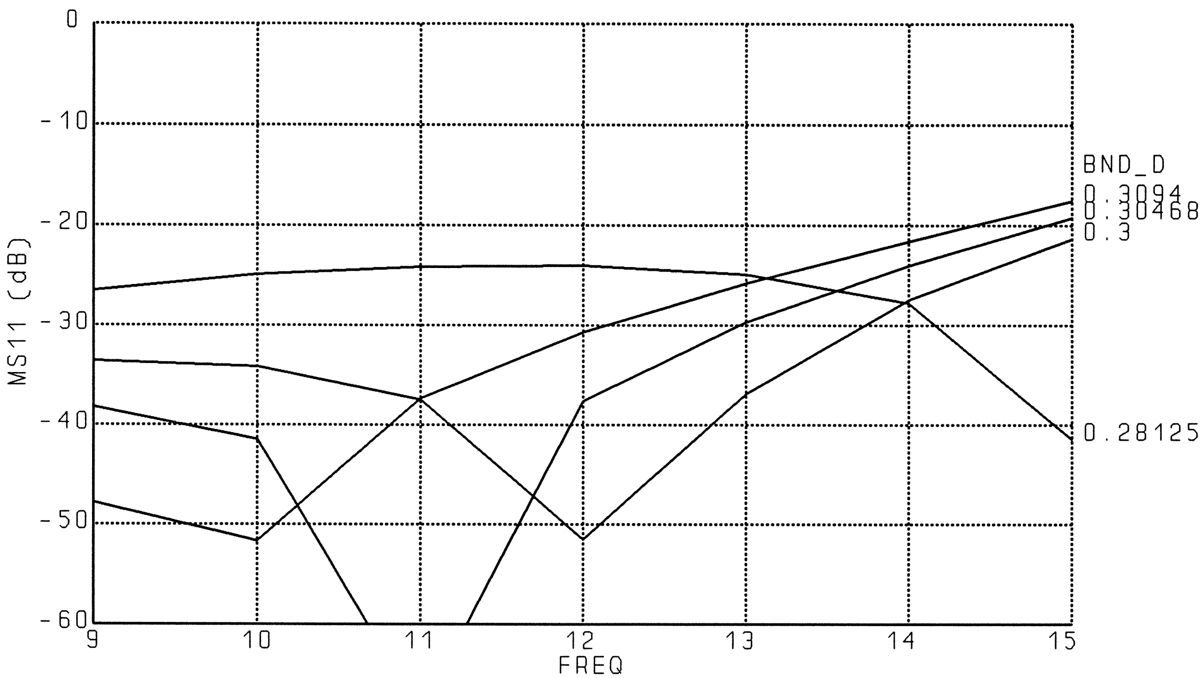


frequencies: from 9 GHz to 15 GHz with a step of 1 GHz

d is swept for 0.09375, 0.1875 and 0.28125 inch

simulation time is approximately 8 CPU hours for each value of *d* (SPARCstation 10, 9 adaptive meshing iterations)

Fine Sweep of the Parameter "d"



to emulate design by hand, we sweep *d* with these values: 0.28125, 0.3, 0.304675 and 0.3094 inch

by visual inspection, we can relate the position of the return loss pole to the parameter *d* as 1 GHz / 0.005 inch

Conclusions

cost-effective yield-driven design technology is indispensable

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

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

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

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

Geometry Capture™ user-defined parameterization allows analysis and optimization of complicated structures as a whole

integration of simulators from various sources into automated design optimization with interpolation, response function modeling and data base techniques will immensely reduce the overall design time

Selected References

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

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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.

New Products from OSA

to be unveiled at the IEEE Int. Microwave Symposium and Exhibition, San Francisco, June 1996

EmpipeExpress™

based on Empipe™ and crafted to the needs of the majority of *em*™ users

available from OSA for users who seek direct support from the developers

available from Sonnet Software as *empath*™ for users who prefer a single vendor

Empipe3D™

driving Ansoft's Maxwell® Eminence or HP's HFSS finite element full-wave 3D field simulators

powerful and friendly software system for automated EM design optimization

the **Empipe** family features OSA's breakthrough Geometry Capture™ front end for optimizing arbitrary structures