PERFORMANCE- AND YIELD-DRIVEN DESIGN OF MICROWAVE CIRCUITS EMPHASIZING DIRECT EM OPTIMIZATION

J.W. Bandler

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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

automated processing of DC, RF and spectrum data

device modeling, statistical estimation of production yield

powerful performance and yield optimization algorithms

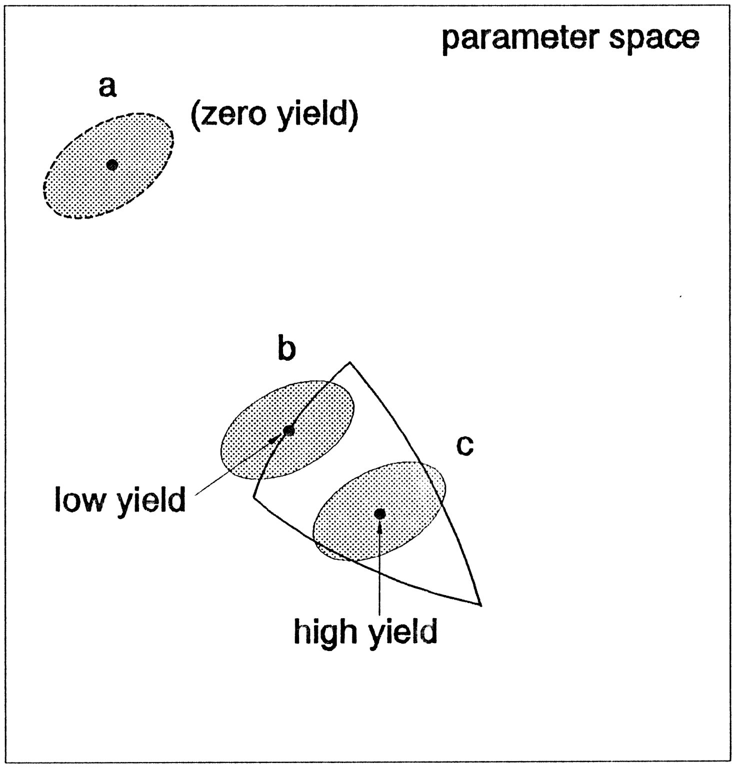
manufacturing tolerance assignment and cost minimization

customized optimizers for large-scale problems

computer optimization of linear and nonlinear networks

algorithms for automated production alignment and tuning

software architectures for integrated approach to design



Yield interpretation in the parameter space

Milestones I

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)

Milestones II

optimal tuning and alignment at the production stage (1980)

fault diagnosis and parameter extraction (1980)

world's fastest multiplexer optimizer (1984)

introduction of powerful minimax optimizers into commercial CAD/CAE products (1985)

large-scale microwave optimization (1986)

foundation of multi-circuit ℓ_1 modeling (1986)

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

computational enhancements of commercial CAD/CAE products (1988)

parameter extraction using novel large-scale concepts (1988)

Milestones III

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)

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)

Milestones IV

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)

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)

Milestones V

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 ***em***™ field simulator (1992)

predictable yield-driven circuit optimization (1992)

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

"fulfills 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

Milestones VI

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)

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 structures with arbitrary geometry (1994)

Milestones VII

breakthrough Geometry Capture™ (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)

Milestones VIII

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

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)

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™ 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

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™ Circuit Features

general nonlinear circuit simulation and optimization
physics-based yield optimization

analytically unified simulation:
DC/small-signal/large-signal harmonic balance

arbitrary topology
multitone, multisource excitations
nonlinear sources controlled by voltages and currents

symbolic subcircuit definition: linear and nonlinear
voltage and current labels (probes)

comprehensive device library
empirical microstrip models
em™ parameterized microstrip models
user-definable models

OSA90/hope™ Math Features

variable definition

expressions including conditional *if else* structures

extensive math library

vector and matrix operations

- multiplication
- transposition
- inverse
- LU factorization
- eigenvalues and eigenvectors
- solving linear equations

vector and matrix elements fully optimizable

Space Mapping™ functions

built-in transformations, including DFT, splines, piecewise linear interpolation, etc.

operation control block

OSA90/hope™ Graphics

continuous, point, bar plots

parametric and multiple plots

histograms, run charts and scatter diagrams

sensitivity displays

waveforms

Smith chart and polar plots

3D visualization including scaling, rotating and smoothing

contours with trace of optimization variables

user-defined legends, colors, views

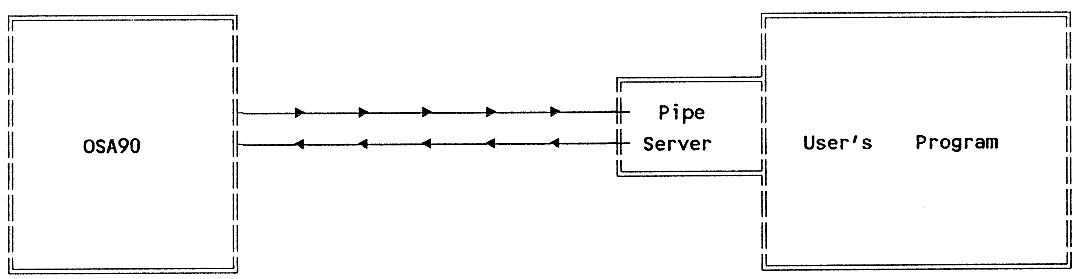
graphics zoom

HPGL and PostScript files

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 (about 350 lines) establishes the protocols; OSA provides the source code of the pipe server

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

OSA90/hope™ Connections

Empipe™ merges *em*™

from Sonnet Software, Inc.

for direct field-level optimizable microstrip designs
under circuit-level linear/nonlinear analysis

optimization of structures with arbitrary geometries

Spicepipe™ merges SPICE

for time-domain simulation, noise analysis, etc.
multidomain (frequency and time) specifications
nominal optimization
yield optimization

OSA90™ can call OSA90™

OSA90™ can call HarPE™

HarPE™ Version 2.0

characterize devices

extract parameters

simulation-driven
data-driven

build equivalent circuit models

build physics-based models

simulate and optimize

single device circuits at DC, small-signal and large-signal harmonic balance

statistically model devices

estimate Monte Carlo yield

cumulative probability distribution and histogram matching

HEMT models (*M. Golio, Motorola*)

HBT thermal modeling of self-heating

Minimax Design Optimization

$$\underset{\phi}{\text{minimize}} \{ \max_{j} (e_j(\phi)) \}$$

where

ϕ the vector of optimization variables

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

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

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

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

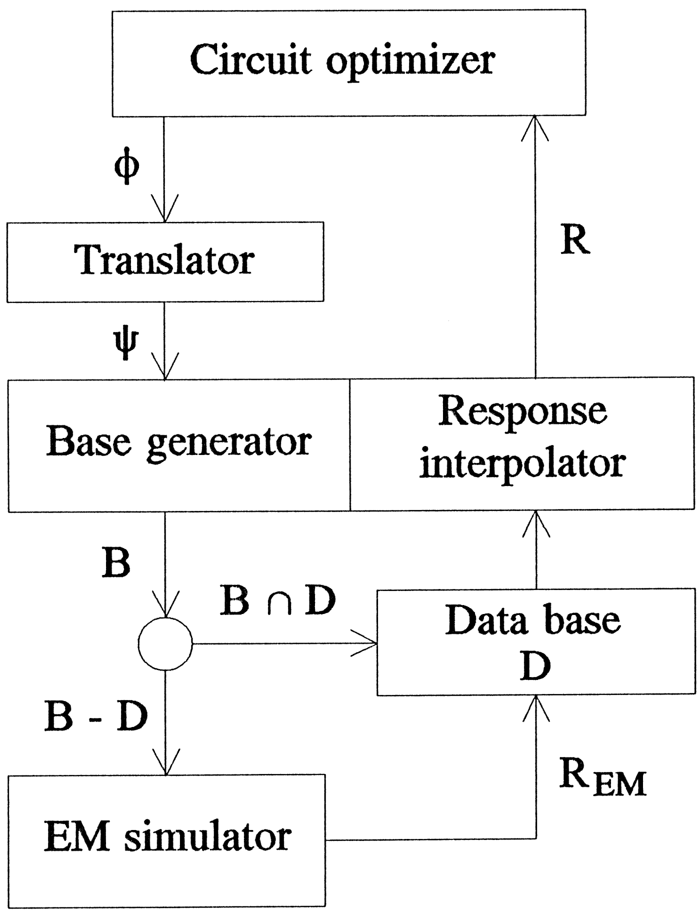
or

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

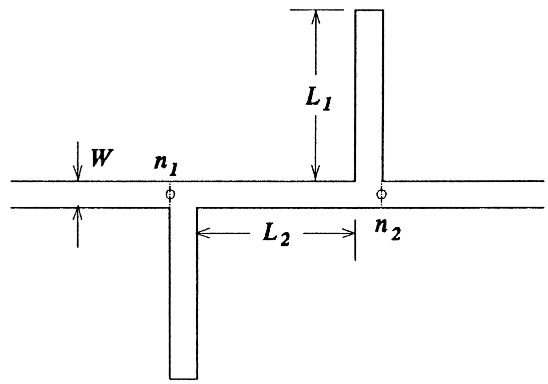
negative/positive error value indicates that the corresponding specification is satisfied/violated

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

Interconnection Between a Circuit Optimizer and a Numerical EM Simulator

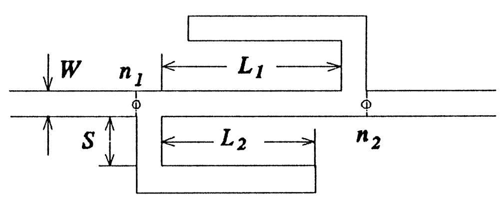


Conventional Double Stub Microstrip Structure



for band-stop filter applications

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



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

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

Design of the Double Folded Microstrip Structure

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

W fixed at 4.8 mils

L_1, L_2 and S - variables (designable parameters)

design specifications

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

substrate thickness - 5 mils

relative dielectric constant - 9.9

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

optimization was carried out in two steps

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

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

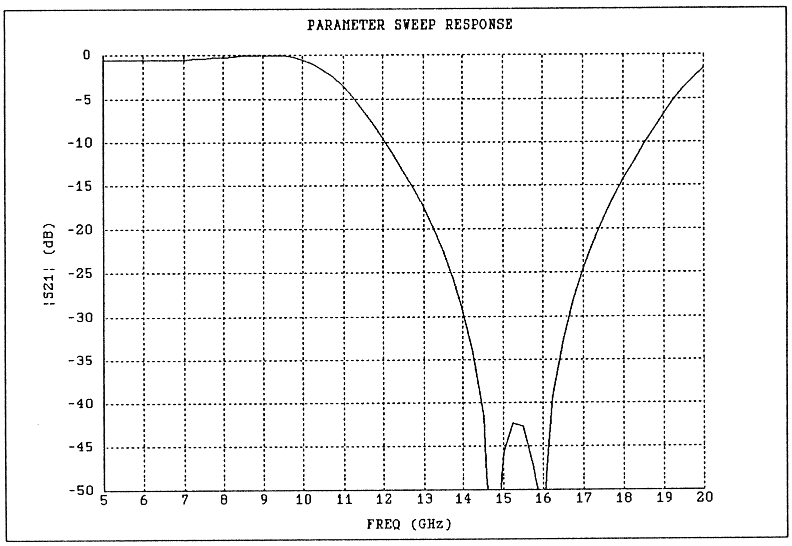
Minimax Optimization of the Double Folded Microstrip Structure

PARAMETER VALUES FOR THE DOUBLE FOLDED STUB
BEFORE AND AFTER OPTIMIZATION

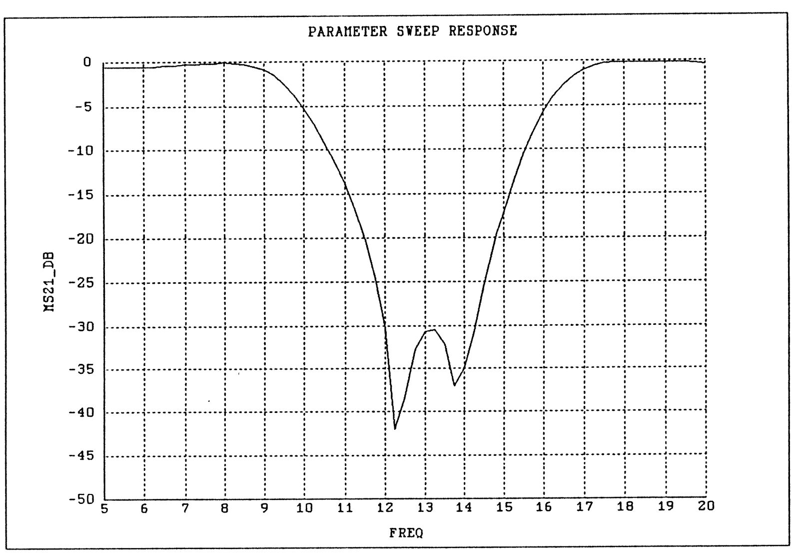
Parameter	Before optimization (mils)	After optimization (mils)
L_1	74.0	91.82
L_2	62.0	84.71
S	13.0	4.80

Results for the Double Folded Microstrip Structure

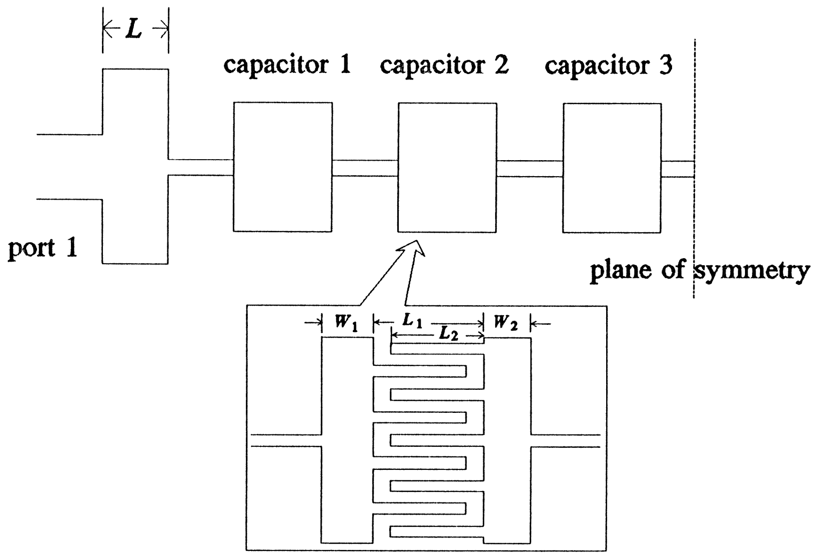
Before Optimization



After Optimization



26-40 GHz Interdigital Microstrip Bandpass Filter



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

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

when the filter was simulated by *em*™ in the whole frequency range the results exhibited significant discrepancies w.r.t. the prototype

it necessitated manual adjustment and made a satisfactory design very difficult to achieve

Design of the 26-40 GHz Interdigital Microstrip Filter

a total of 13 designable parameters including the distance between the patches L_1, the finger length L_2 and two patch widths W_1 and W_2 for each of the three interdigital capacitors, and the length L of the end capacitor

the second half of the circuit, to the right of the plane of symmetry, is assumed identical to the first half, so it contains no additional variables

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

design specifications

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

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

substrate thickness - 10 mils

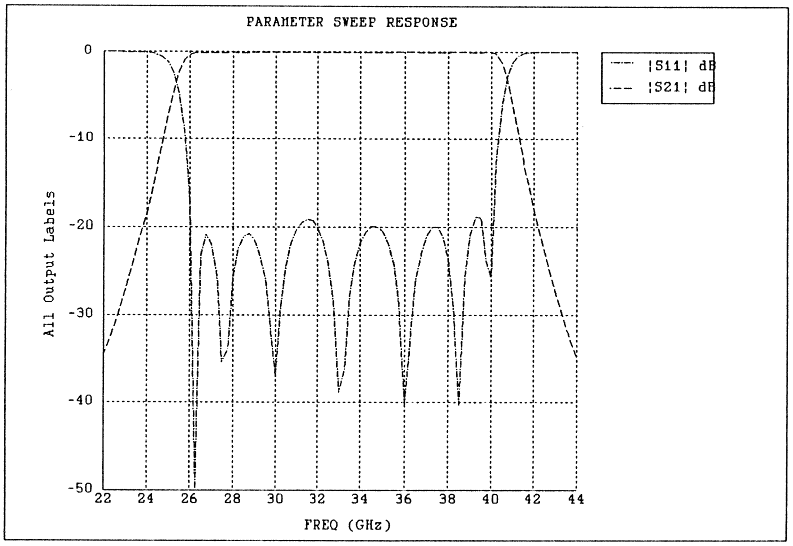
dielectric constant - 2.25

shielding height - 120 mils

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

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

filter response after optimization

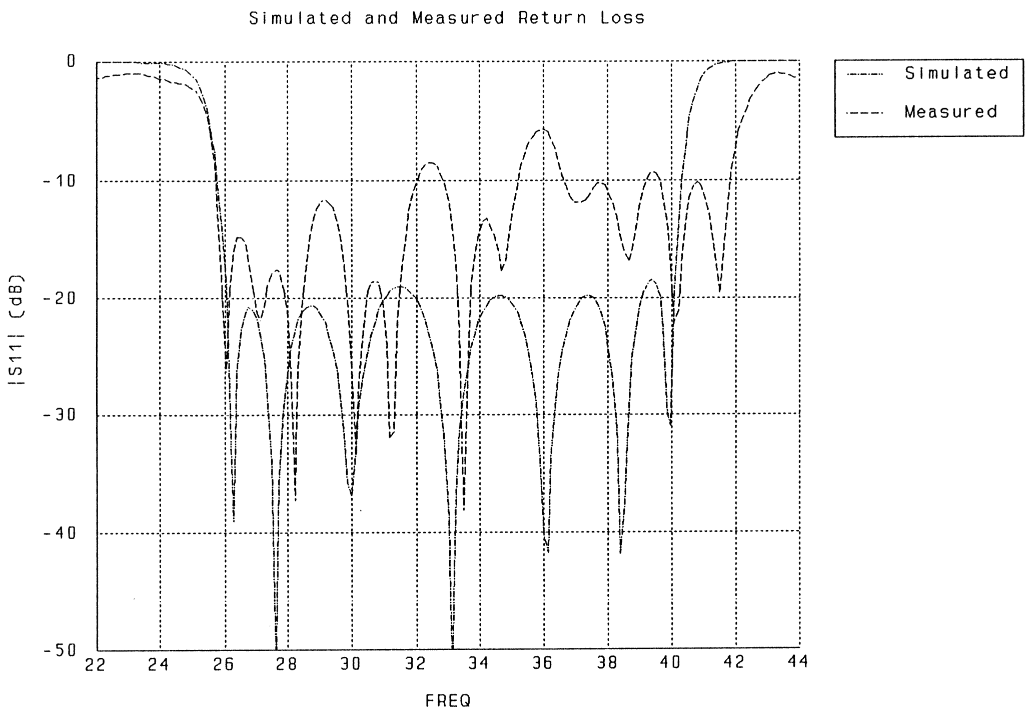


a typical minimax equal-ripple response of the filter was achieved after a series of consecutive optimizations with different subsets of optimization variables and frequency points

the resulting geometrical dimensions were finally rounded to 0.1 mil resolution

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

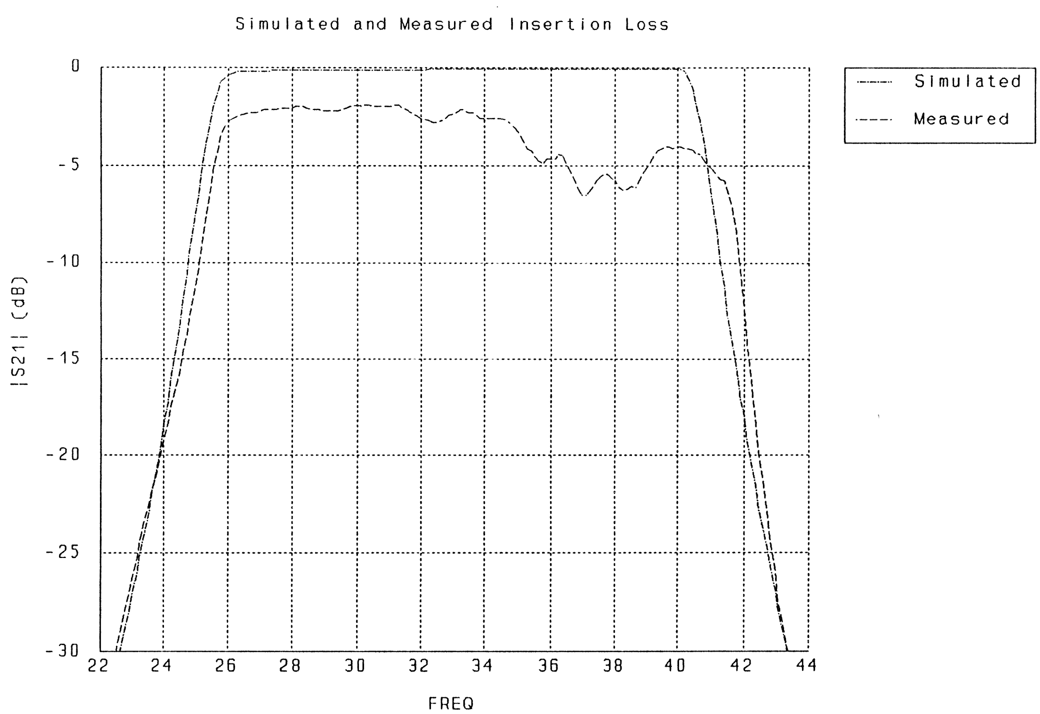
measured and simulated $|S_{11}|$ of the filter after manufacturing



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

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

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



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

Yield Optimization

the problem of yield optimization can be formulated as

$$\underset{\phi^0}{maximize} \left\{ Y(\phi^0) = \int_{R^n} I_a(\phi) f_\phi(\phi^0, \phi) d\phi \right\}$$

where

ϕ^0	nominal circuit parameters
ϕ	actual circuit outcome parameters
$Y(\phi^0)$	design yield
$f_\phi(\phi^0, \phi)$	probability density function of ϕ around ϕ^0

$$I_a(\phi) = \begin{cases} 1 & if \quad \phi \in A \\ 0 & if \quad \phi \notin A \end{cases}$$

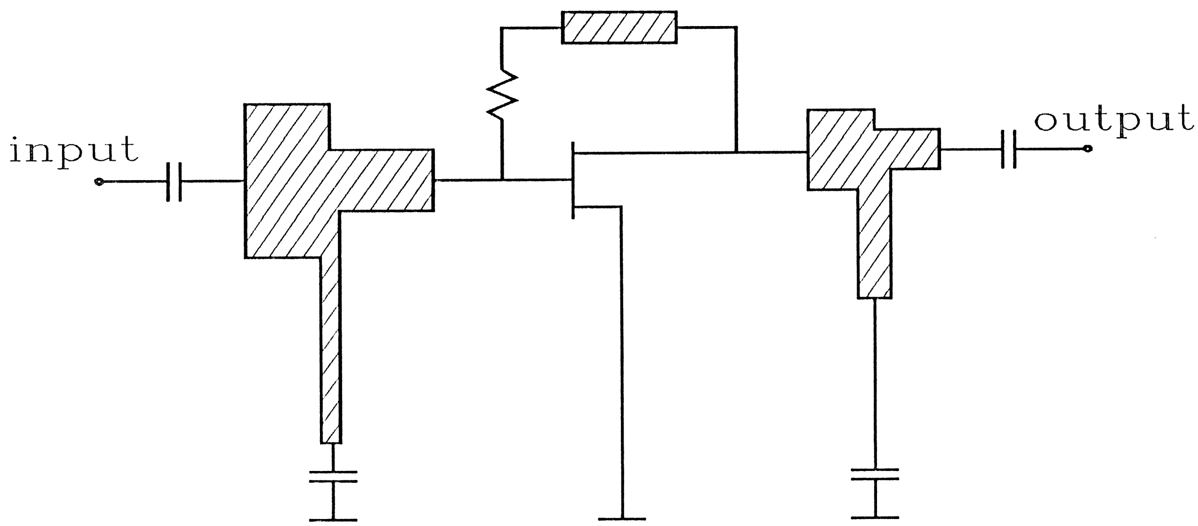
A	acceptability region

in practice, the integral is approximated using K Monte Carlo circuit outcomes ϕ^i and yield is estimated by

$$Y(\phi^0) \simeq \frac{1}{K} \left(\sum_{i=1}^{K} I_a(\phi^i) \right)$$

the outcomes ϕ^i are generated by a random number generator according to $f_\phi(\phi^0, \phi)$

Optimization of a Small-Signal Amplifier



the specifications for yield optimization of the amplifier are

$$7 \text{ dB} \leq |S_{21}| \leq 8 \text{ dB} \qquad \text{for} \qquad 6 \text{ GHz} < f < 18 \text{ GHz}$$

the gate and drain circuit microstrip T-junctions and the feedback microstrip line are built on a 10 mil thick substrate with relative dielectric constant 9.9

the microstrip components of the amplifier are simulated using component level Q-models built from EM simulations

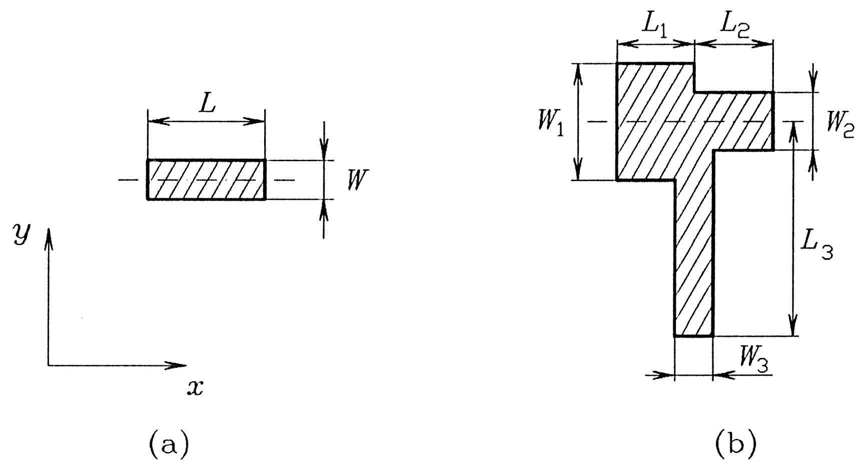
we used ***em***™ from *Sonnet Software* for EM simulations

Optimization Variables

W_{g1}, L_{g1}, W_{g2}, L_{g2} of the gate circuit T-junction and W_{d1}, L_{d1}, W_{d2}, L_{d2} of the drain circuit T-junction are the optimization variables

W_{g3}, L_{g3}, W_{d3} and L_{d3} of the T-junctions, W and L of the feedback microstrip line, as well as the FET parameters are not optimized

parameters of the microstrip line (a) and the T-junctions (b)

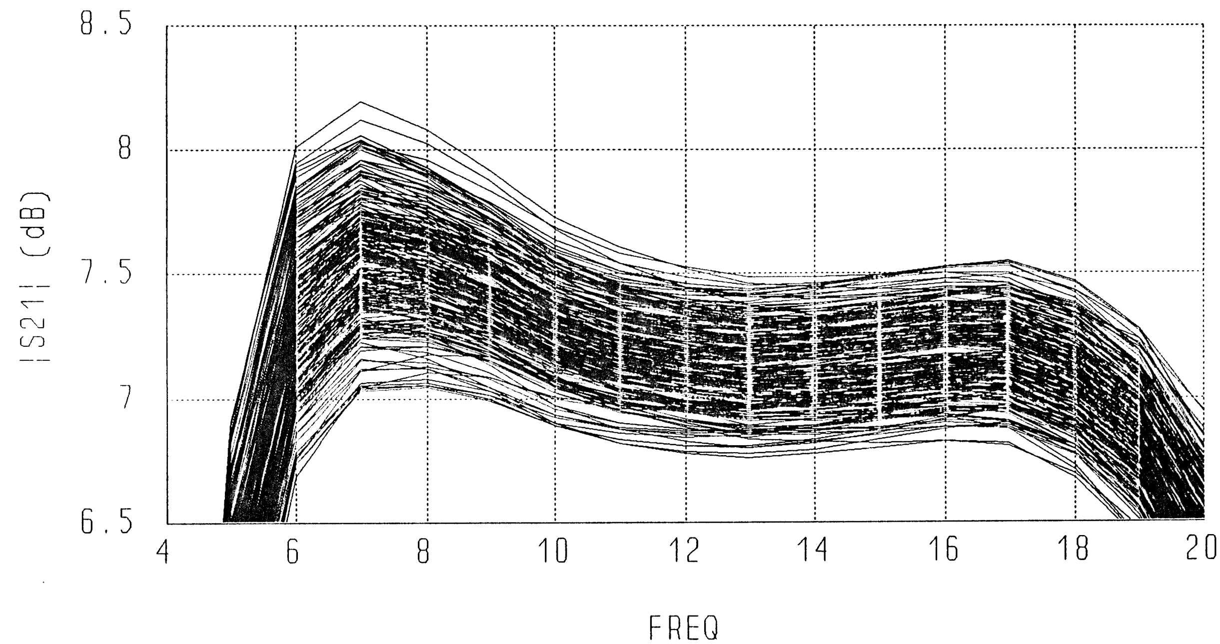


we assumed 0.5 mil tolerance and uniform distribution for all geometrical parameters of the microstrip components

the statistics of the small-signal FET model were extracted from measurement data

Small-Signal Amplifier Yield Before Optimization

the starting point for yield optimization was obtained by nominal minimax optimization using analytical/empirical microstrip component models



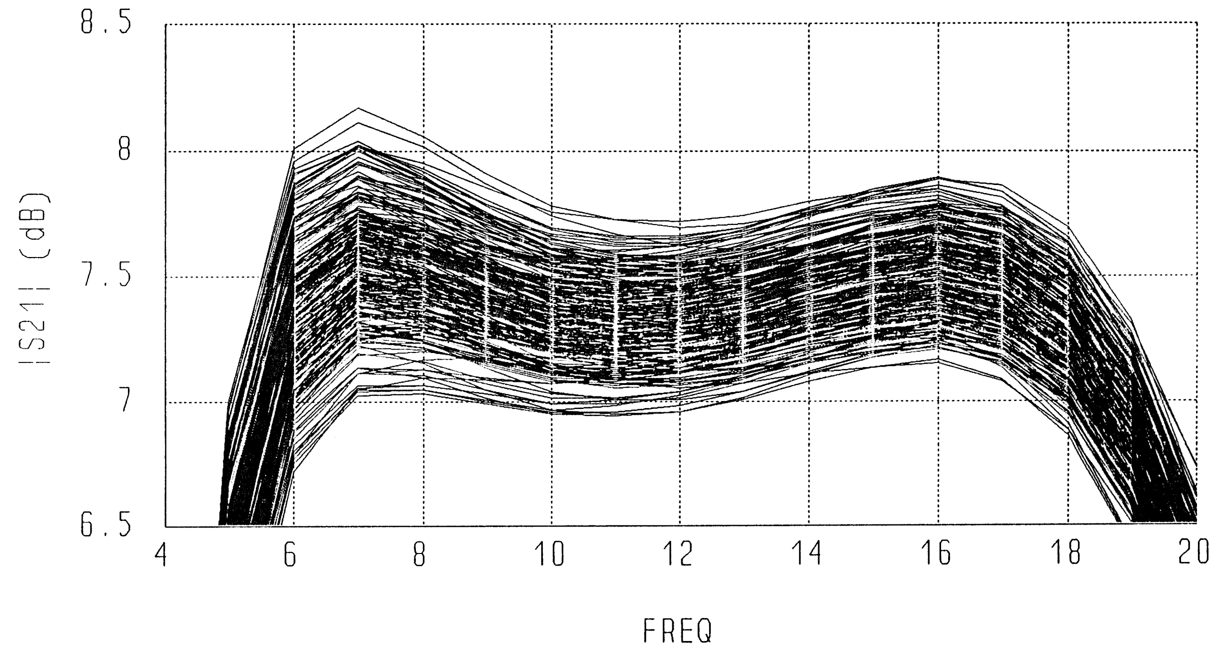
Monte Carlo simulation

250 outcomes

55% yield

Small-Signal Amplifier Yield After Optimization

the component level Q-models were used in yield optimization



yield estimated by 250 Monte Carlo simulations increased to 82%

optimization was performed by OSA90/hope™ with Empipe™ driving *em*™

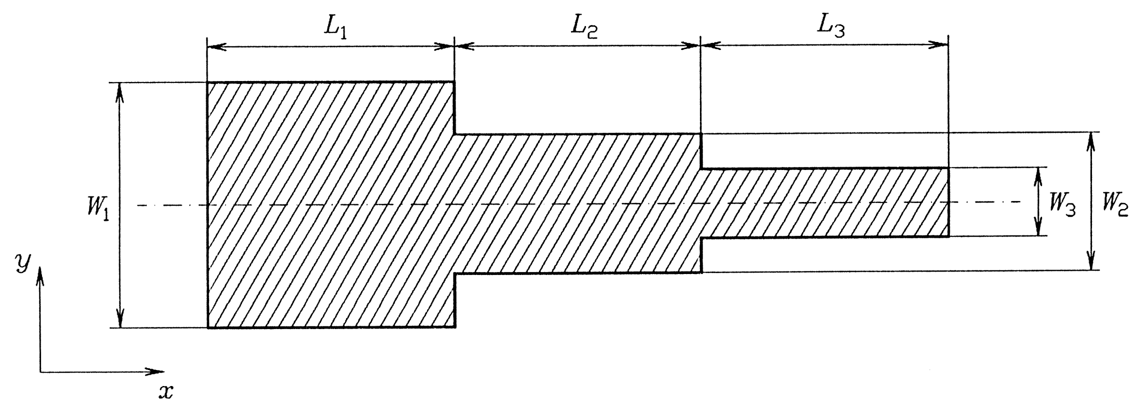
Optimization Results

MICROSTRIP PARAMETERS OF THE AMPLIFIER

Parameters	Nominal design	Centered design
W_{g1}	17.45	19.0
L_{g1}	35.54	34.53
W_{g2}	9.01	8.611
L_{g2}	30.97	32.0
W_{g3}	3.0*	3.0*
L_{g3}	107.0*	107.0*
W_{d1}	8.562	7.0
L_{d1}	4.668	6.0
W_{d2}	3.926	3.628
L_{d2}	9.902	11.0
W_{d3}	3.5*	3.5*
L_{d3}	50.0*	50.0*
W	2.0*	2.0*
L	10.0*	10.0*
Yield (250 outcomes)	55%	82%

* Parameters not optimized.
Dimensions of the parameters are in mils. 50 outcomes were used for yield optimization. 0.5 mil tolerance and uniform distribution were assumed for all the parameters.

Three-Section 3:1 Microstrip Impedance Transformer



designed on a 0.635 mm thick substrate with relative dielectric constant of 9.7

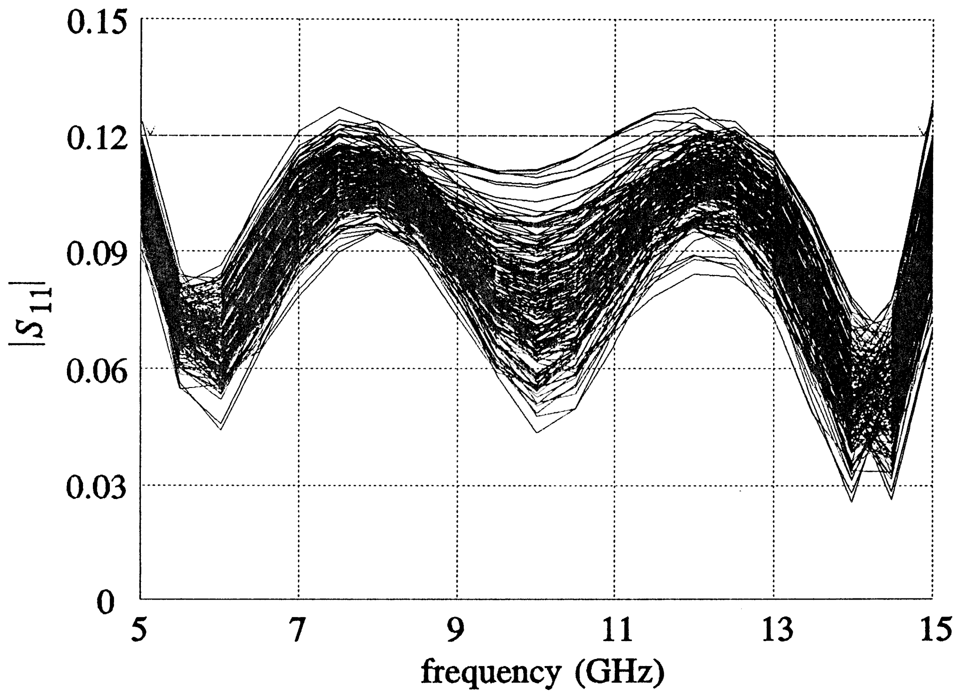
the source and load impedances are 50 and 150 ohms

design specification set for the input reflection coefficient

$$|S_{11}| \leq 0.12, \text{ from 5 GHz to 15 GHz}$$

normal distributions with 2% standard deviations assumed for W_1, W_2 and W_3 and 1% standard deviations assumed for L_1, L_2 and L_3

Three-Section Microstrip Transformer
After Yield Optimization



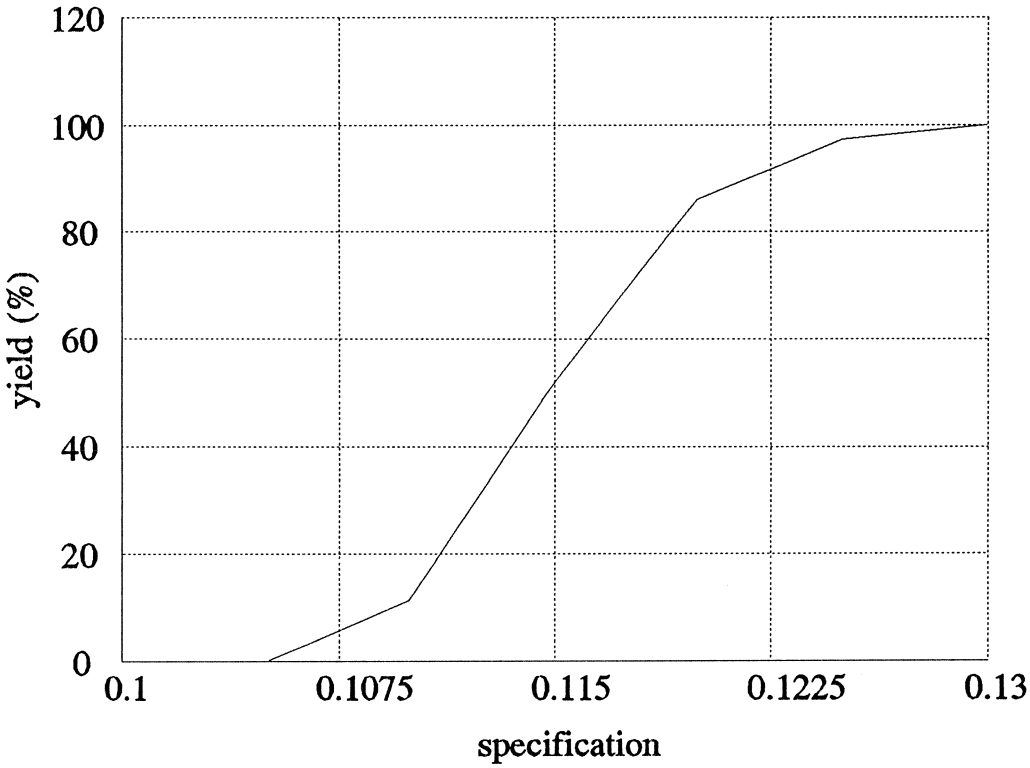
modulus of the reflection coefficient vs. frequency

optimization using single-level (component) Q-models

100 statistical outcomes used for yield optimization

yield is increased to 86%

Yield Sensitivity of the Microstrip Transformer



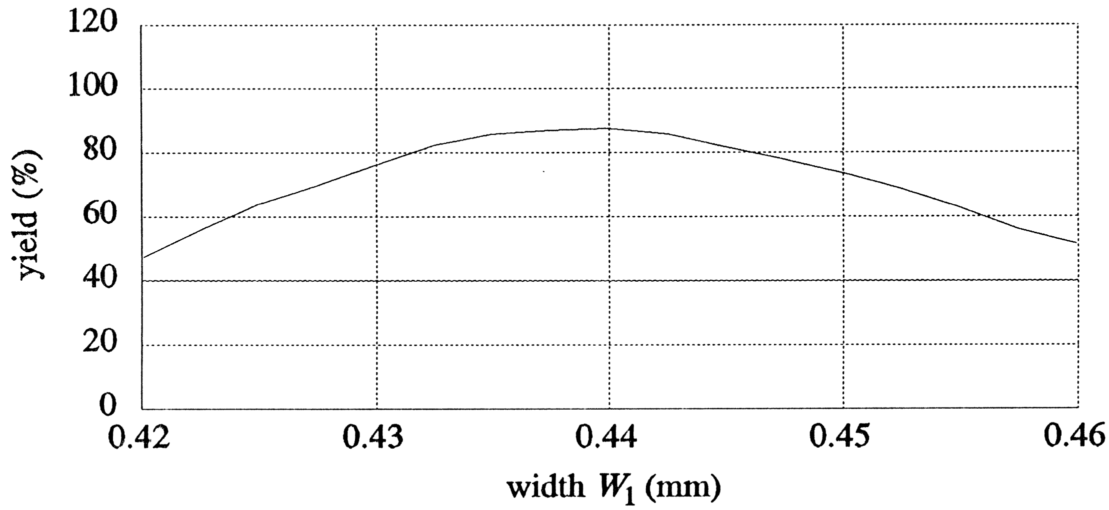
yield vs. specification on $|S_{11}|$

high sensitivity of yield w.r.t. the specification

yield varies from 0% to 100% over a very small range of the specification

yield estimated with 250 Monte Carlo outcomes

Yield Sensitivity of the Microstrip Transformer

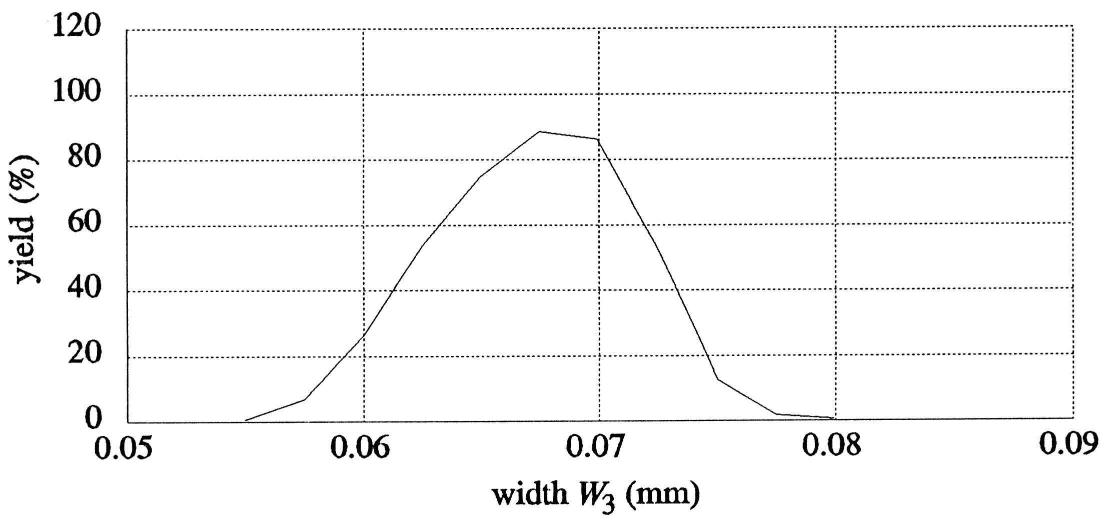


yield vs. W_1

relatively high sensitivity of yield w.r.t. W_1

yield estimated with 250 Monte Carlo outcomes

Yield Sensitivity of the Microstrip Transformer

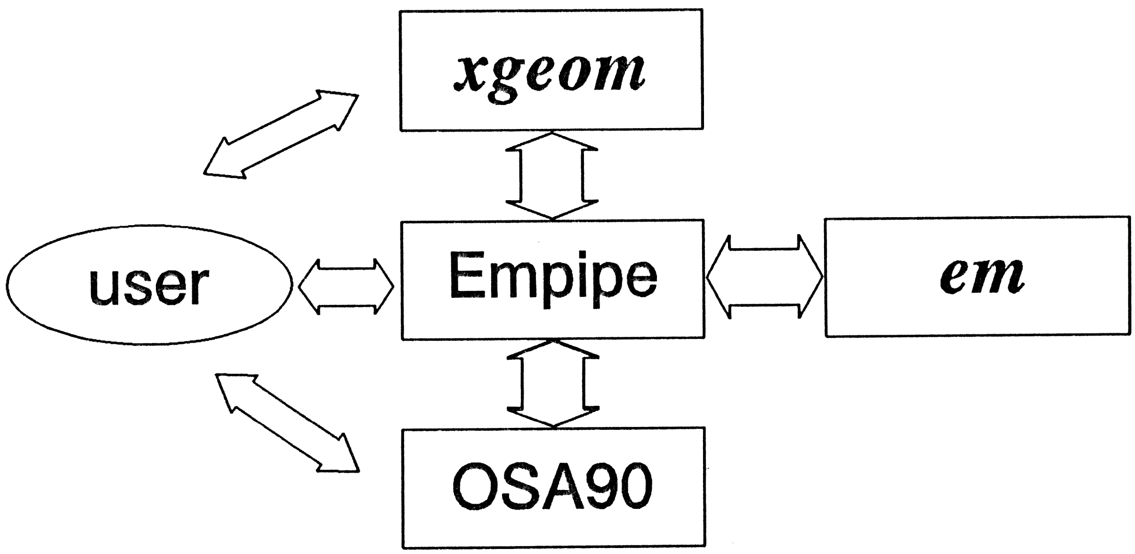


yield vs. W_3

high sensitivity of yield w.r.t. W_3

yield estimated with 250 Monte Carlo outcomes

Data Flow in Empipe™ Version 3.1



Parameterized (Optimizable)
Microstrip Library of Empipe™

bend
cross junction
coupled line filter
double patch capacitors
interdigital capacitors
microstrip 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

Electromagnetic Design of HTS Microwave Filters

available low-loss and narrow-bandwidth (0.5 - 3 %) filter banks are of very large size which in some satellite and airborne applications is intolerable

small conventional microstrip filters are too lossy for narrow-band applications

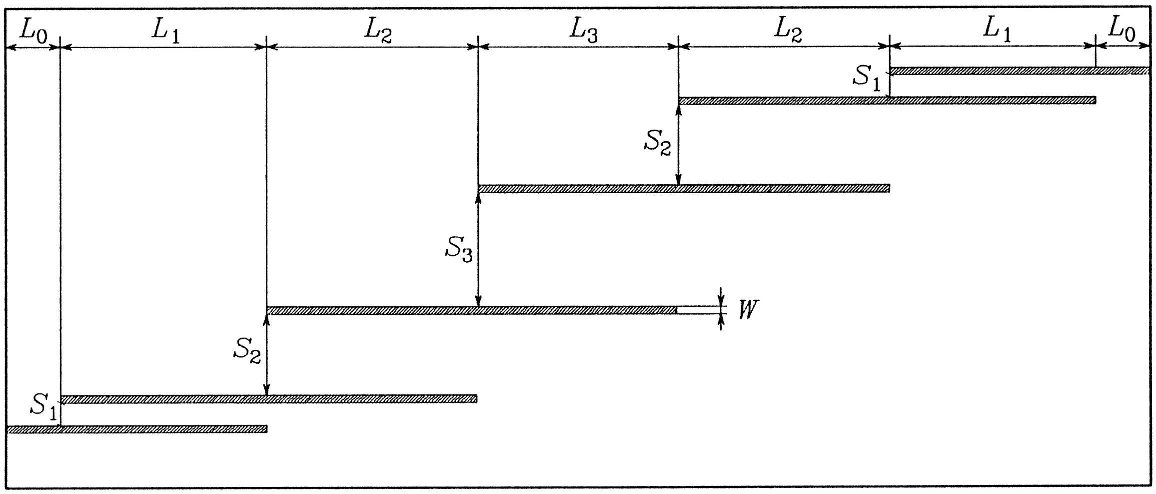
low-loss, narrow-bandwidth microstrip filters can be made using HTS technology with relatively inexpensive cooling

the dielectric constant of substrate materials used in HTS technology is too large to be accurately treated by traditional microwave circuit design software packages with analytical/empirical models

we employ electromagnetic field simulation which can provide results in good agreement with experimental data

high sensitivity requires a very fine grid in numerical EM simulations

The HTS Quarter-Wave Parallel Coupled-Line Filter



20 mil thick lanthanum aluminate substrate

the dielectric constant is 23.4

the x and y grid sizes for ***em*** simulations 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 for the HTS Filter

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

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

narrow 1.2 % bandwidth

the lengths of the line sections: L_1, L_2 and L_3 and the gaps between the sections: S_1, S_2 and S_3 are the design parameters

the line width W is the same for all sections and is kept fixed

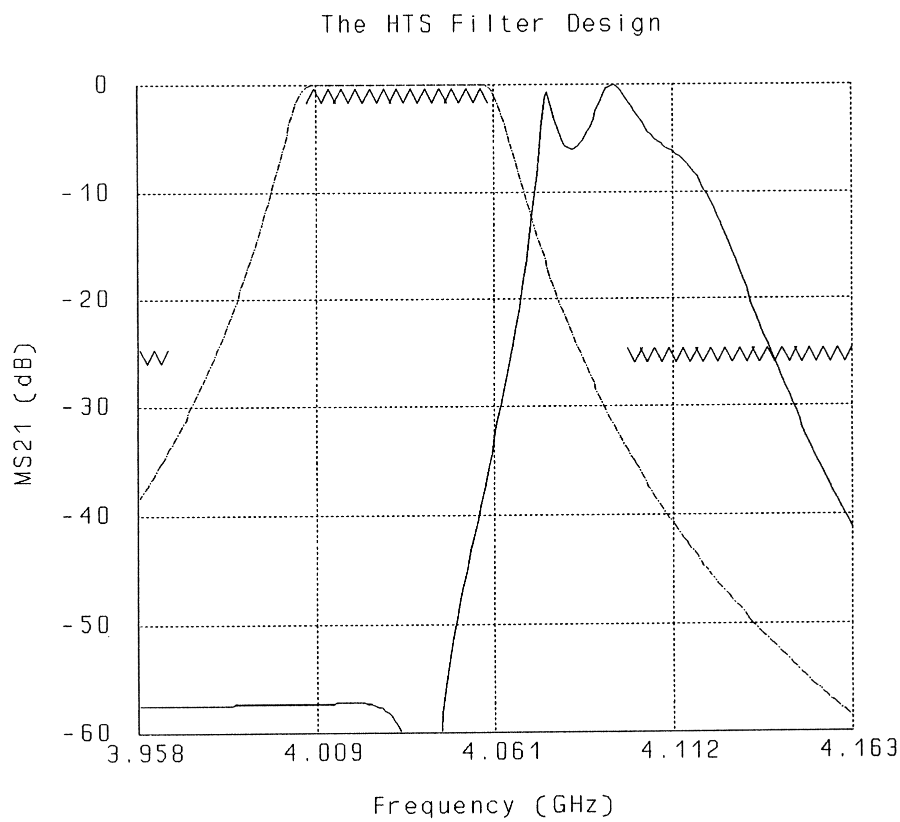
the length of the input and output lines L_0 is kept fixed

design carried out in cooperation with Westinghouse Science and Technology Center

Filter Design Using Traditional Simulators

we tested two commercial microwave CAD packages: OSA90/hope and Touchstone

Touchstone Results:



em simulation results differ significantly from Touchstone results and do not satisfy the specifications

The Space Mapping™ Technique

particularly attractive for designs involving CPU intensive simulators

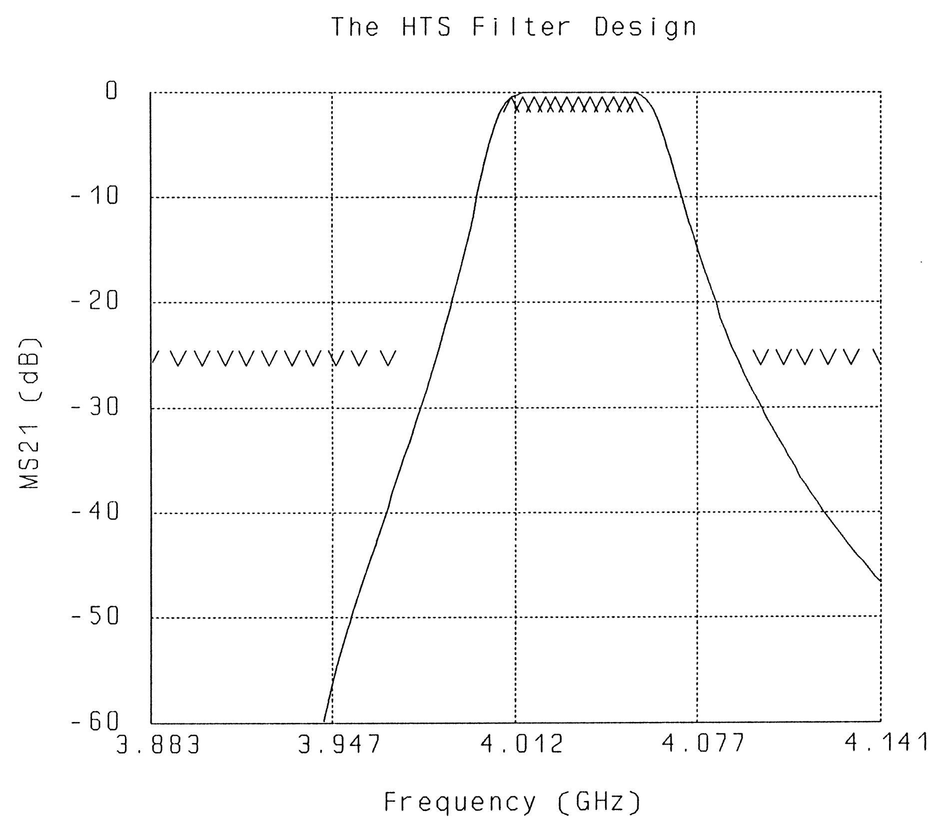
it substantially decreases the number of necessary exact (EM) simulations

we create and iteratively refine a mapping from the EM simulator input space onto the parameter space of the model used by the optimizer

the initial mapping is found using a preselected set of *k* points in the EM input space

the set of corresponding points in the optimizer parameter space is determined by fitting the EM simulation results to the model used by the optimizer

HTS Filter Design Using Space Mapping Optimization



em interfaced to OSA90/hope through Empipe

all the processing needed to establish the mapping was performed within the OSA90/hope environment

a total of 13 *em* simulations was sufficient to establish the mapping

$|S_{21}|$ at the solution well exceeds the design specifications

Selected Users of OSA Technology

- Alcatel
- AMTEL
- Alenia
- BNR
- British Telecom
- ComDev
- Compact Software
- COMSAT
- CRC
- Daimler Benz
- EEsof
- French Telecom
- GE
- Hughes
- IMST
- M/A-COM
- MIT Lincoln Labs
- NAWC
- Raytheon
- Rockwell
- Schrack Aerospace
- Siemens
- Telettra
- TRW
- Watkins-Johnson

University Users of OSA Technology

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