PERFORMANCE- AND YIELD-DRIVEN OPTIMIZATION OF MICROWAVE CIRCUITS USING DIRECT EM SIMULATION

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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 ICs

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

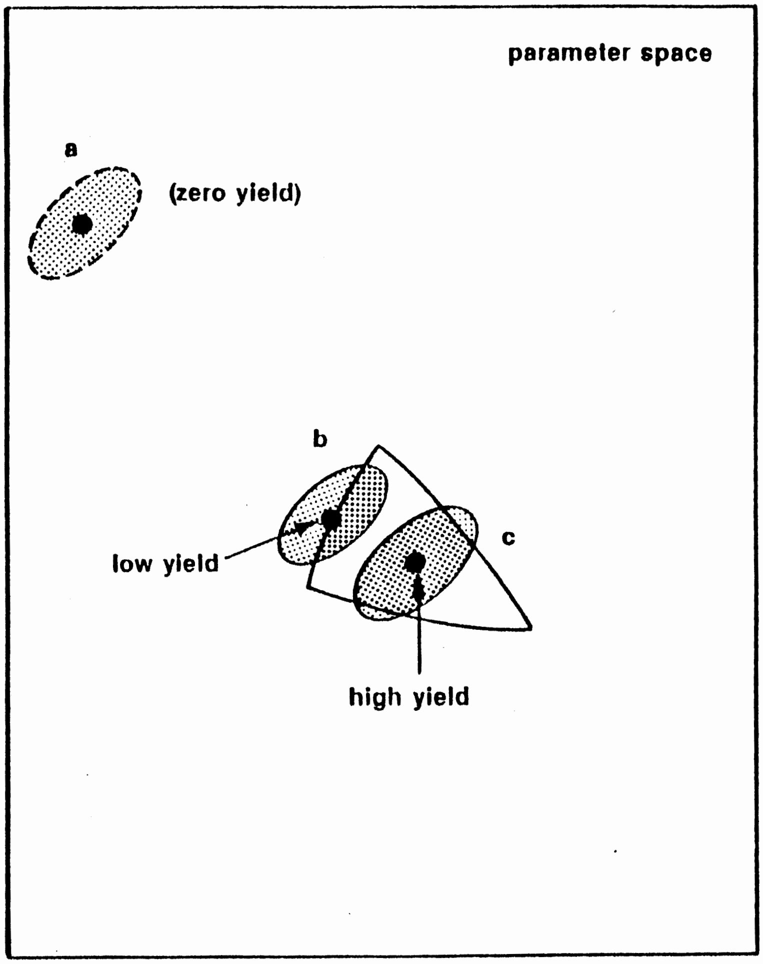
manufacturing tolerance assignment and cost minimization

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)

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)

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

Milestones VI

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)

OSA90/hope™ Version 2.5

general nonlinear circuit simulation and optimization
analytically unified
- large-signal harmonic balance analysis
- small-signal AC analysis
- nonlinear DC analysis

statistical analysis and yield optimization
interconnects external simulators
- Empipe™ merges *em*™
- Spicepipe™ merges SPICE-PAC
- user's simulators

customization oriented optimization shell

HarPE™ Version 1.7

parameter extraction and device characterization
single-device circuit simulation and optimization
statistical modeling
Monte Carlo analysis

OSA90™ (OSA90/hope™ Engine)

OSA90/hope™ Optimization

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

L1
least squares (L2)
Huber
minimax
quasi-Newton
conjugate gradient
simplex
random
yield (one-sided L1) for statistical 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

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 arbitrary voltages

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
- solving linear equations

vector and matrix elements fully optimizable

built-in transformations, including DFT, splines

operation control block

OSA90/hope™ Graphics

continuous, point, bar plots

parametric and multiple plots

histograms and run charts

sensitivity displays

waveforms

Smith chart and polar plots

user-defined legends, colors, views

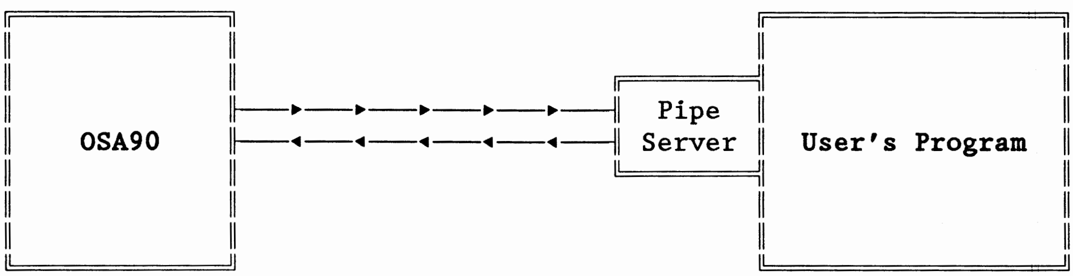
graphics zoom

graphics hardcopies (HPGL 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

Spicepipe™ merges SPICE-PAC

for time-domain simulation, noise analysis, etc.
nominal optimization
yield optimization

OSA90™ can call OSA90™

HarPE™ Version 1.7

characterize devices

extract parameters

simulation-driven
data-driven

build equivalent circuit models

build physics models

simulate and optimize

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

statistically model devices

estimate Monte Carlo yield

Minimax Design Optimization

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

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

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

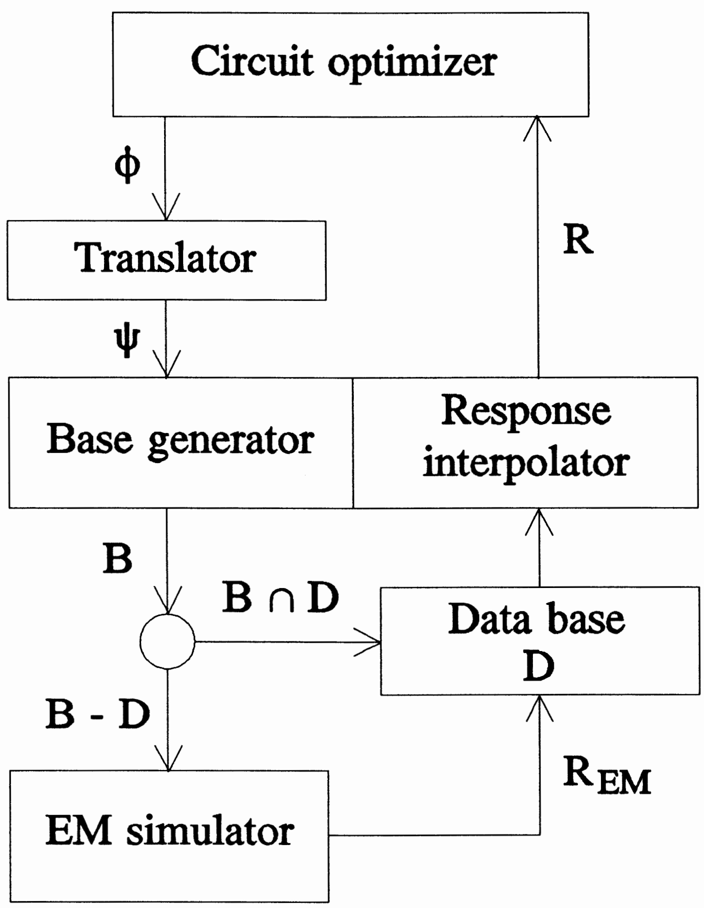
or

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

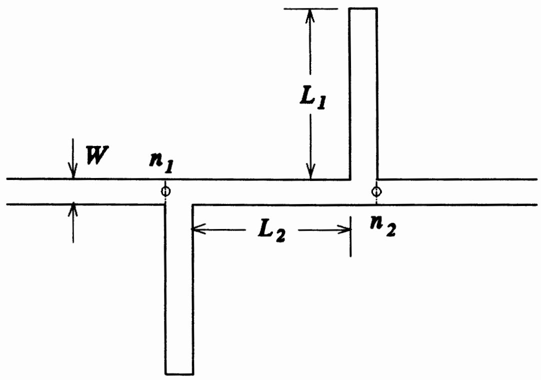
negative/positive error value indicates that the corresponding specification is satisfied/violated

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

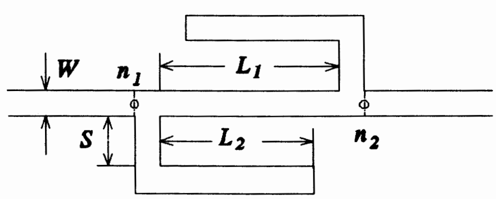


Conventional Double Stub Microstrip Structure



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

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

$|S_{21}| < -30$ 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

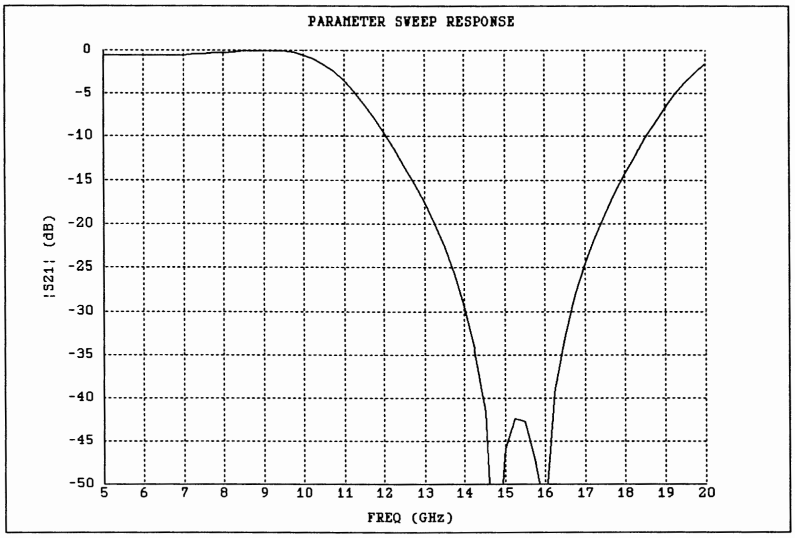
Minimax Optimization of the Double Folded Microstrip Structure

PARAMETER VALUES FOR THE DOUBLE FOLDED STUB
BEFORE AND AFTER OPTIMIZATION

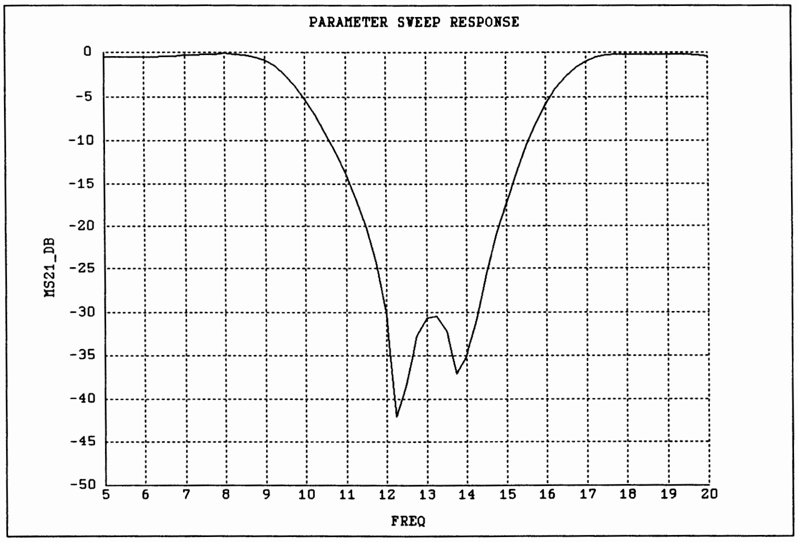
Parameter	Before optimization (mils)	After optimization (mils)
L_1	74.0	91.82
L_2	62.0	84.71
S	13.0	4.80

Results for the Double Folded Microstrip Structure

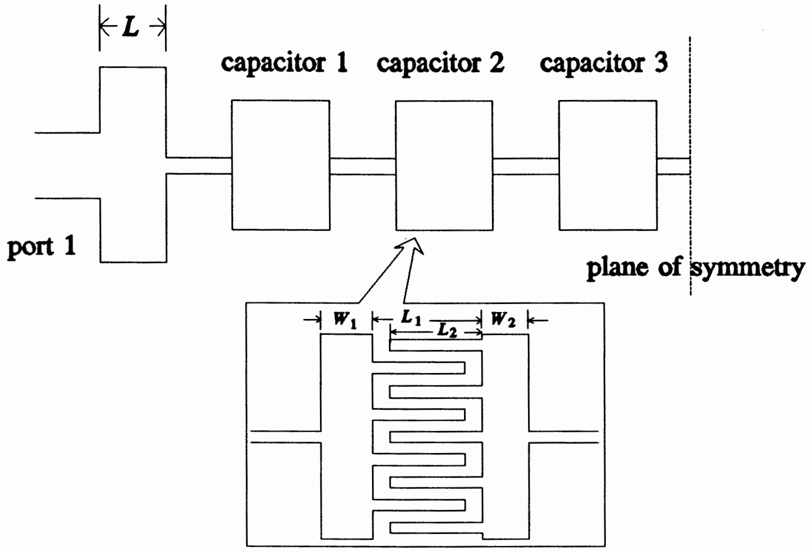
Before Optimization



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

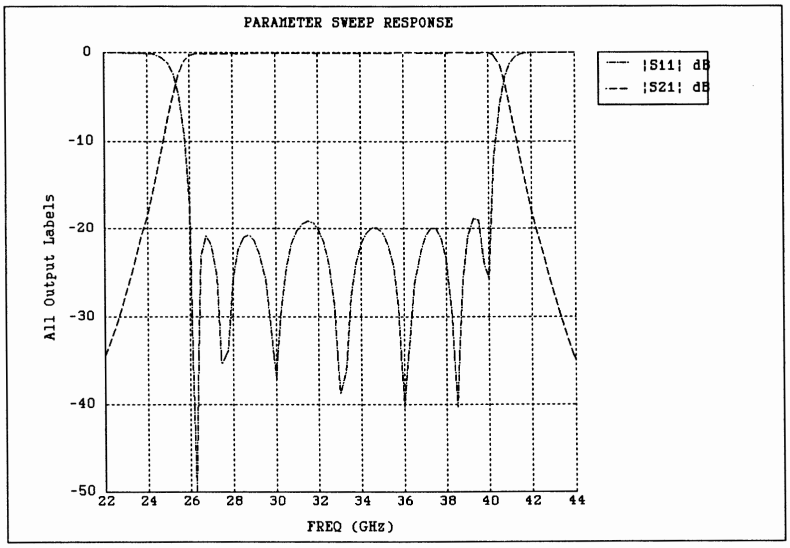
dielectric constant - 2.25

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

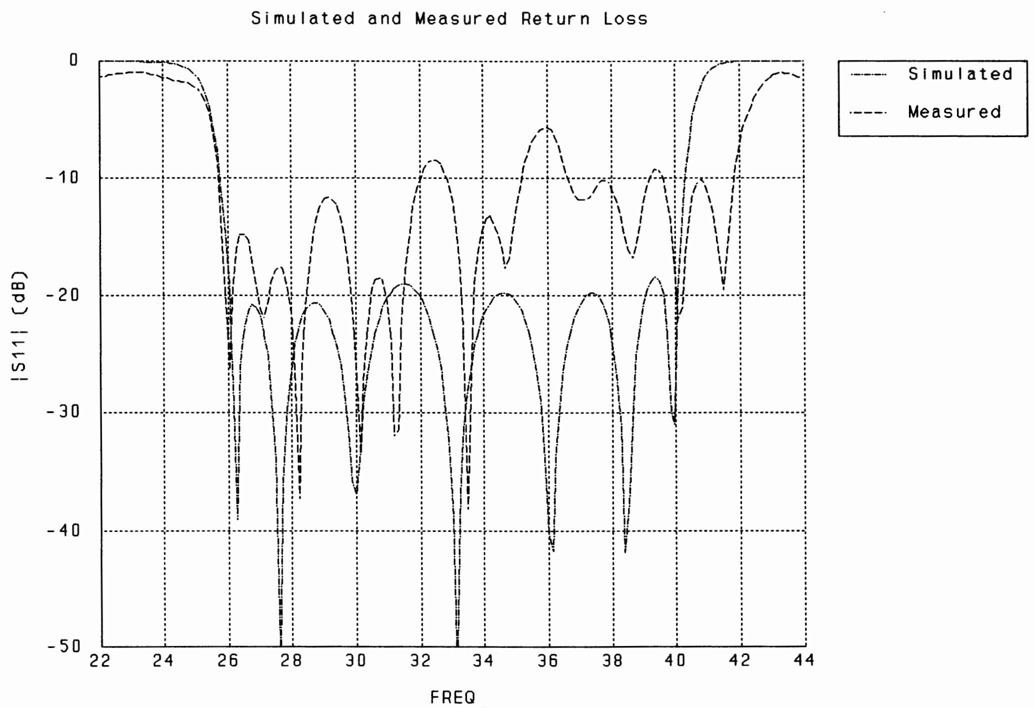


a typical minimax equal-ripple response of the filter was achieved after a series of consecutive optimizations with different subsets of optimization variables and frequency points

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

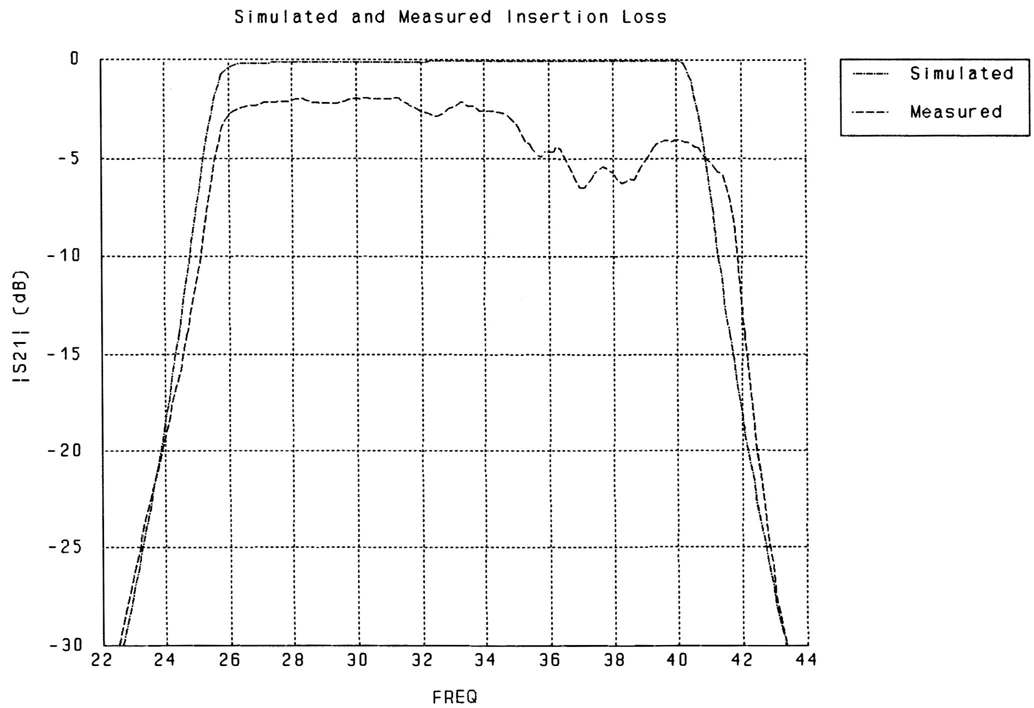
measured and simulated $|S_{11}|$ of the filter after manufacturing



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

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

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

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

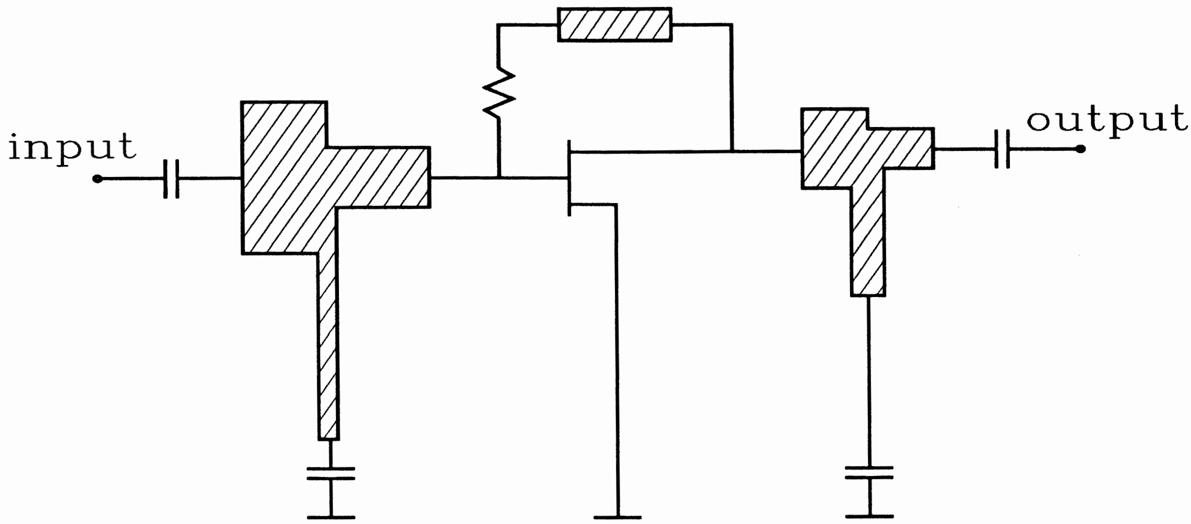
A	acceptability region

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

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

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

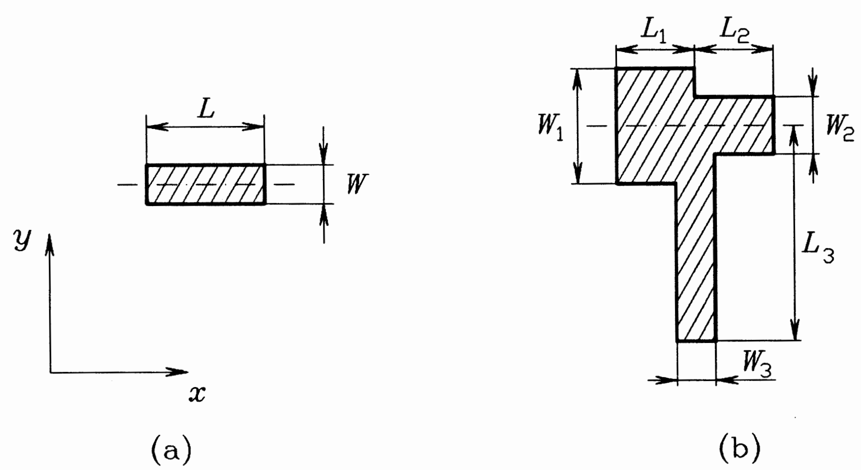
we used *em*™ from *Sonnet Software* for EM simulations

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)

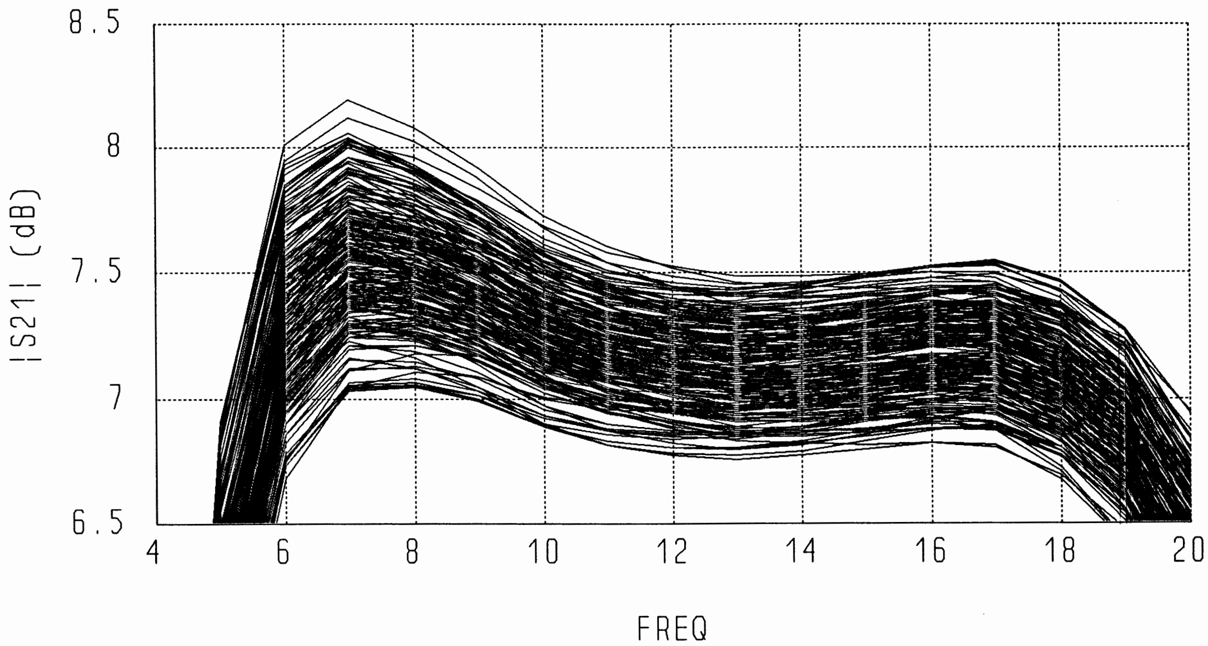


we assumed 0.5 mil tolerance and uniform distribution for all geometrical parameters of the microstrip components

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



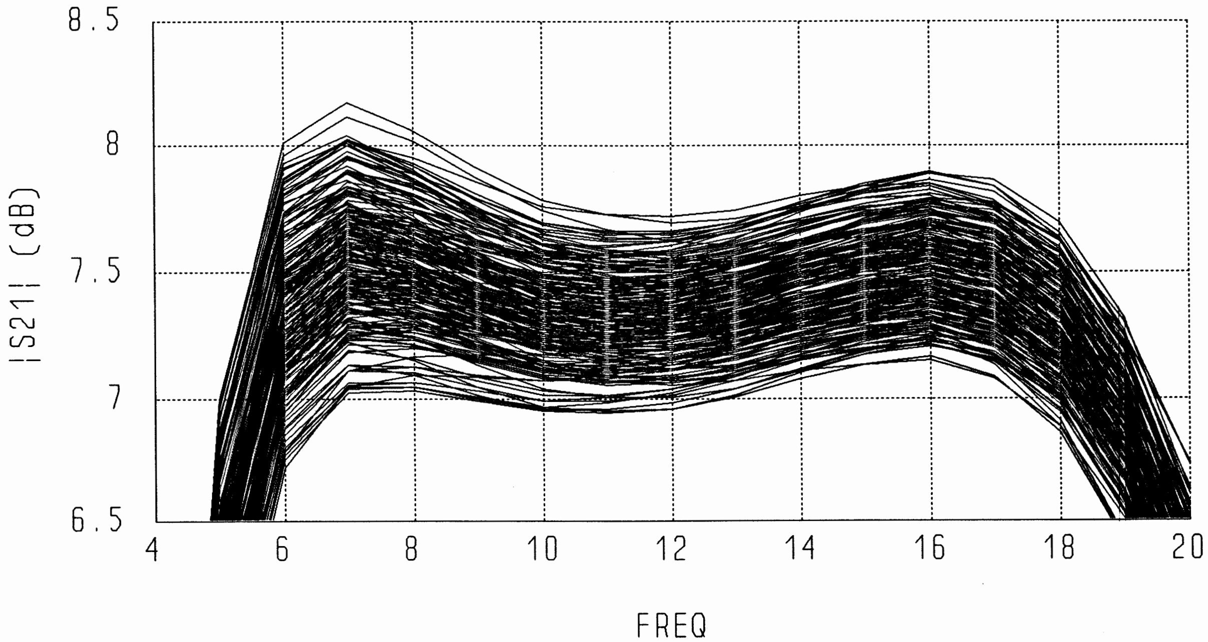
Monte Carlo simulation

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*™

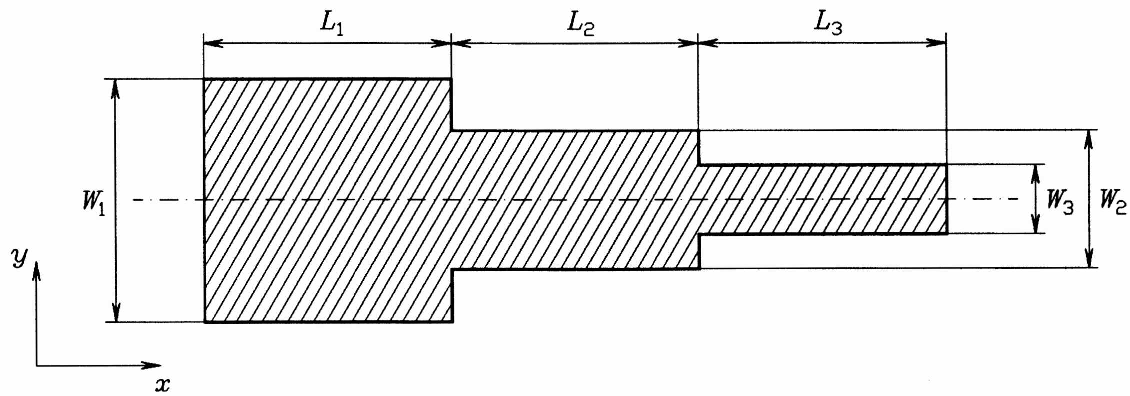
Optimization Results

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

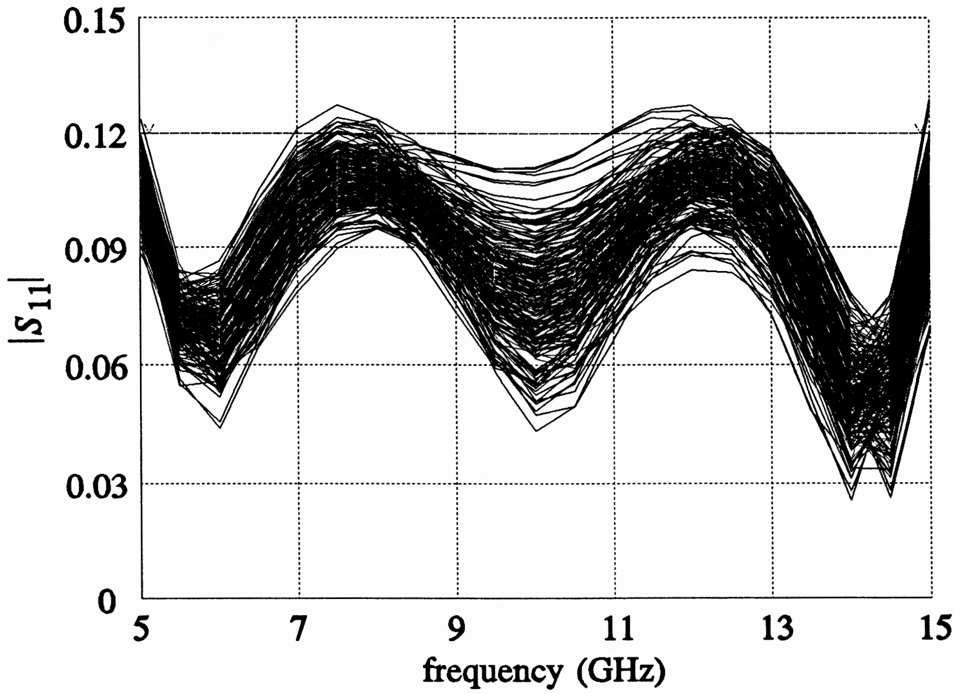
the source and load impedances are 50 and 150 ohms

design specification set for the input reflection coefficient

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

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



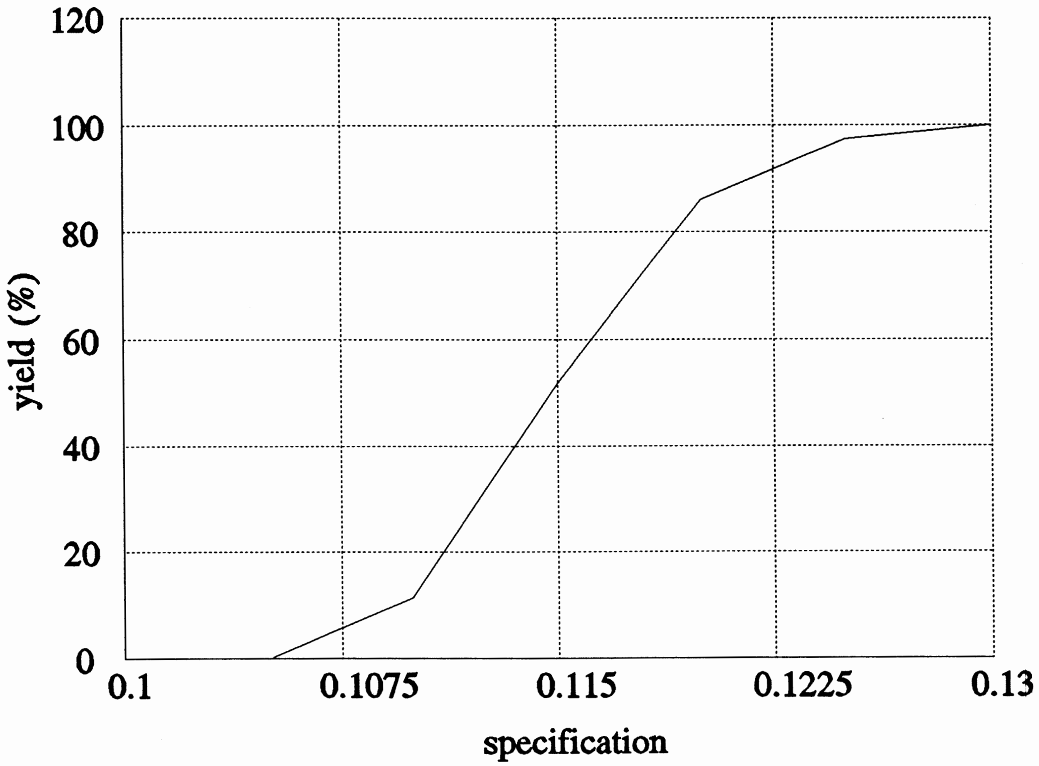
modulus of the reflection coefficient vs. frequency

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



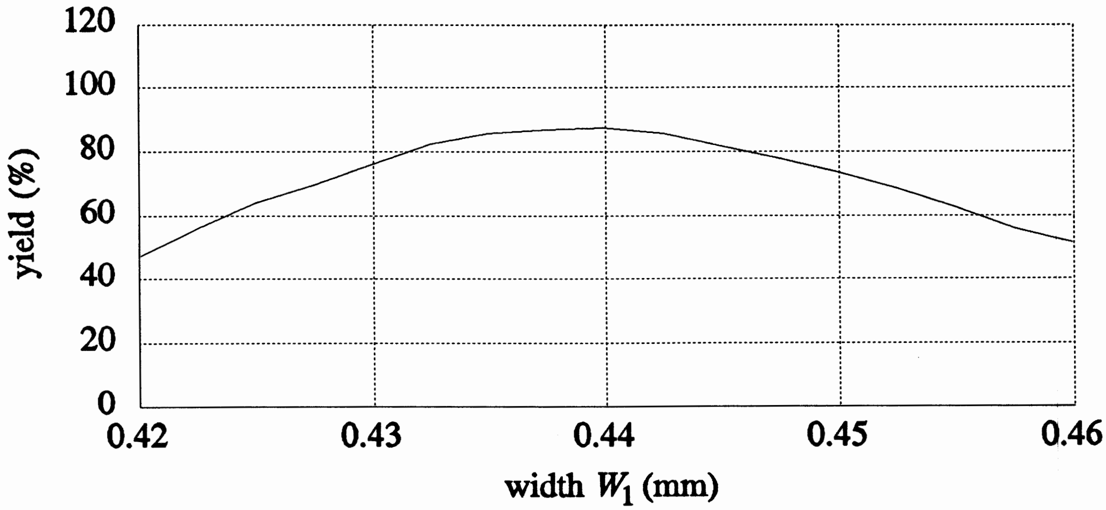
yield vs. specification on $|S_{11}|$

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

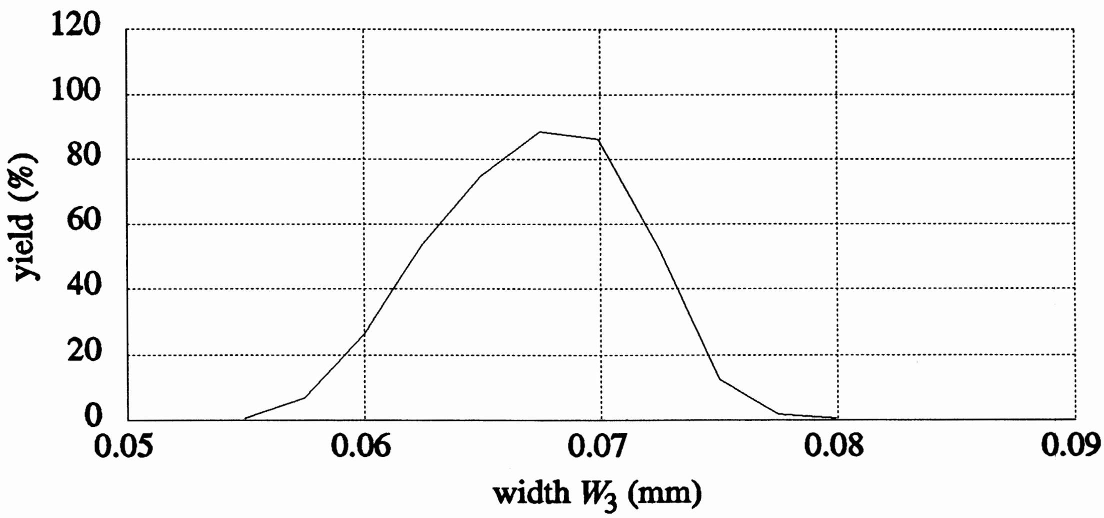


yield vs. W_1

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

Empipe™ (1992)

smart connection of OSA90/hope™ with Sonnet's ***em***™ field simulator for interprocessing circuit/field/measurement data

a significant step towards the required <u>integrated approach</u> offering

simulation, modeling, parameter extraction
optimization, sensitivity analysis, statistical analysis
error analysis (probability of satisfying error specs)
automated processing of circuit/field/measurement data
fixed or optimizable geometries simulated by ***em***™

recent applications include

EM microstrip filter design
yield-driven direct EM optimization
EM statistical sensitivity analyses

more relevant experimental validation applications to come!

Parameterized (Optimizable) Microstrip Library of Empipe™

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