ANALOG DIAGNOSIS AND OPTIMIZATION TECHNOLOGY FOR EXPERIMENTAL VALIDATION

John W. Bandler

OSA-93-OS-5-V

April 27, 1993

Presented at the 1993 MTT-S Workshop "Critical Issues in Experimental Validation"
Atlanta, GA, June 14, 1993

Introduction

questions (*Rautio, 1992*)

design of experiments
error analysis
sensitivity analysis
experimental significance
experimental objective

our aim

to find answers in microwave CAD technology
to find answers in analog fault diagnosis
to suggest software solutions now available
to suggest some open areas for investigation

Background (*Rautio, 1991*)

no sensitivity evaluation

no error analysis

measurements made at a difficult frequency
(data with large scatter)

too many "confounding" variables

the experimenter has a desired outcome in mind

incorrect objective

Our Points of View

we could take the view that the feature being measured is a "fault" to be diagnosed

or we could take the view that the feature being measured is obscured by elements which may be uncertain or "faulty"

in validation a fluctuation or uncertainty is often under investigation; the experiment must be designed so that the effect is not obscured

examine <u>common denominators</u> of experimental validation, device characterization, parameter extraction and network testing such as approach, objectives, accuracy, uniqueness

soft (faults) deviations

- the (faulty) element deviates from its nominal value without reaching its extreme bounds
- result from manufacturing tolerances, aging, parasitic effects

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Relevant Approaches from Fault Analysis

fault dictionary approach

- dictionary construction
- selecting an optimal set of measurements
- dealing with ambiguity sets
- fault isolation techniques
- efficient methods of fault simulation

parameter identification techniques

- DC or time-domain testing of nonlinear networks
- multifrequency testing of linear networks
  - select test frequencies to optimize a measure of the solvability of the diagnosis equations?
  - how solvable are the equations given an optimal choice of test frequencies?
- linear techniques for element value determination

fault verification techniques (consistency checking)

techniques to determine the most likely faults

CAT Techniques

computer-aided analog testing

fault detection
fault location
parameter identification
postproduction tuning

uniqueness often essential

sensitivity to changes, fluctuations and uncertainties should be exposed

some challenges

robustness against deviations of other elements
robustness against measurement uncertainties
establish a measure of testability
how to use the minimum number of tests
insufficient data (degree of diagnosability)

Analog Circuit Theory

1. Circuit Analysis and Simulation

component values assumed
all possible solutions of interest
relevant to experimental validation

2. Circuit Design and Optimization

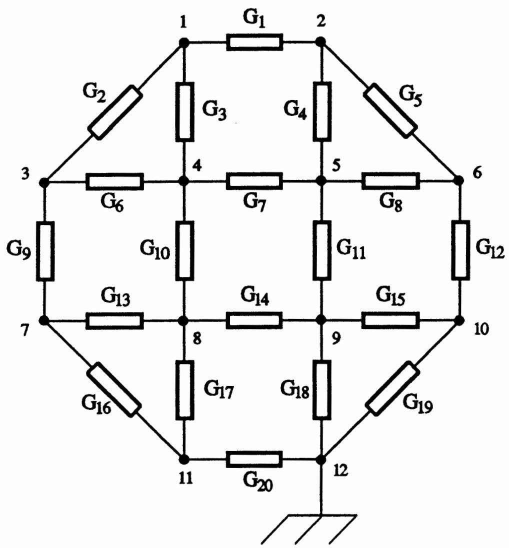
component values optimizable
good solutions of interest
more relevant to experimental validation

3. Circuit Diagnosis and Testing

components under investigation
unique solutions of interest
most relevant to experimental validation

(*Bandler and Salama, "Fault diagnosis of analog circuits", Proc. IEEE, 1985, pp. 1279-1325*)

Analog Diagnosis Problem



resistive mesh circuit

only external nodes are available for excitation and measurements

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Analog Diagnosis Using ℓ_1 Optimization

$$\underset{x}{\textit{minimize}} \quad \sum_{i=1}^{n} |\Delta x_i / x_i^0|$$

subject to

$$V_1^c(x) - V_1^m = 0$$

$$\vdots$$

$$V_K^c(x) - V_K^m = 0$$

where

$x = [x_1 \, x_2 \, ... \, x_n]^T$	circuit parameters
x^0	nominal or assumed parameter values
$\Delta x_i = x_i - x_i^0$	deviations from the nominal or assumed values
$V_1^m, ..., V_K^m$	measurements on the circuit under test
$V_1^c(x), ..., V_K^c(x)$	calculated circuit responses

Analog Diagnosis Using Huber Optimization

penalty function approach

$$\underset{\boldsymbol{x}}{\textit{minimize}} \sum_{j=1}^{n+K} \rho_k(f_j(\boldsymbol{x}))$$

where

$$f_i(x) = \Delta x_i / x_i^0, \quad i = 1, 2, ..., n$$

$$f_{n+i}(x) = \beta_i(V_i^c(x) - V_i^m), \quad i = 1, 2, ..., K$$

β_i are appropriate multipliers for the penalty terms

Huber Functions

$$\rho_k(f) = \begin{cases} f^2/2 & \text{if } |f| \leq k \\ k|f| - k^2/2 & \text{if } |f| > k \end{cases}$$

where k is a positive constant

the Huber function ρ_k is a hybrid of the least-squares (ℓ_2) (when $|f| \leq k$) and the ℓ_1 (when $|f| > k$)

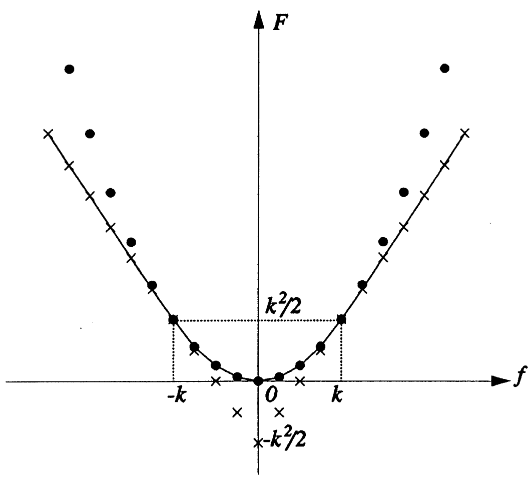
Huber Optimization

$$\underset{\boldsymbol{x}}{\textit{minimize}} \quad F(\boldsymbol{x}) \triangleq \sum_{j=1}^{m} \rho_k(f_j(\boldsymbol{x}))$$

where $\boldsymbol{x} = [x_1\, x_2 \, ... \, x_n]^T$ is the set of variables

f_j, $j = 1, 2, ..., m$, are error functions

Huber Function as a Hybrid ℓ_1 / ℓ_2



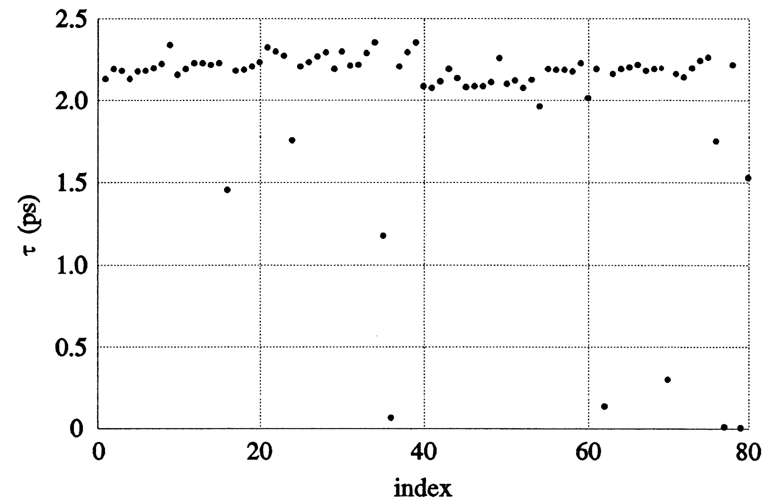
the Huber, ℓ_1 and ℓ_2 objective functions in the one-dimensional case

the strikes represent the discrete points on the ℓ_1 curve

the dots represent the discrete points on the ℓ_2 curve

the continuous curve indicates the Huber objective function

Data Containing Wild Points



run chart of the FET time-delay τ

extracted from multi-device measurements

Huber Solution of Analog Diagnosis Problem

FAULT LOCATION OF THE RESISTIVE MESH CIRCUIT

Element	Nominal Value	Actual Value	Percentage Deviation		
			Actual	ℓ_1	Huber
G_1	1.0	0.98	-2.0	0.00	-0.11
G_2	1.0	0.50	-50.0*	-48.89	-47.28
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G_7	1.0	1.02	2.0	0.00	-0.19
G_8	1.0	1.05	5.0	0.00	-0.41
G_9	1.0	1.02	2.0	2.41	3.75
G_{10}	1.0	0.98	-2.0	0.00	0.39
G_{11}	1.0	1.04	4.0	0.00	-0.37
G_{12}	1.0	1.01	1.0	2.73	1.32
G_{13}	1.0	0.99	-1.0	0.00	-0.26
G_{14}	1.0	0.98	-2.0	0.00	-0.50
G_{15}	1.0	1.02	2.0	0.00	-0.05
G_{16}	1.0	0.96	-4.0	-3.36	-2.67
G_{17}	1.0	1.02	2.0	0.00	-0.61
G_{18}	1.0	0.50	-50.0*	-50.09	-47.33
G_{19}	1.0	0.98	-2.0	-1.41	-3.81
G_{20}	1.0	0.96	-4.0	-4.40	-4.72

* Faults

Relevant Optimization and Analog Diagnosis Benchmarks

"A nonlinear programming approach to optimal design centering, tolerancing and tuning," (*IEEE Trans. CAS, 1976*)

"An interactive optimal post-production tuning technique utilizing simulated sensitivities and response measurements," (*MTT-S Symp., 1981*)

"Fault isolation in linear analog circuits using the L1 norm," (*CAS Symp., 1982*)

"Integrated approach to microwave post production tuning," (*MTT-S Symp., 1983*)

"Microwave device modelling using efficient ℓ_1 optimization: a novel approach," (*MTT-S Symp., 1986*)

"Robustizing circuit optimization using Huber functions," (*MTT-S Symp., 1993*)

Experimental Validation of Microstrip Filter Designs

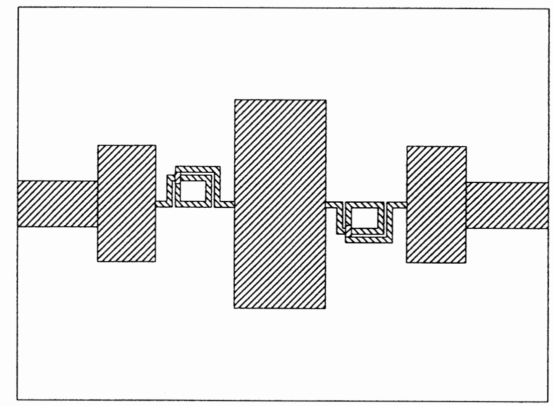
conventional use of EM simulation to validate designs

low-pass microstrip filter: microstrip components derived from a synthesized LC prototype *(Swanson, 1991)*

common sense judgement used to "validate" the design

sophisticated validation algorithms could enhance the common sense judgement approach

A Low-Pass Microstrip Filter
(Swanson, 1991)



built on a 25 mil thick alumina substrate with a relative dielectric constant of 9.8

the rectangular inductors utilize air bridges with vias

EM Simulation of the Low-Pass Microstrip Filter
(Swanson, 1991)

for simulation the whole structure is partitioned into individual components

approximate simulation times per one frequency point:

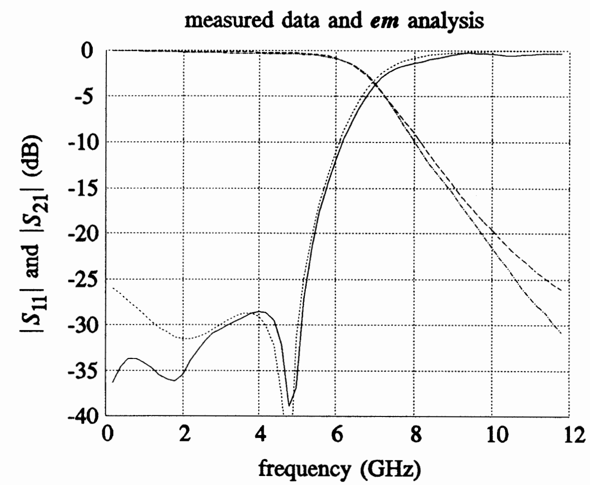
100 seconds for the inductor
10 seconds for the center capacitor
8 seconds for the end capacitor

the resulting S parameters of individual components are combined to determine the S parameters of the overall filter

symmetry of the filter is utilized by simulating only one inductor and one end capacitor

additional pieces of transmission lines are added for each component and de-embedded for better accuracy and to account for discontinuities at both sides of each capacitor

EM Simulation and Measurements of the Low-Pass Filter
(Swanson, 1991)



(---)	simulated $\lvert S_{11}\rvert$	(-·-·-)	measured $\lvert S_{11}\rvert$
(······)	simulated $\lvert S_{21}\rvert$	(—)	measured $\lvert S_{21}\rvert$

electromagnetic simulation using ***em***™

very good approximation of filter behaviour, in particular around the cut-off frequency

Optimization Technology for Automated CAD

parameterized models
    based on physics, fields, circuits, experiments

circuit theory for interconnection

numerical algorithms for simulation and optimization

objectives

- meet parameter constraints
- exceed performance specifications
- tolerance optimization
- yield maximization
- cost minimization

uniqueness not essential

sensitivity to changes, fluctuations and uncertainties should be considered but their effects minimized

Integrated Approach to Microwave Design

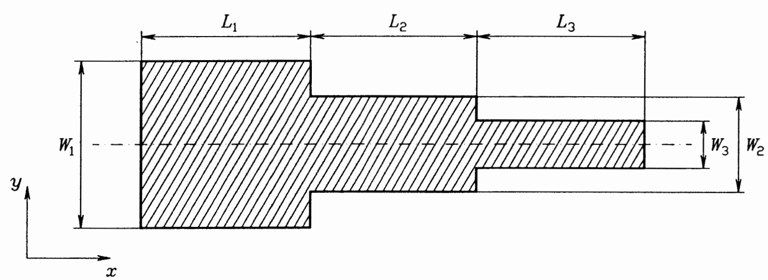
(*Bandler Liu and Tromp, 1975*)

benchmark considerations of the integrated approach

- optimal design centering
- optimal design tolerancing
- optimal design tuning
- parasitic effects
- uncertainties in models and reference plane
- mismatched terminations

we now need an <u>integrated approach</u> to experimental validation to address some of Rautio's questions

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

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EM Simulation of the Microstrip Transformer

decomposed into three components simulated as two-ports

the first two sections simulated as step discontinuities

the last section simulated as a microstrip line

data base of simulated results

three component level Q-models established for each section of the transformer at the nominal point using ***em***™

the entire transformer structure also simulated as one piece

simulation results by the two approaches were practically identical

Yield-Driven Electromagnetic Optimization of the Microstrip Transformer

yield optimization started from the solution of a nominal minimax design

single vs. multilevel modeling - two experiments:

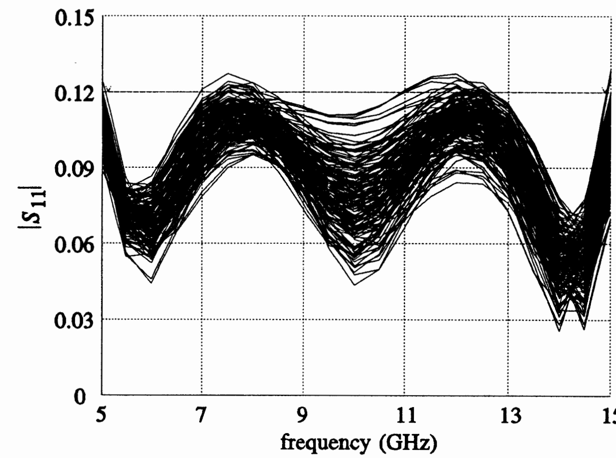
- yield optimization using single-level (component) modeling
- yield optimization using two-level (component and circuit response) modeling

the Q-models were updated during optimization whenever necessary

selection of optimization variables - two experiments:

- all six variables W_1, W_2, W_3, L_1, L_2 and L_3 selected
- only three variables W_1, W_2 and W_3 selected

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 Analysis of the Microstrip Transformer

three-section 3:1 microstrip transformer

sensitivity analysis performed at the solution of yield optimization with all six optimization variables

seven experiments:

- the specification is swept from 0.10 to 0.13
- each of the six optimization variables is individually swept

yield is very sensitive to the widths of all the sections and is quite insensitive to the lengths

250 Monte Carlo outcomes used for yield estimation

the results were obtained with little additional computational effort

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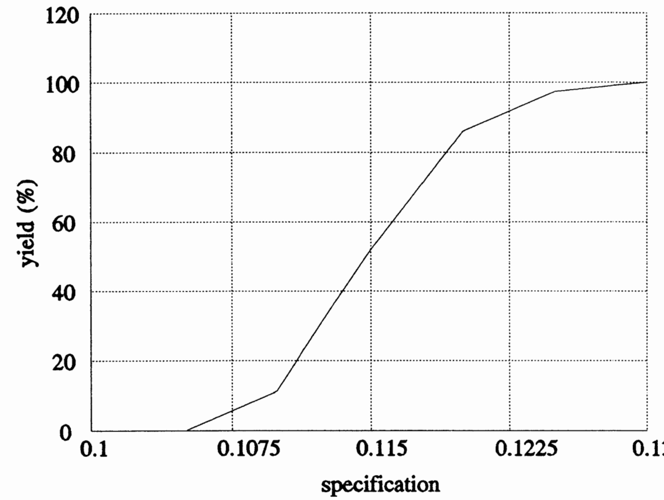
Yield Sensitivity of the Microstrip Transformer



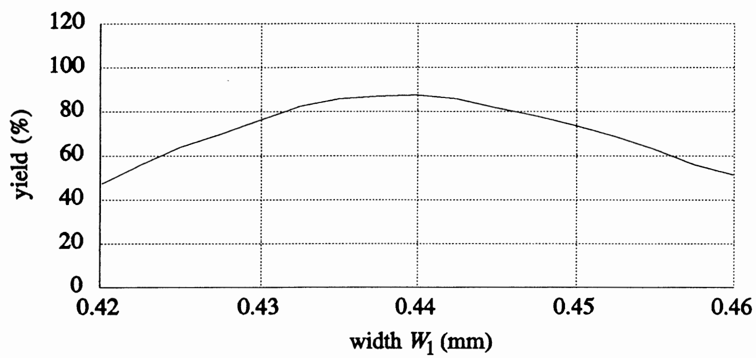
yield vs. specification on $|S_{11}|$

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

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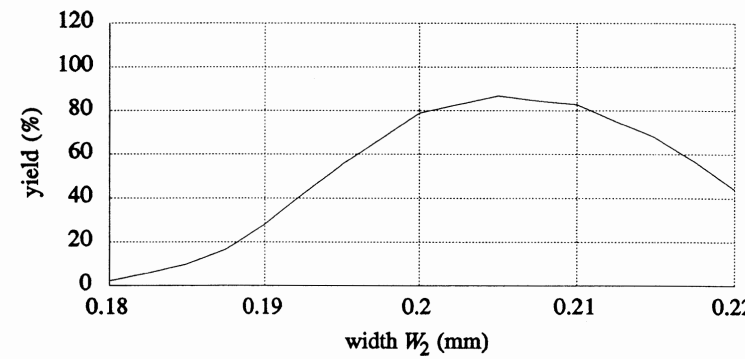
Yield Sensitivity of the Microstrip Transformer

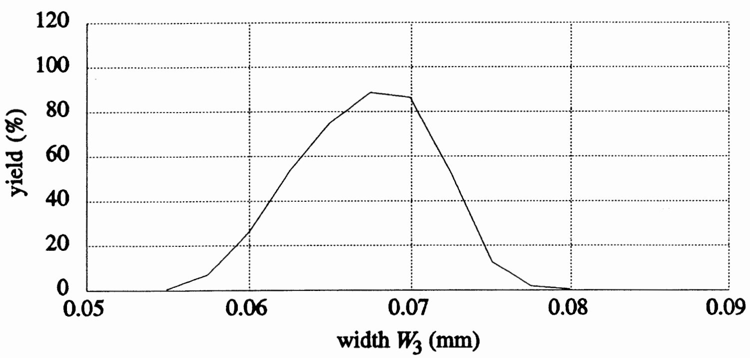


yield vs. W_2

high sensitivity of yield w.r.t. W_2

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

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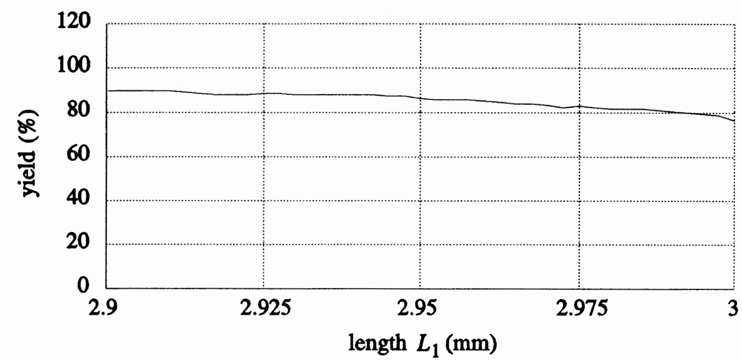
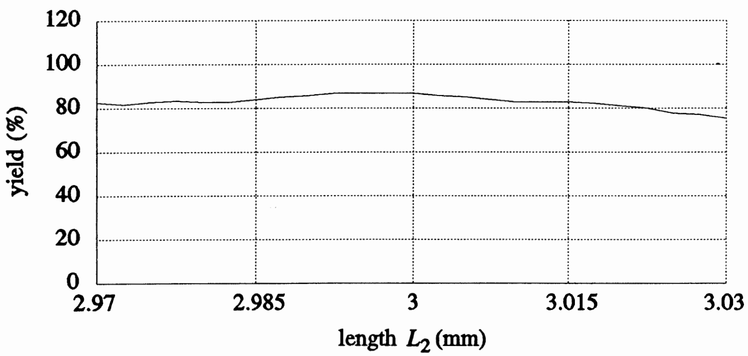


yield vs. L_1

low sensitivity of yield w.r.t. L_1

yield estimated with 250 Monte Carlo outcomes

Yield Sensitivity of the Microstrip Transformer

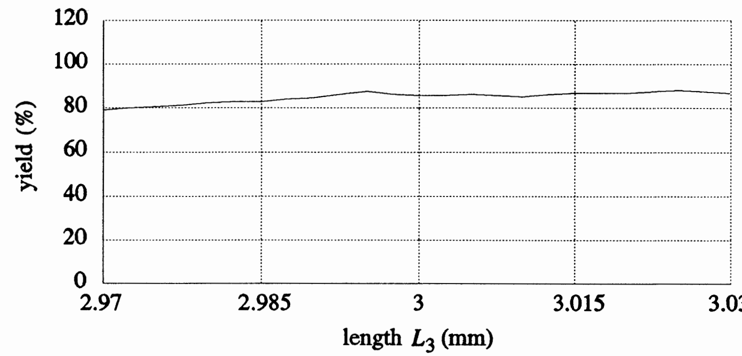


yield vs. L_2

low sensitivity of yield w.r.t. L_2

yield estimated with 250 Monte Carlo outcomes

Yield Sensitivity of the Microstrip Transformer



yield vs. L_3

low sensitivity of yield w.r.t. L_3

yield estimated with 250 Monte Carlo outcomes

Software Implementing Statistical/Diagnosis Concepts

RoMPE™ (1988)
FET parameter extraction (DC data, S parameters)

HarPE™ (1989)
statistical FET parameter extraction (DC, SS, HB)

OSA90™ (1990)
friendly optimization engine for performance- and yield-driven design

OSA90/hope™ (1991)
OSA90 integrated with unified DC/SS/HB

these CAD tools merge multi-circuit/device/domain/bias modeling principles with novel ℓ_1 objectives to enhance precision and uniqueness

robustized modeling and design using Huber functions are coming

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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 integrated approach 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

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Conclusions

sensitivity evaluation
- well-understood in analysis, design and testing

error analysis
- already part of statistical modeling/design systems

measurements made at a difficult frequency
- see work on multifrequency testing

too many "confounding" variables
- similar treatment as for "soft faults"

the experimenter has a desired outcome in mind
- quite an opposite outcome in fault diagnosis!

incorrect objective
- answered by diagnosability and testability theory

CAD software
- frameworks available for immediate exploitation

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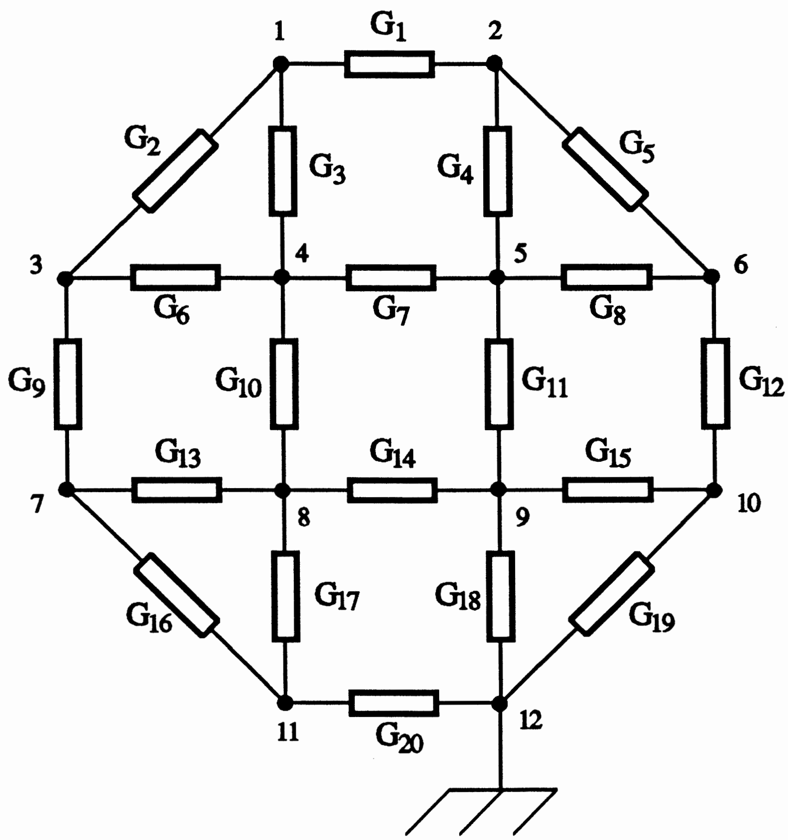

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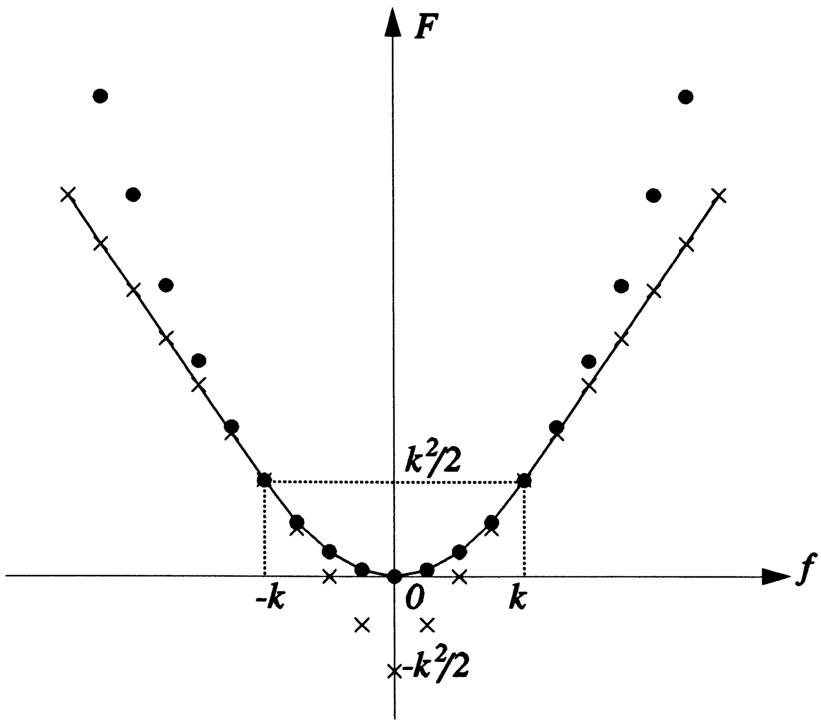

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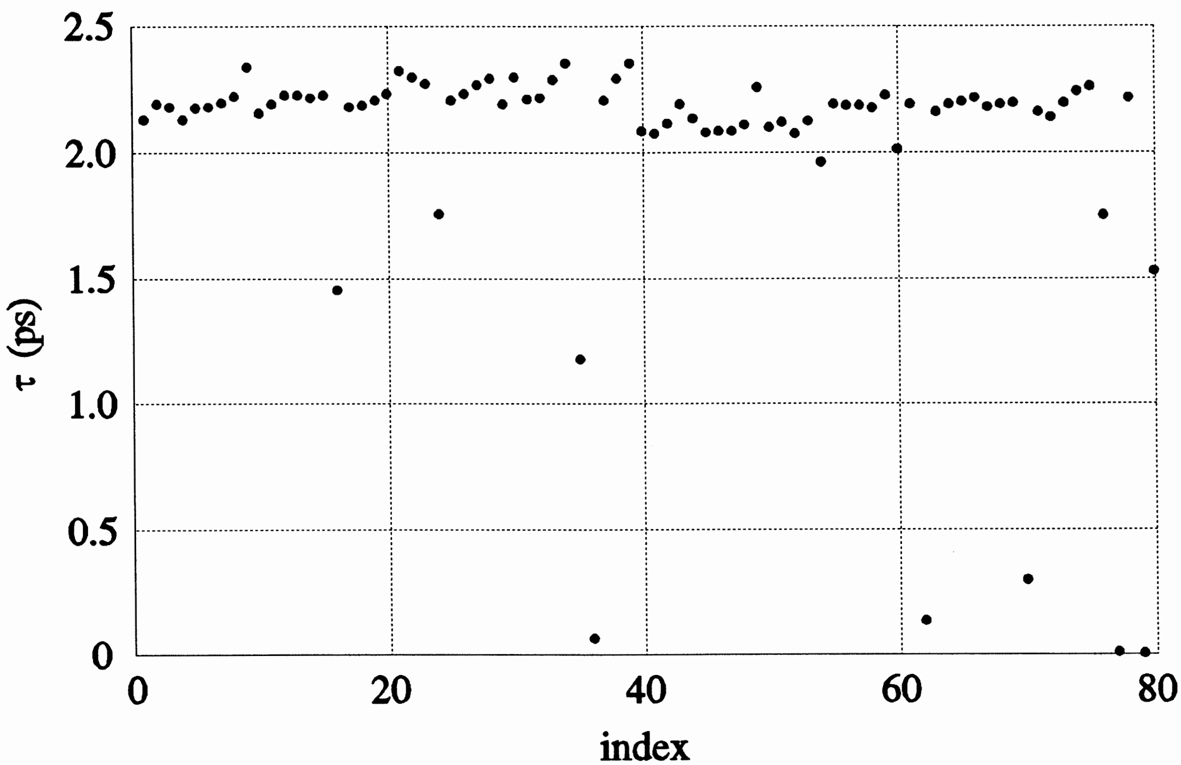

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G_{16}	1.0	0.96	-4.0	-3.36	-2.67
G_{17}	1.0	1.02	2.0	0.00	-0.61
G_{18}	1.0	0.50	-50.0*	-50.09	-47.33
G_{19}	1.0	0.98	-2.0	-1.41	-3.81
G_{20}	1.0	0.96	-4.0	-4.40	-4.72

* Faults

Relevant Optimization and Analog Diagnosis Benchmarks

"A nonlinear programming approach to optimal design centering, tolerancing and tuning," (*IEEE Trans. CAS, 1976*)

"An interactive optimal post-production tuning technique utilizing simulated sensitivities and response measurements," (*MTT-S Symp., 1981*)

"Fault isolation in linear analog circuits using the L1 norm," (*CAS Symp., 1982*)

"Integrated approach to microwave post production tuning," (*MTT-S Symp., 1983*)

"Microwave device modelling using efficient ℓ_1 optimization: a novel approach," (*MTT-S Symp., 1986*)

"Robustizing circuit optimization using Huber functions," (*MTT-S Symp., 1993*)

Experimental Validation of Microstrip Filter Designs

conventional use of EM simulation to validate designs

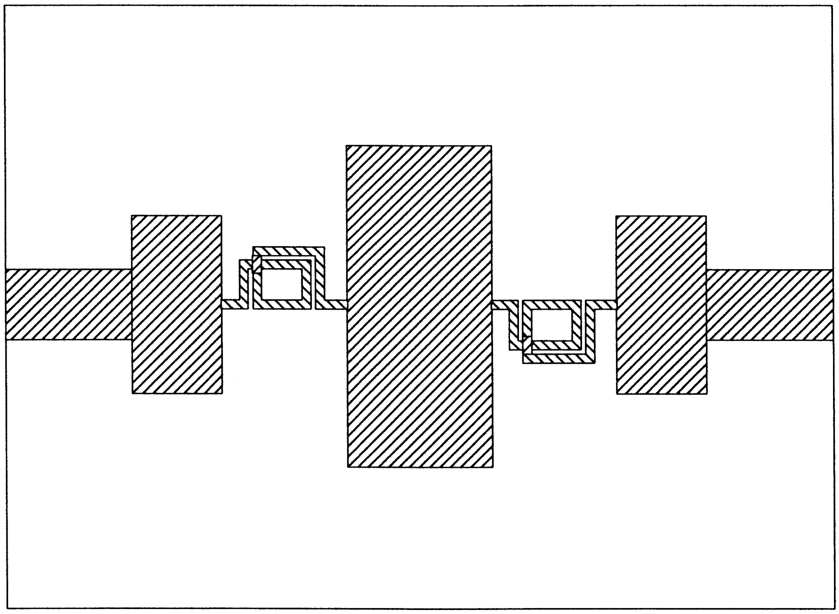
low-pass microstrip filter: microstrip components derived from a synthesized LC prototype *(Swanson, 1991)*

common sense judgement used to "validate" the design

sophisticated validation algorithms could enhance the common sense judgement approach

A Low-Pass Microstrip Filter

(Swanson, 1991)



built on a 25 mil thick alumina substrate with a relative dielectric constant of 9.8

the rectangular inductors utilize air bridges with vias

EM Simulation of the Low-Pass Microstrip Filter
(Swanson, 1991)

for simulation the whole structure is partitioned into individual components

approximate simulation times per one frequency point:

100 seconds for the inductor
10 seconds for the center capacitor
8 seconds for the end capacitor

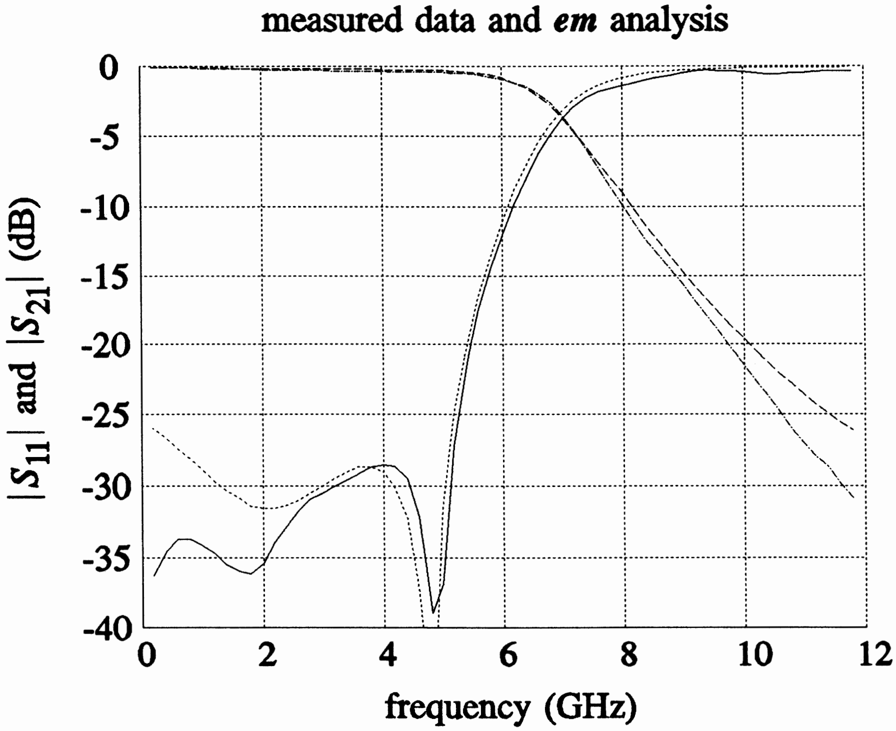
the resulting S parameters of individual components are combined to determine the S parameters of the overall filter

symmetry of the filter is utilized by simulating only one inductor and one end capacitor

additional pieces of transmission lines are added for each component and de-embedded for better accuracy and to account for discontinuities at both sides of each capacitor

EM Simulation and Measurements of the Low-Pass Filter

(Swanson, 1991)



(---)	simulated $\|S_{11}\|$	(-····-)	measured $\|S_{11}\|$
(······)	simulated $\|S_{21}\|$	(—)	measured $\|S_{21}\|$

electromagnetic simulation using *em*™

very good approximation of filter behaviour, in particular around the cut-off frequency

Optimization Technology for Automated CAD

parameterized models

based on physics, fields, circuits, experiments

circuit theory for interconnection

numerical algorithms for simulation and optimization

objectives

meet parameter constraints
exceed performance specifications
tolerance optimization
yield maximization
cost minimization

uniqueness not essential

sensitivity to changes, fluctuations and uncertainties should be considered but their effects minimized

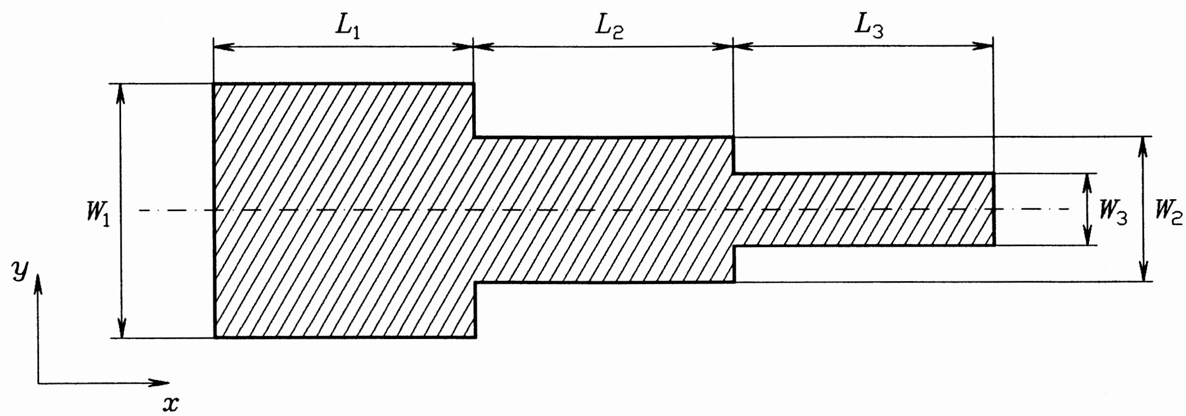
Integrated Approach to Microwave Design
(*Bandler Liu and Tromp, 1975*)

benchmark considerations of the integrated approach

optimal design centering
optimal design tolerancing
optimal design tuning
parasitic effects
uncertainties in models and reference plane
mismatched terminations

we now need an <u>integrated approach</u> to experimental validation to address some of Rautio's questions

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

EM Simulation of the Microstrip Transformer

decomposed into three components simulated as two-ports

the first two sections simulated as step discontinuities

the last section simulated as a microstrip line

data base of simulated results

three component level Q-models established for each section of the transformer at the nominal point using *em*™

the entire transformer structure also simulated as one piece

simulation results by the two approaches were practically identical

Yield-Driven Electromagnetic Optimization of the Microstrip Transformer

yield optimization started from the solution of a nominal minimax design

single vs. multilevel modeling - two experiments:

yield optimization using single-level (component) modeling

yield optimization using two-level (component and circuit response) modeling

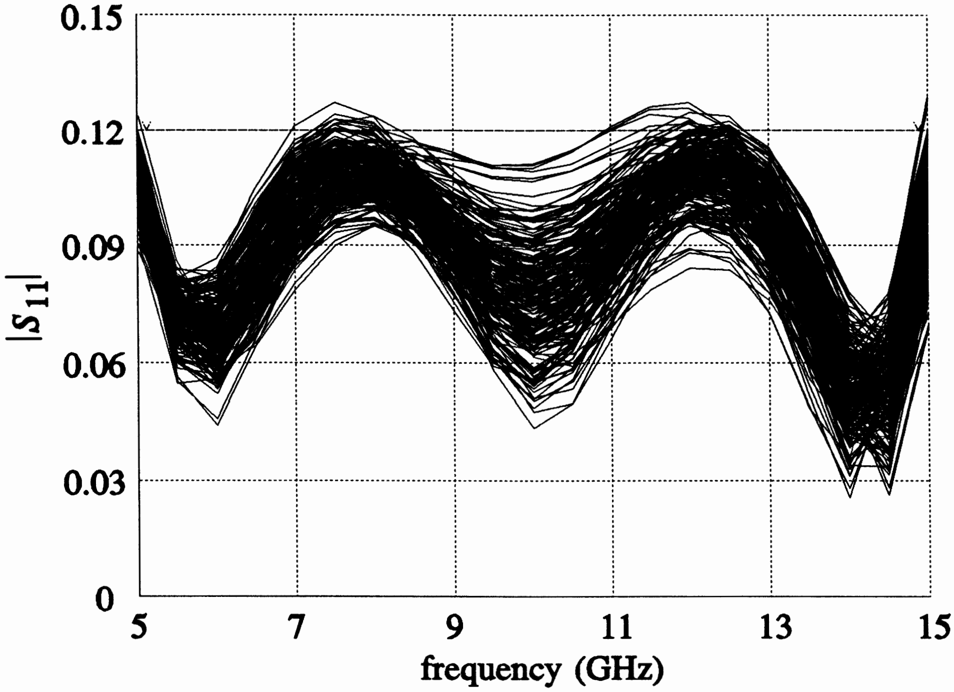
the Q-models were updated during optimization whenever necessary

selection of optimization variables - two experiments:

all six variables W_1, W_2, W_3, L_1, L_2 and L_3 selected

only three variables W_1, W_2 and W_3 selected

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 Analysis of the Microstrip Transformer

three-section 3:1 microstrip transformer

sensitivity analysis performed at the solution of yield optimization with all six optimization variables

seven experiments:

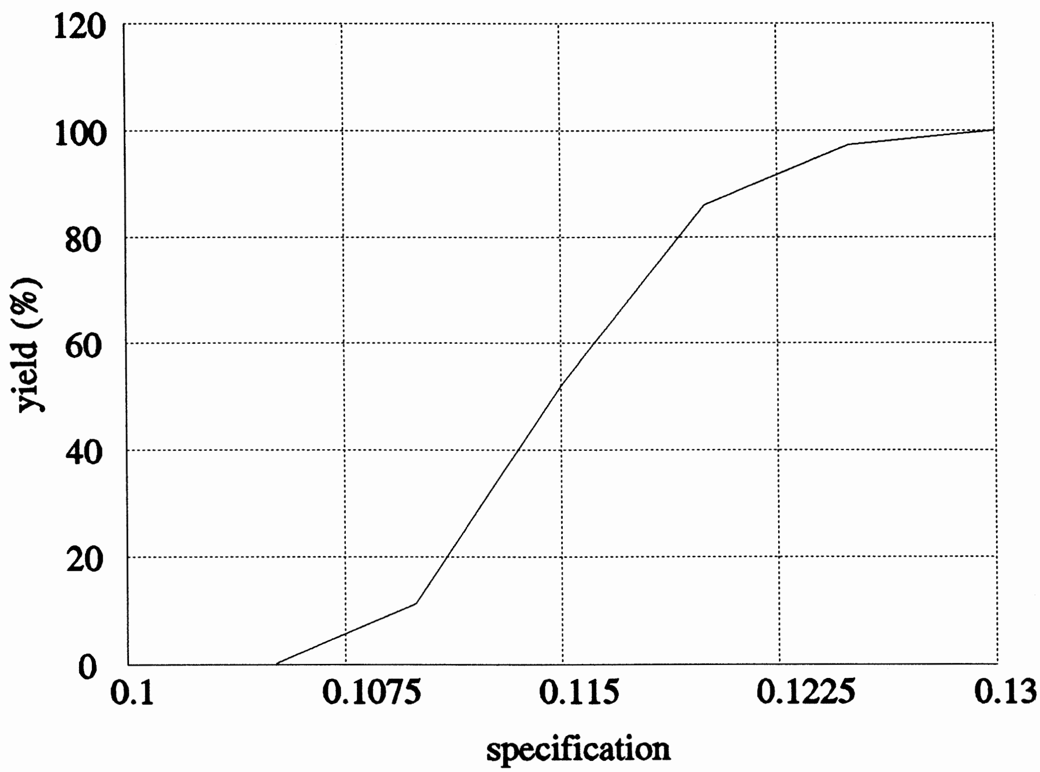
> the specification is swept from 0.10 to 0.13
>
> each of the six optimization variables is individually swept

yield is very sensitive to the widths of all the sections and is quite insensitive to the lengths

250 Monte Carlo outcomes used for yield estimation

the results were obtained with little additional computational effort

Yield Sensitivity of the Microstrip Transformer



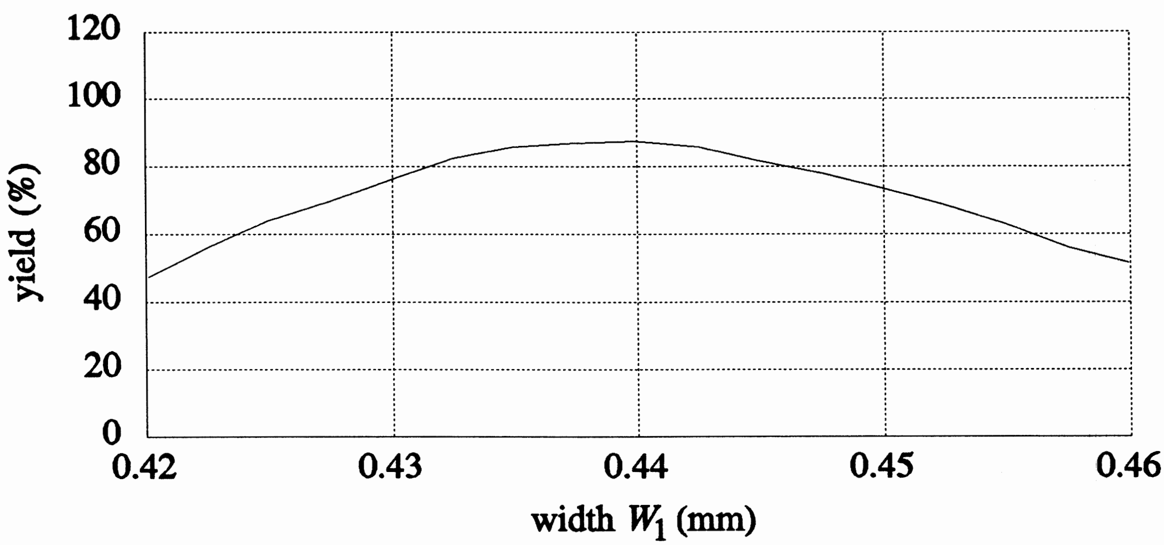
yield vs. specification on $|S_{11}|$

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

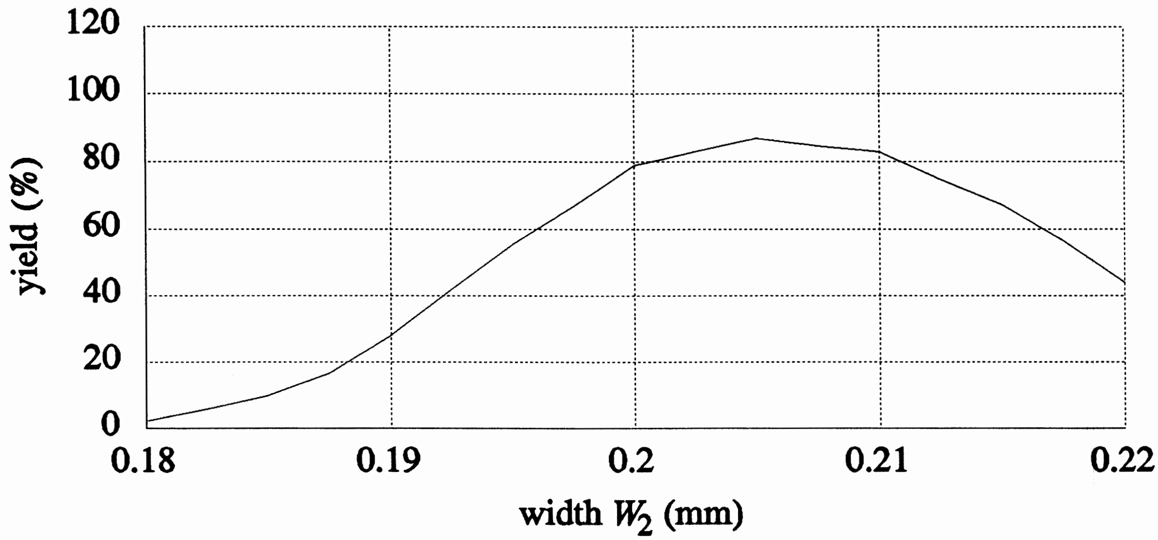


yield vs. W_1

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

yield estimated with 250 Monte Carlo outcomes

Yield Sensitivity of the Microstrip Transformer

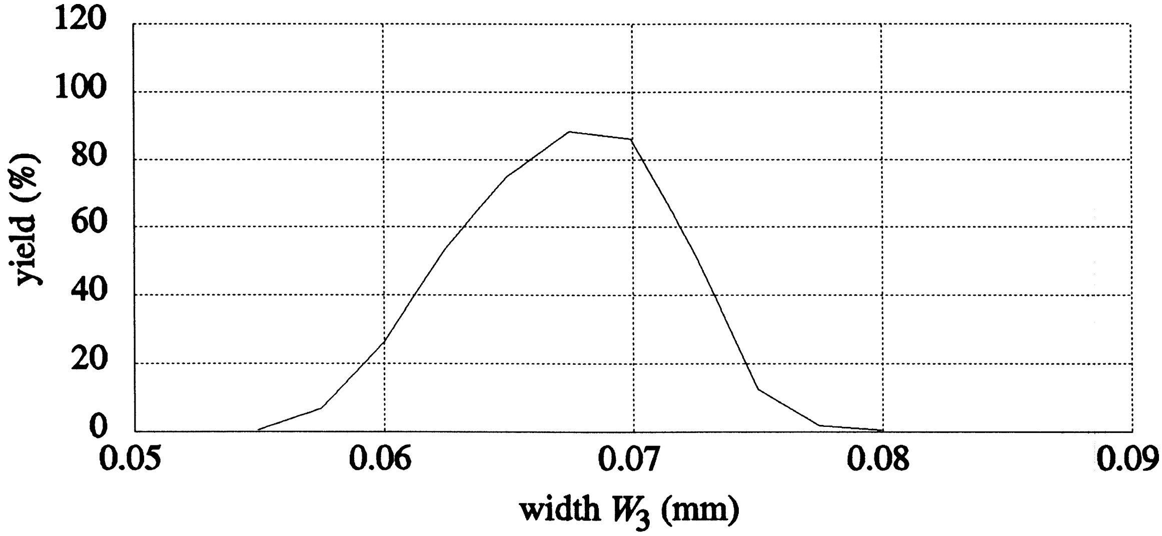


yield vs. W_2

high sensitivity of yield w.r.t. W_2

yield estimated with 250 Monte Carlo outcomes

Yield Sensitivity of the Microstrip Transformer

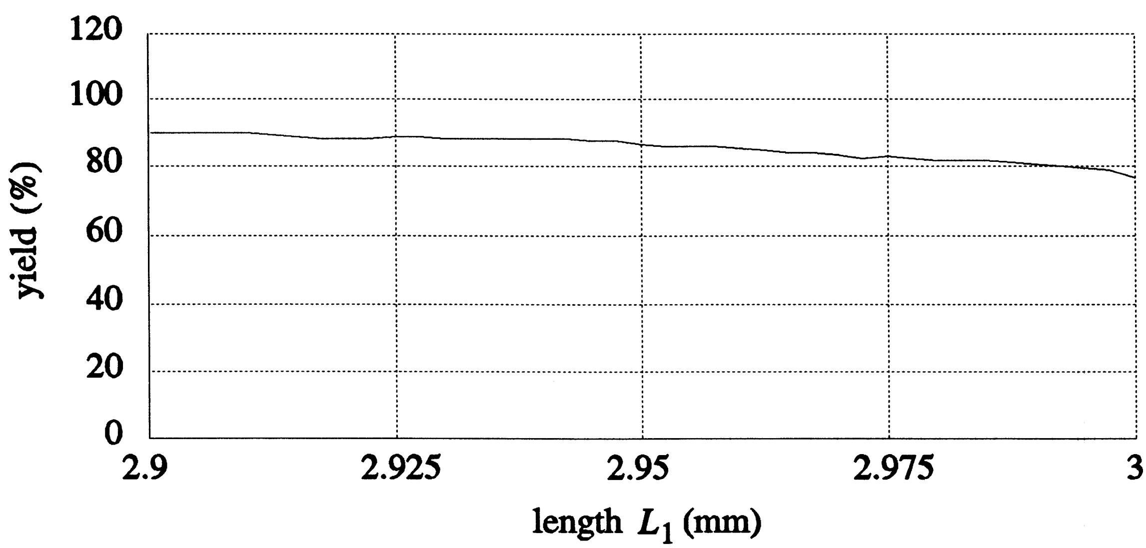


yield vs. W_3

high sensitivity of yield w.r.t. W_3

yield estimated with 250 Monte Carlo outcomes

Yield Sensitivity of the Microstrip Transformer

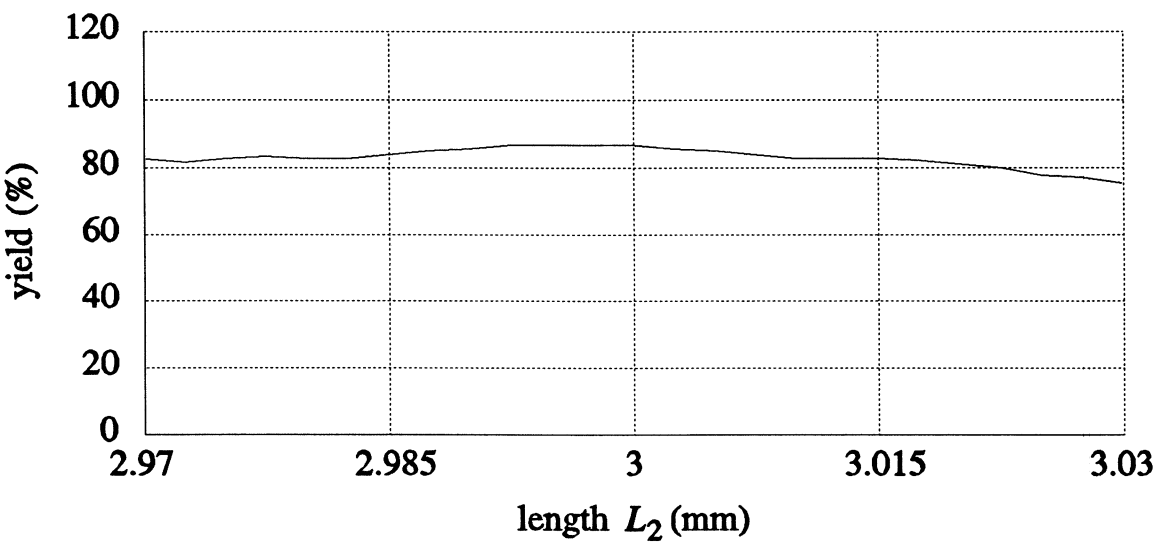


yield vs. L_1

low sensitivity of yield w.r.t. L_1

yield estimated with 250 Monte Carlo outcomes

Yield Sensitivity of the Microstrip Transformer

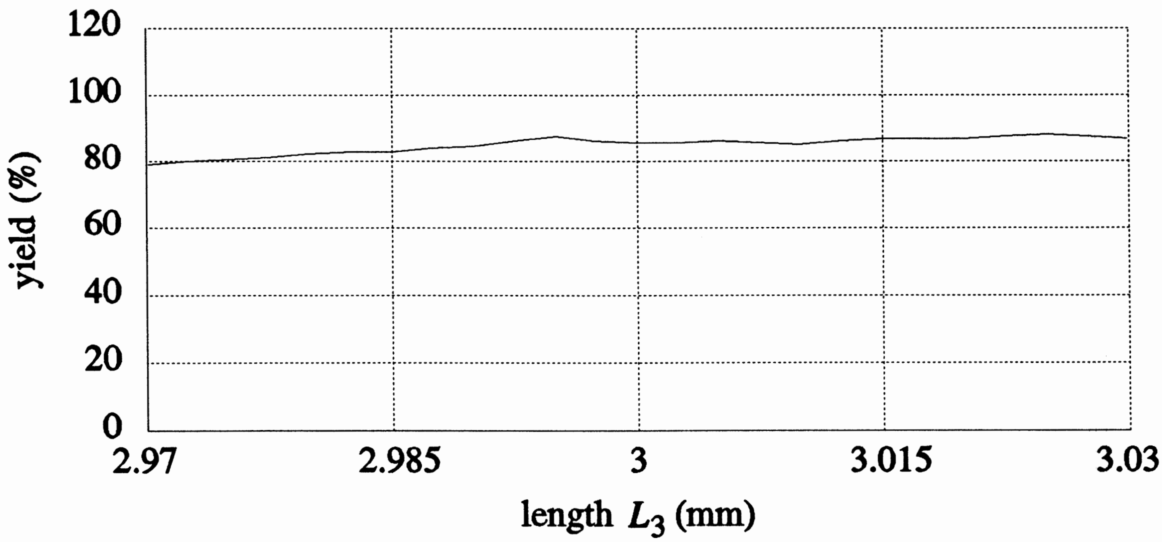


yield vs. L_2

low sensitivity of yield w.r.t. L_2

yield estimated with 250 Monte Carlo outcomes

Yield Sensitivity of the Microstrip Transformer



yield vs. L_3

low sensitivity of yield w.r.t. L_3

yield estimated with 250 Monte Carlo outcomes

Software Implementing Statistical/Diagnosis Concepts

RoMPE™ (1988)
FET parameter extraction (DC data, S parameters)

HarPE™ (1989)
statistical FET parameter extraction (DC, SS, HB)

OSA90™ (1990)
friendly optimization engine for performance- and yield-driven design

OSA90/hope™ (1991)
OSA90 integrated with unified DC/SS/HB

these CAD tools merge multi-circuit/device/domain/bias modeling principles with novel ℓ_1 objectives to enhance precision and uniqueness

robustized modeling and design using Huber functions are coming

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 integrated approach 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

Conclusions

sensitivity evaluation

well-understood in analysis, design and testing

error analysis

already part of statistical modeling/design systems

measurements made at a difficult frequency

see work on multifrequency testing

too many "confounding" variables

similar treatment as for "soft faults"

the experimenter has a desired outcome in mind

quite an opposite outcome in fault diagnosis!

incorrect objective

answered by diagnosability and testability theory

CAD software

frameworks available for immediate exploitation