YIELD OPTIMIZATION

OF LARGE SCALE MICROWAVE CIRCUITS

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OF LARGE SCALE MICROWAVE CIRCUITS

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Outline

discuss yield optimization of large scale microwave circuits

propose a combined strategy to attack this difficult problem

demonstrate the feasibility of yield optimization of large scale microwave circuits using a 5 channel multiplexer example

Features of Our Combined Strategy

use of the most up-to-date computational tool —
supercomputers

very efficient quadratic approximation to the circuit responses

use of fast, dedicated simulation techniques

Impact of Our Approach

capable of dealing with yield optimization problems with a large number of real world variables

highly efficient to ensure an acceptable design cycle and affordable cost

applicable to microwave circuits including tunable and nontunable circuits

Manufacturing Yield

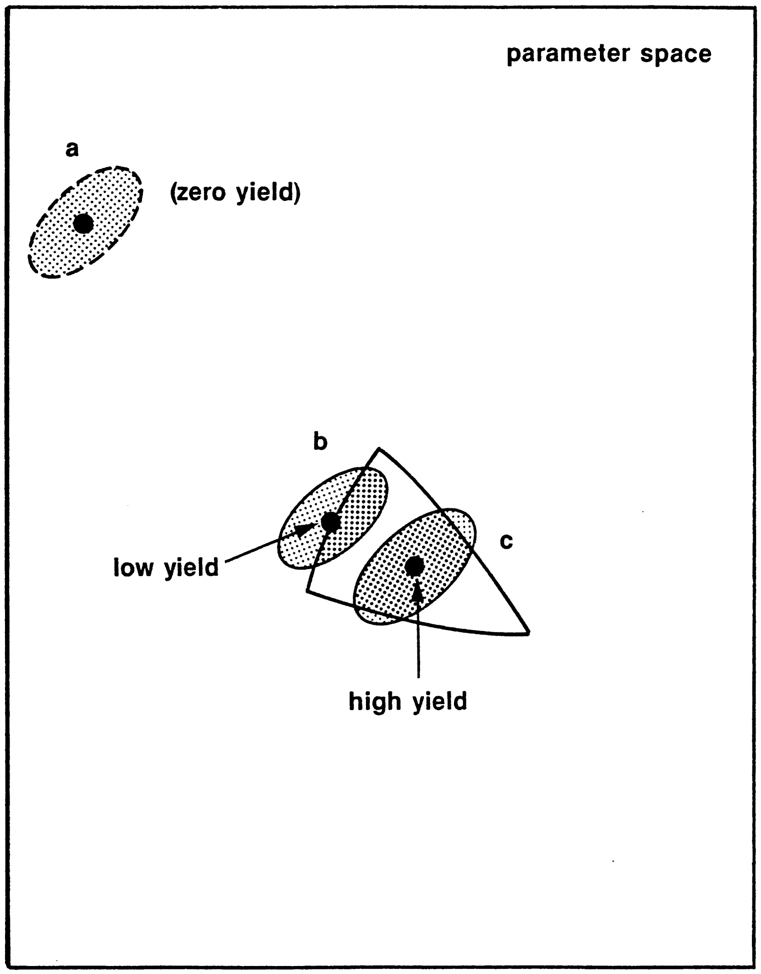
Manufacturing yield is simply the ratio

N_{pass}/N_t

where

N_{pass} is number of circuit outcomes satisfying the design specifications

N_t is total number of circuit outcomes


parameter space
a
(zero yield)
b
low yield
c
high yield

Outcomes

let $\mathbf{x}^0$ denote the nominal design parameter vector

the *k*th tunable outcome $\mathbf{x}^k$ may be described by

$$\mathbf{x}^k = \mathbf{x}^0 + \mathbf{r}^k, \quad \mathbf{r}^k = \mathbf{s}^k + \mathbf{t}^k + \mathbf{s}_t^k, \quad k = 1, 2, \ldots, N_t$$

where

$\mathbf{s}^k$ represents model uncertainties and manufacturing tolerances

$\mathbf{t}^k$ represents postproduction tuning adjustments

$\mathbf{s}_t^k$ represents tuning imprecisions

Acceptance Index and Yield Estimate

each sample circuit is associated with an acceptance index given by

$$I_a(x^k) = \begin{cases} 1, & \text{if } x^k \text{ satisfies the specifications} \\ 0, & \text{otherwise} \end{cases}$$

yield is estimated by

$$Y \approx \left[\sum_{k=1}^{N_t} I_a(x^k) \right] / N_t$$

Yield Optimization

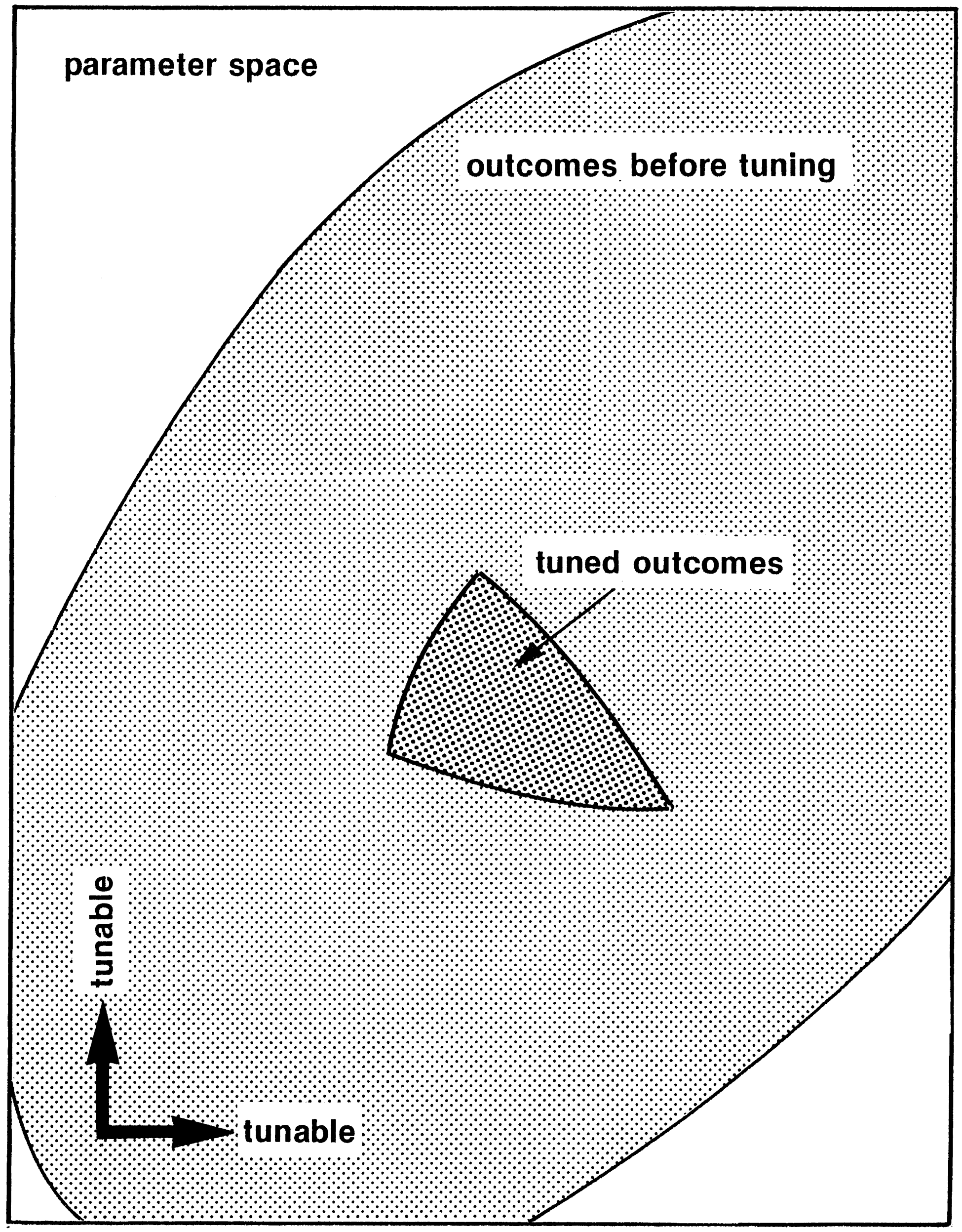
$$\underset{\mathbf{x}^0}{\text{maximize}}\ Y$$

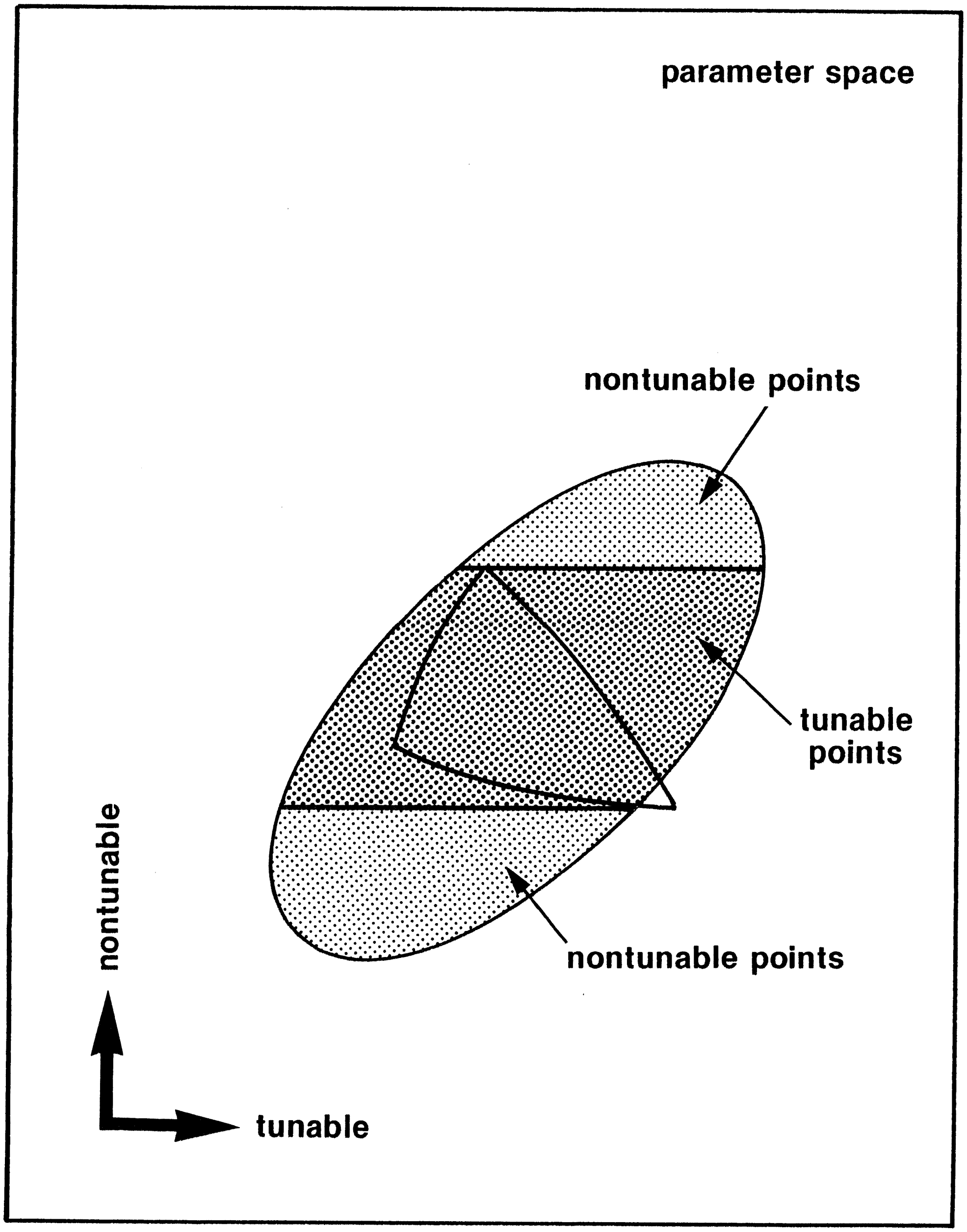
this is called a centering problem with fixed tolerances

Impact of Yield Optimization on Tunable Circuit Design

drive up the probability of obtaining circuits that exhibit good initial responses for the tuning process

increase the possibility of the circuit outcomes satisfying specifications after tuning easy-to-tune elements


parameter space
outcomes before tuning
tuned outcomes
tunable
tunable


parameter space
nontunable points
tunable
points
nontunable points
nontunable
tunable

Quadratic Approximation to Circuit Responses

use a quadratic function q(x) to approximate a response f(x)

design variables are $\mathbf{x} = [x_1\ x_2\ \dots\ x_n]^T$

the quadratic function q(x) is of the form

$$q(\mathbf{x}) = a_0 + \sum_{i=1}^{n} a_i(x_i - x_i^0) + \sum_{\substack{i,j=1 \\ i \geq j}}^{n} a_{ij}(x_i - x_i^0)(x_j - x_j^0)$$

where $\mathbf{x}^0$ is the reference point

Procedure to Obtain the Quadratic Models

simulate the circuit at certain points (sets of parameter values, called base points)

use coordinates of base points and circuit responses to set up a system of linear equations with the coefficients of the quadratic as unknowns

solve the system to get the coefficients

System of Linear Equations to Determine the Quadratic Function

$$\begin{bmatrix} \mathbf{Q}_{11} & \mathbf{Q}_{12} \\ \mathbf{Q}_{21} & \mathbf{Q}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{a} \\ \mathbf{v} \end{bmatrix} = \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{f}_2 \end{bmatrix}$$

where

$\mathbf{Q}_{ij}$ is a submatrix determined by the coordinates of the base points

a and **v** contain the coefficients a_i and a_{ij}, respectively

$\mathbf{f}_1$ and $\mathbf{f}_2$ contain function values at m base points, $f(x^i)$,

$i = 1, 2, \ldots, m$

Scheme to Obtain the Maximally Flat Quadratic Interpolation (Biernacki and Styblinski 1986)

$$\mathbf{v} = \mathbf{C}^T(\mathbf{C}\mathbf{C}^T)^{-1}\mathbf{e}$$

$$\mathbf{a} = \mathbf{Q}_{11}^{-1}\mathbf{f}_1 - \mathbf{Q}_{11}^{-1}\mathbf{Q}_{12}\mathbf{v}$$

where

$$\mathbf{C} = \mathbf{Q}_{22} - \mathbf{Q}_{21}\mathbf{Q}_{11}^{-1}\mathbf{Q}_{12}$$

$$\mathbf{e} = \mathbf{f}_2 - \mathbf{Q}_{21}\mathbf{Q}_{11}^{-1}\mathbf{f}_1$$

Our Novel Quadratic Approximation

principles

applying least squares constraints to the second order coefficients

choosing a fixed pattern of base points

advantage

much higher efficiency in computational effort compared with the traditional approach and the original quadratic interpolation of Biernacki and Styblinski (1986)

Selection of Base Points

the first n + 1 base points

$x^i = x^0 + [0\ 0\ \ldots\ 0\ \beta_i\ 0\ \ldots\ 0]^T$, $i = 1, 2, \ldots, n$

remaining k ($k \leq n$) base points

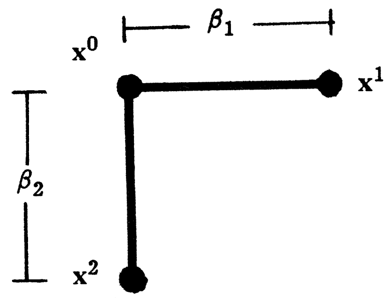
$x^{n+j} = x^0 + [0\ 0\ \ldots\ 0\ \gamma_j\ 0\ \ldots\ 0]^T$, $j = 1, 2, \ldots, k$

where

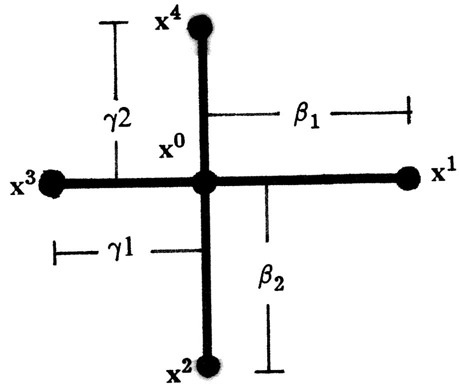
x^0 is the reference point

β_i is a certain perturbation

γ_j is another perturbation, $\gamma_j \neq \beta_i$, for $i = j$



The first 3 base points in two dimensions



Further 2 base points after the
first 3 base points in two dimensions

Simple and Explicit Formulas to Calculate the Coefficients

$a_{ii} = \{[f(x^{n+i}) - f(x^0)]/\gamma_i - [f(x^i) - f(x^0)]/\beta_i\}/(\gamma_i - \beta_i),$

$i = 1, 2, \ldots, k$

$a_{ii} = 0, \quad i = k + 1, \ldots, n$

$a_{ij} = 0, \quad i \neq j, \quad i, j = 1, 2, \ldots, n$

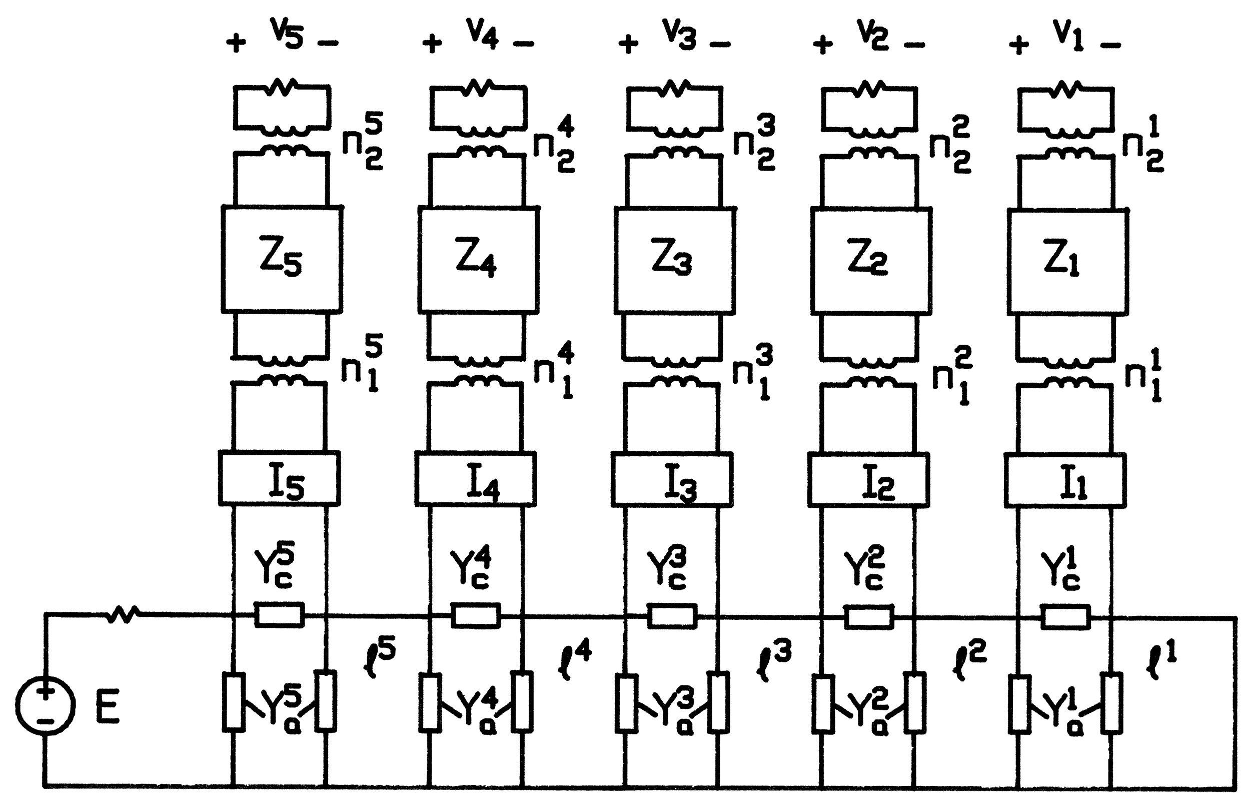
$a_0 = f(x^0)$

$a_i = [f(x^i) - f(x^0)]/\beta_i - \beta_i a_{ii}, \quad i = 1, 2, \ldots, n$

Yield Optimization of a 5-Channel Multiplexer

a 5-channel 12 GHz contiguous band microwave multiplexer, consisting of multicavity filters distributed along a waveguide manifold

(Bandler, Daijavad and Zhang 1986)


+ V5 –
+ V4 –
+ V3 –
+ V2 –
+ V1 –
n2 5
n2 4
n2 3
n2 2
n2 1
Z5
Z4
Z3
Z2
Z1
n1 5
n1 4
n1 3
n1 2
n1 1
I5
I4
I3
I2
I1
Yc 5
Yc 4
Yc 3
Yc 2
Yc 1
ℓ5
ℓ4
ℓ3
ℓ2
ℓ1
E
Ya 5
Ya 4
Ya 3
Ya 2
Ya 1

Details of the Example

scale of the problem

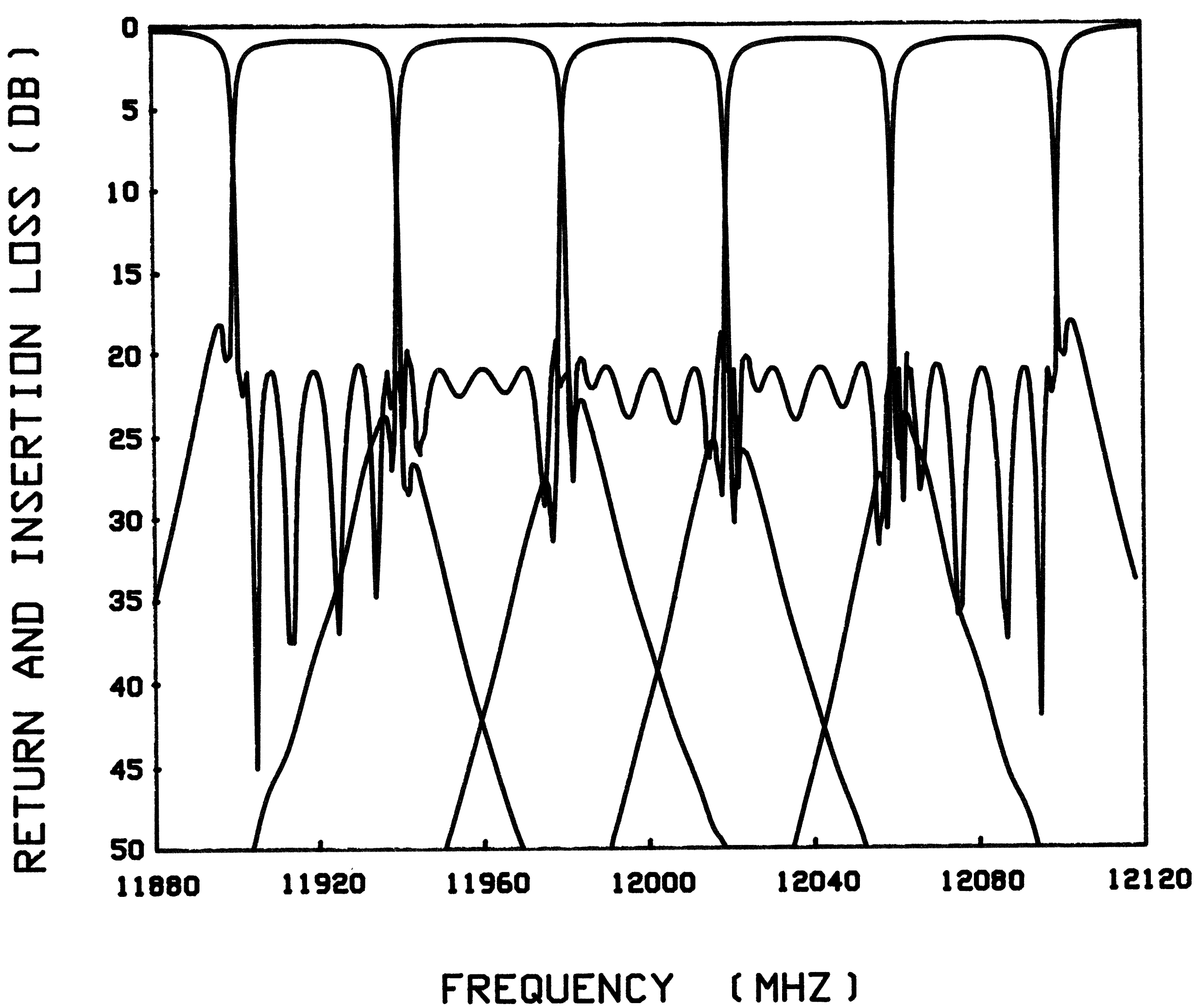
124 nonlinear constraint functions for each outcome
total of 75 toleranced design variables
up to 200 outcomes uniformly distributed between tolerance extremes

specifications for the original design

20dB for the common port return loss and 20dB for the individual channel stopband insertion losses

specifications for our statistical design

10dB for the return and stopband insertion losses


RETURN AND INSERTION LOSS (DB)
0
5
10
15
20
25
30
35
40
45
50
11880
11920
11960
12000
12040
12080
12120
FREQUENCY (MHZ)

Results

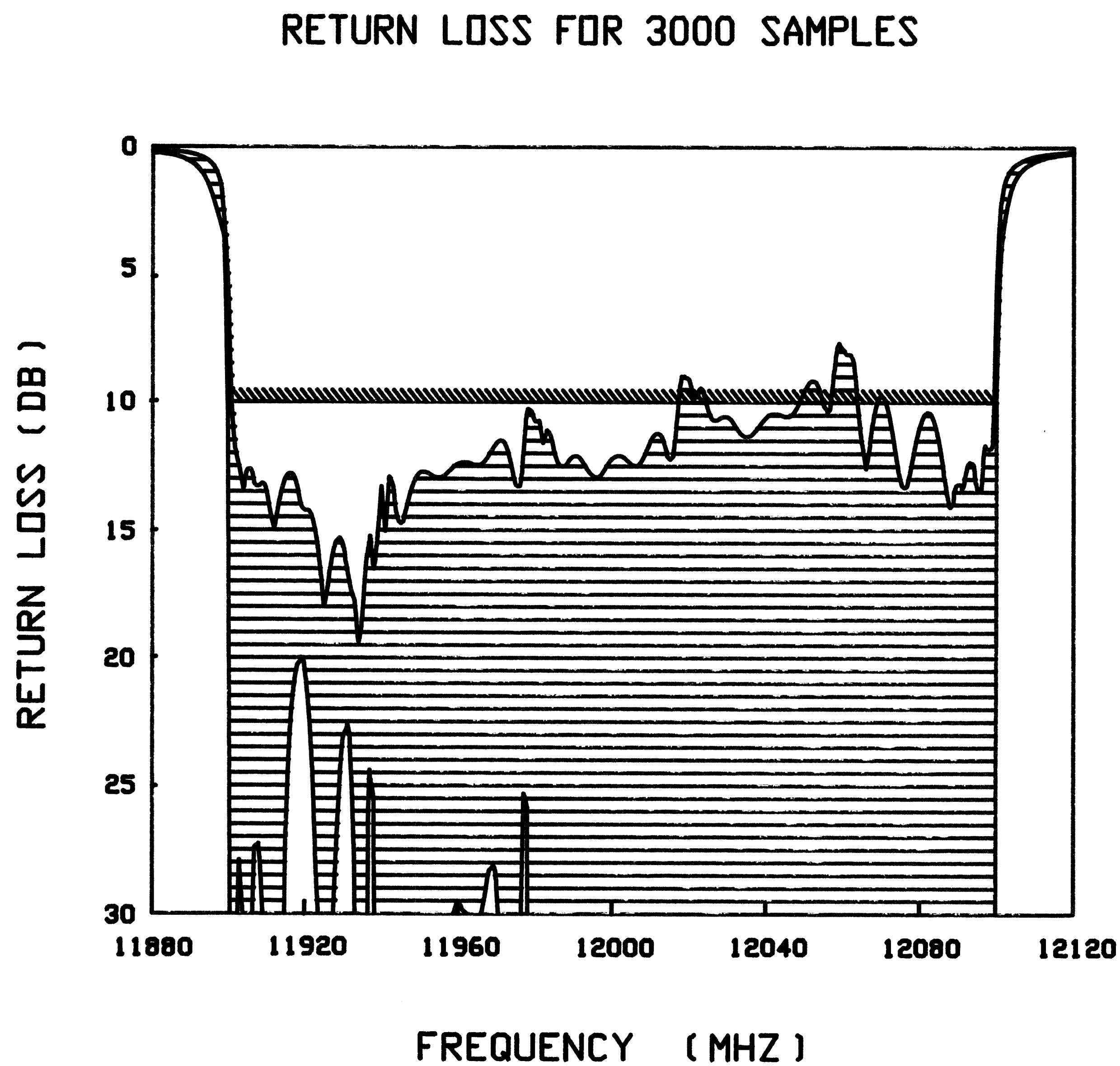
yield increased from 75% to 90%

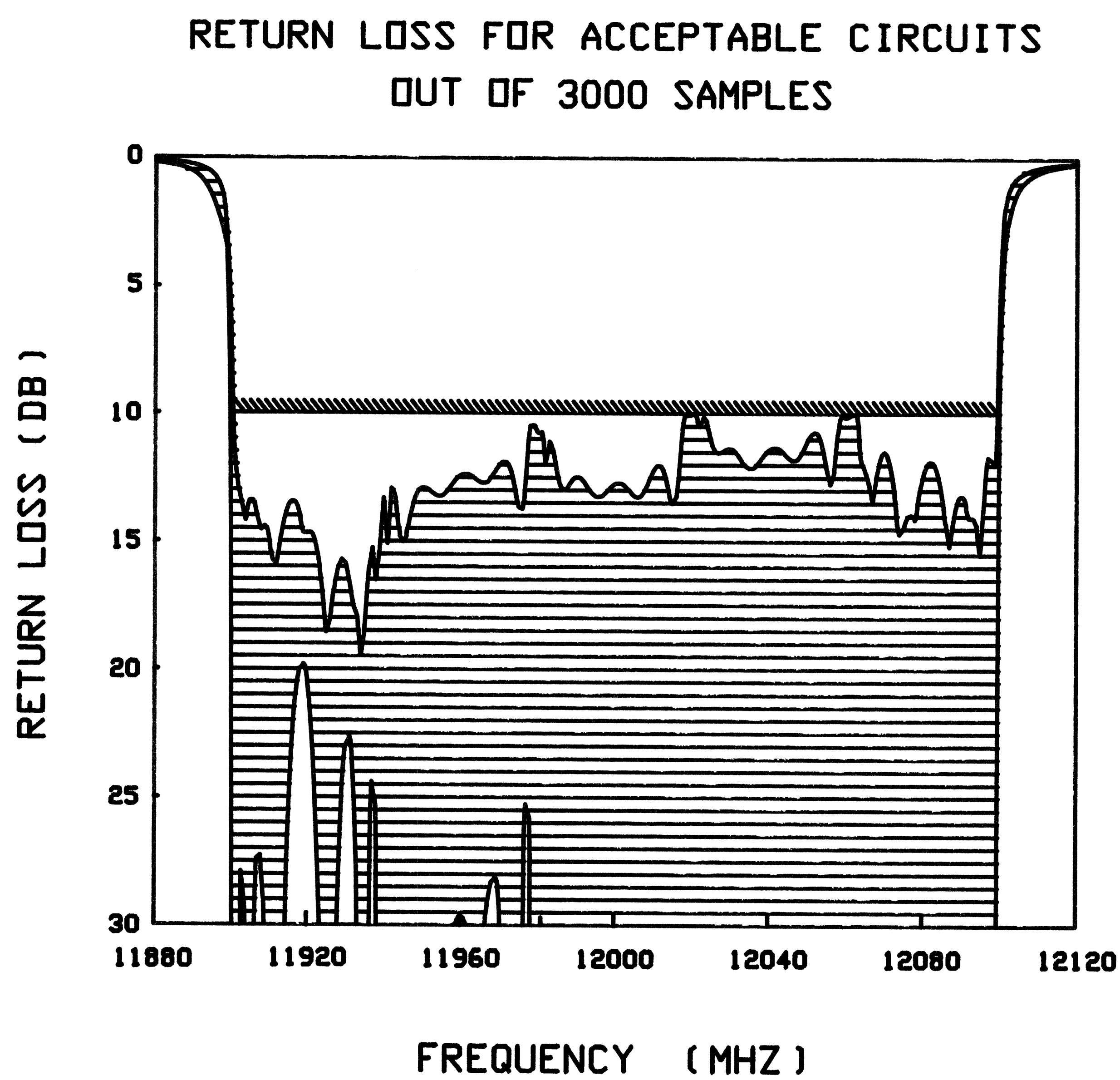
CPU time on CRAY X-MP/22 was 69.5 seconds

STATISTICAL DESIGN OF A 5-CHANNEL MULTIPLEXER USING QUADRATIC APPROXIMATION

		Phase 1	Phase 2	Phase 3	Phase 4
Initial Yield index	*	75.00%	(81.00%)	(84.33%)	(90.00%)
	**	56.33%	69.00%	69.33%	92.00%
Final Yield Index	*	81.00%	84.33%	90.00%	90.33%
	**	77.33%	77.33%	91.33%	94.00%
No. of Outcomes in Design		50	100	150	200
No. of Iterations		4	6	6	4
CPU Time (CRAY X-MP/22)		16.5s	17.6s	17.8s	17.6s

CPU times do not include yield index estimation based on actual simulation.
All yield indices are estimated from 300 outcomes.
* The yield index is estimated by actual simulation.
** The yield index is estimated by maximally flat approximation.


RETURN LOSS FOR 3000 SAMPLES
RETURN LOSS (DB)
0
5
10
15
20
25
30
11880
11920
11960
12000
12040
12080
12120
FREQUENCY (MHZ)


RETURN LOSS FOR ACCEPTABLE CIRCUITS
OUT OF 3000 SAMPLES
RETURN LOSS (DB)
0
5
10
15
20
25
30
11880
11920
11960
12000
12040
12080
12120
FREQUENCY (MHZ)

Conclusions

yield optimization is essential to reduce costs

yield optimization of large scale microwave circuits is feasible

we have presented a combined approach, using supercomputers, very efficient approximation techniques, and fast simulation

we have demonstrated yield optimization of a 5 channel multiplexer

no microwave circuit design of this type and on this scale has ever been reported

our approach is applicable to nonlinear circuit design