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A NEW FORMULATION FOR YIELD OPTIMIZATION

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Optimization Systems Associates Inc.

Dundas, Ontario, Canada

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A NEW FORMULATION FOR YIELD OPTIMIZATION

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Outline

introduction

new formulation for yield optimization

applications to microwave circuits:

a small-signal amplifier

a nonlinear FET frequency doubler

comparison with the one-sided ℓ_1 centering

summary

Introduction

yield optimization must be integral to the design process to

- improve first-pass design success
- reduce manufacturing cost

new and elegant formulation for yield optimization

- suitable for gradient-based optimization
- extends conventional discrete Monte Carlo estimate of yield to a continuous *yield probability function*

OSA's general-purpose CAD system OSA90/hope™ used to obtain the numerical results

Theoretical Yield

a function $H(\phi)$ is defined such that

$H(\phi) \leq 0$ if all specifications are satisfied

$H(\phi) > 0$ if some specifications are violated

where ϕ is the vector of circuit parameters subject to statistical variations

theoretical yield can be represented by the probability

$$P(H(\phi) \leq 0)$$

for a given distribution of statistical variables

$H(\phi)$ can be defined as a generalized least pth error function (*Bandler et al.*)

Monte Carlo Yield Estimation

a finite number of random outcomes are sampled according to the distribution of statistical variables

Monte Carlo yield is estimated by the percentage of acceptable outcomes

$$Y = \Sigma\, I(\phi^k) \,/\, N$$

where N is the total number of outcomes and the acceptance index $I(\phi)$ is defined as

$$I(\phi) = \begin{cases} 1 & \text{if } H(\phi) \leq 0 \\ 0 & \text{if } H(\phi) > 0 \end{cases}$$

not suitable for gradient-based optimization

discrete nature of $I(\phi)$

discontinuity at $H(\phi) = 0$

Yield in a Neighborhood of an Outcome

yield in a neighborhood Ω^k of the outcome ϕ^k is the probability

$$P^k = P(H(\phi) \leq 0 \mid \phi \in \Omega^k)$$

the overall yield can be estimated by

$$Y = \Sigma P^k / N$$

where N is the total number of outcomes involved in yield optimization

the classical Monte Carlo estimate becomes a special case when Ω^k consists of a single outcome

by extending Ω^k from a point to a *region* P^k becomes a continuous measure of the intersection of Ω^k and the acceptability region and the value of P^k varies continuously between 0 and 1

Using Monte Carlo Sample Mean

to evaluate P^k precisely we would need to know the distribution of $H(\phi)$ in Ω^k

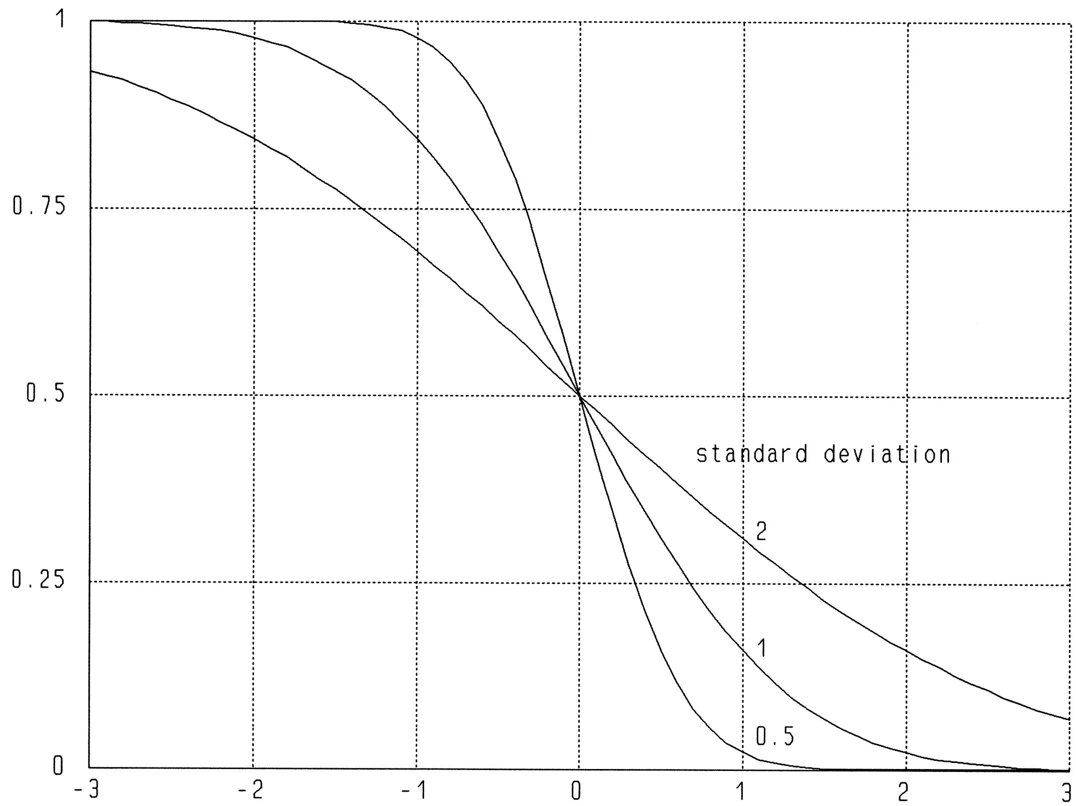
as an approximation the sample mean $\bar{H}(\phi)$ replaces $H(\phi)$

$$P^k \approx \bar{P}^k = P(\bar{H}(\phi) \leq 0 \mid \phi \in \Omega^k)$$

the frequency distribution of $\bar{H}(\phi)$ can be assumed normal and $\bar{P}^k$ is evaluated according to the normal distribution

the standard deviation of $\bar{H}(\phi)$ provides a measure of the circuit performance variation in Ω^k and affects $\bar{P}^k$ as a scaling factor

Yield Probability Function



yield probability function $\bar{P}^k$ versus the mean value of $\bar{H}(\phi)$ in Ω^k

Implementation of Yield Probability Function

$H(\phi)$ is chosen as a generalized least squares function

$H(\phi^k)$ is used directly as the sample mean in Ω^k

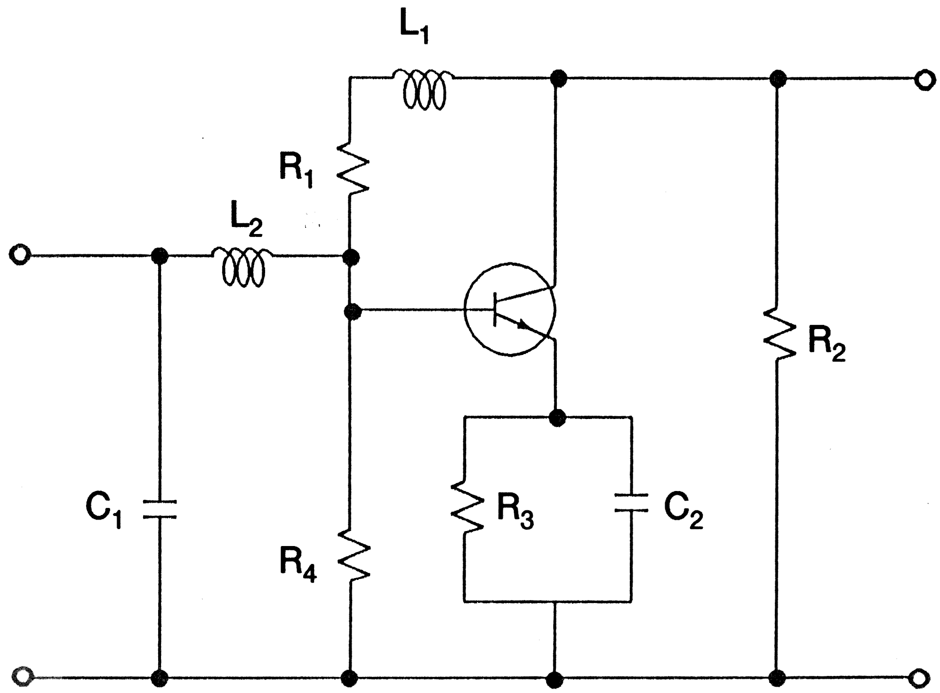
the objective function to be minimized is defined as

$$F = 1 - \Sigma \bar{P}^k / N$$

quasi-Newton optimizer based on Powell's algorithm is employed to minimize F

the new method has been tested in our general-purpose microwave CAD system OSA90/hope™

Small-Signal Amplifier



design specifications

input/output return loss ≤ −8dB
9dB ≤ gain ≤ 10dB

R_1, L_1, L_2 and C_2 are design variables

starting point for yield optimization obtained by minimax nominal design

Small-Signal Amplifier Parameters

Parameter	Nominal Design	After Yield Optimization	Tolerance or Standard Deviation
R_1 (Ω)	154.2	151.3	10% (normal)
R_2 (Ω)	300.0	300.0	-
R_3 (Ω)	5.0	5.0	5% (normal)
R_4 (Ω)	550.0	550.0	-
L_1 (nH)	23.39	25.34	-
L_2 (nH)	8.269	7.283	15% (uniform)
C_1 (pF)	4.0	4.0	5% (normal)
C_2 (pF)	15.09	10.55	-

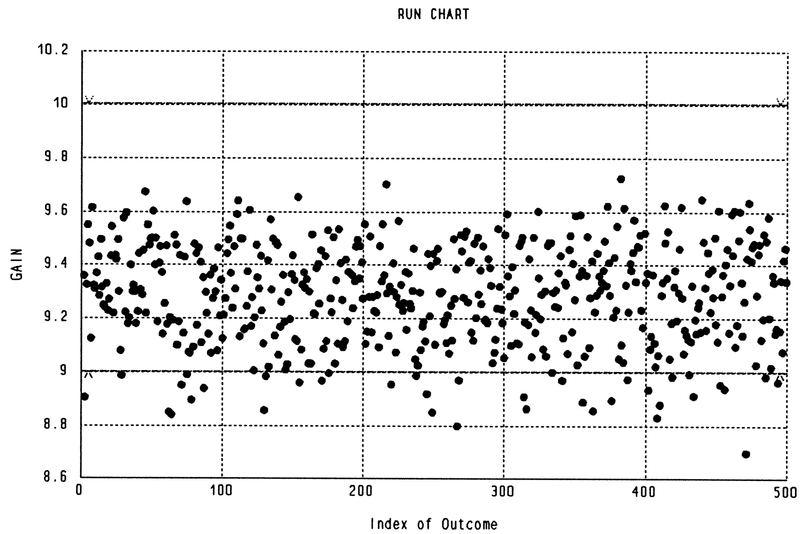
20 outcomes used in yield optimization

500 outcomes used for Monte Carlo estimation

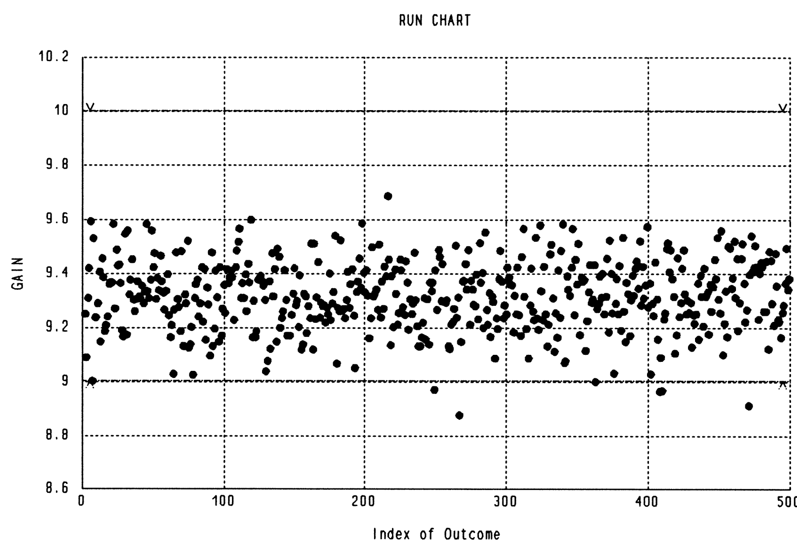
initial yield of 37% is increased to 50%

Run Charts of Small-Signal Amplifier Gain

before yield optimization

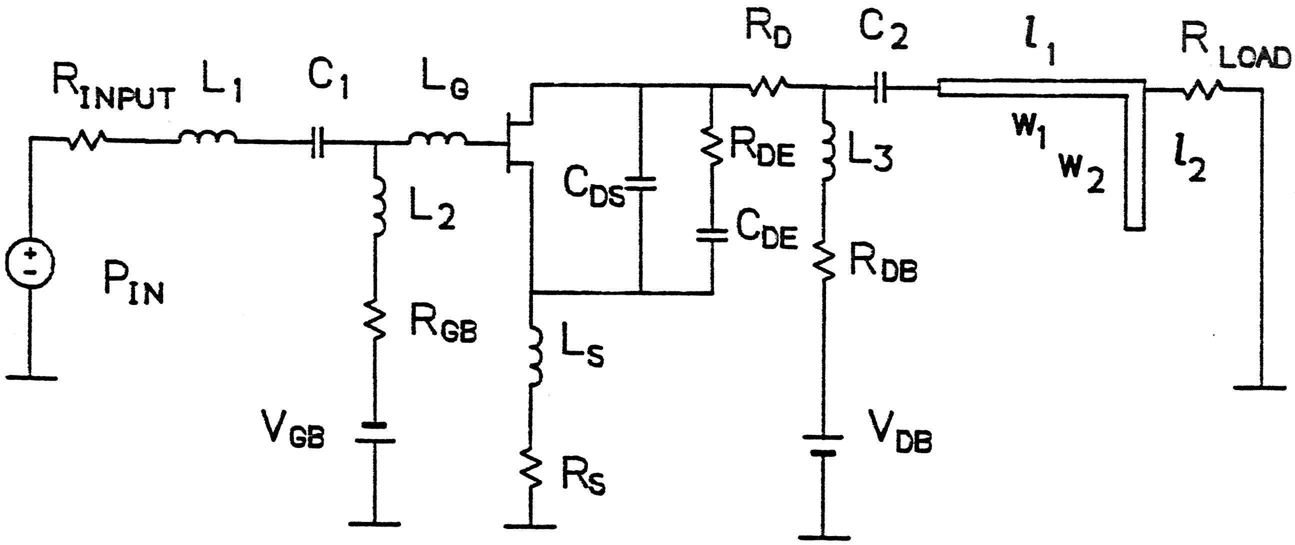


after yield optimization



amplifier gain at 1GHz for 500 Monte Carlo outcomes

Yield Optimization of a FET Frequency Doubler



design specifications

lower specification of 2.5 dB on conversion gain
lower specification of 19 dB on spectral purity

optimization variables

input inductance L_1
microstrip lengths l_1 and l_2

Yield Optimization of the FET Frequency Doubler (cont'd)

tolerances assumed

uniform distributions with 3% tolerances for 6 optimization variables

uniform distributions with 5% tolerances for 6 other elements

the large-signal FET model

modified Materka and Kacprzak model, normal distributions and correlations assumed for 22 parameters

mean values, standard deviations and correlations based on information given by *Purviance et al.* (1988)

FET Frequency Doubler Parameters

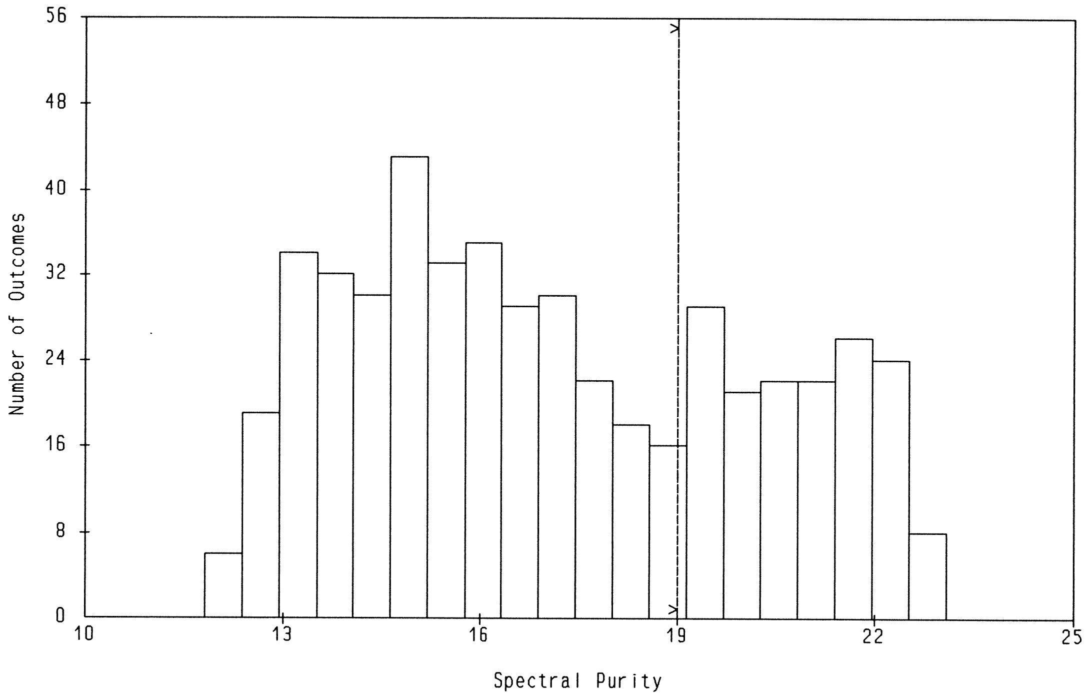
Optimization Variable	Before Yield Optimization	After Yield Optimization
L_1 (nH)	5.462	5.350
l_1 (mm)	1.483	1.655
l_2 (mm)	5.771	5.915

50 outcomes used in yield optimization

500 outcomes used for Monte Carlo estimation

initial yield of 31% is increased to 74%

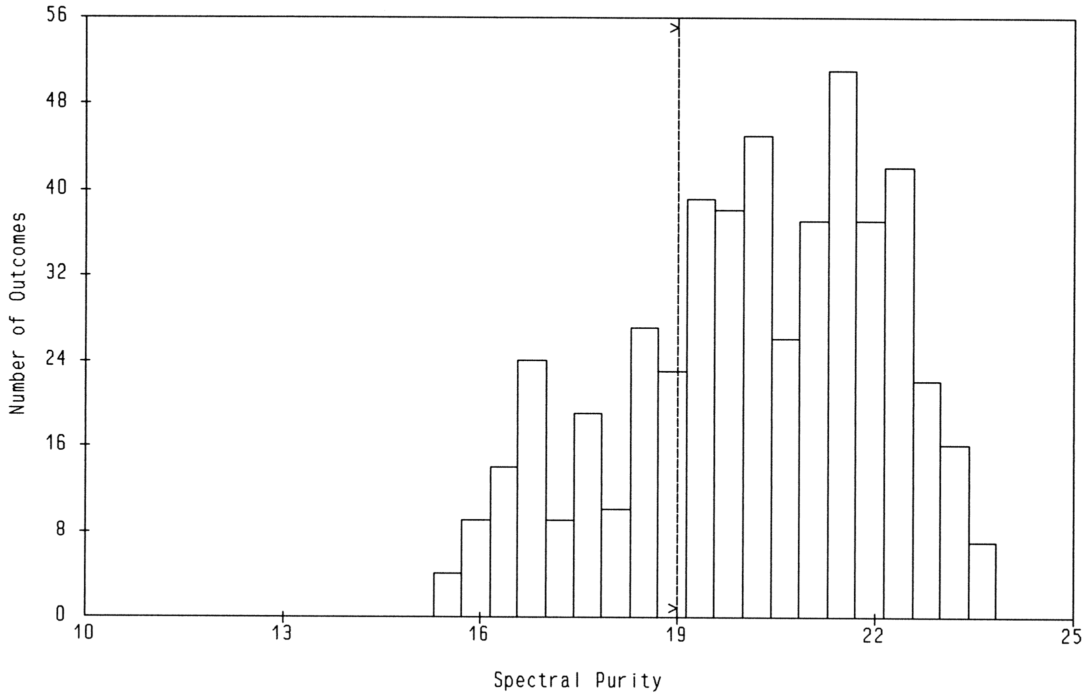
Frequency Doubler before Yield Optimization



yield estimated by Monte Carlo analysis using 500 outcomes

initial yield of 31%

Frequency Doubler after Yield Optimization



yield estimated by Monte Carlo analysis using 500 outcomes

final yield of 74%

Comparison with One-Sided ℓ_1 Centering

small-signal amplifier

efficiency: similar

solution: better - the one-sided ℓ_1 algorithm required two phases of optimization and did not reach the same yield

frequency doubler

efficiency: similar

solution: similar

clear advantages: no restart of optimization is needed

the predicted yield is more precise

a better solution can be achieved without increasing the number of outcomes in optimization

Summary

methods which attempt to optimize the theoretical yield as an integral function are usually too complicated for practical implementation in circuit CAD programs

typically, circuit CAD programs estimate yield by Monte Carlo simulation

yield estimated by Monte Carlo simulation is a discrete function and cannot be directly optimized by gradient-based methods

the new formulation replaces the discrete acceptance index with a continuous *yield probability function* suitable for gradient-based optimization