STATISTICAL DESIGN/YIELD OPTIMIZATION OF NONLINEAR MICROWAVE CIRCUITS

OSA-90-OS-7-V

September 28, 1990

STATISTICAL DESIGN/YIELD OPTIMIZATION

OF NONLINEAR MICROWAVE CIRCUITS

John W. Bandler, Radoslaw M. Biernacki,
Shao Hua Chen and Qi-jun Zhang

Optimization Systems Associates Inc.
Dundas, Ontario, Canada

Introduction

advances in GaAs MMIC technology demand the next generation CAE software

efficient algorithms for large-scale optimization of nonlinear circuits are crucial

cost reduction is a primary goal

yield-driven optimization methodology is essential

statistical representation of physical, process and geometrical parameters must be integral to CAE

Increasing Sophistication of Design Methodology

deterministic

- performance-driven design
- fixed tolerance worst-case design
- variable tolerance worst-case design

statistical

- fixed tolerance yield-driven design
- correlated tolerances
- variable tolerance cost-driven design

Nonlinear Circuit Simulation

most analog microwave circuits operate under steady-state conditions

harmonic balance has become the major simulation tool for nonlinear circuits

popular harmonic balance software:

typical algorithms inhibit fast optimization

yield-driven design may be prohibitively CPU intensive

inaccurate, slow sensitivity/gradient evaluation

OSA's research and development successfully addresses these issues

Yield Optimization

high yield is essential for large volume production of MMICs

useful CAE must account for manufacturing tolerances, model uncertainties, variations of process parameters, environmental uncertainties, etc.

yield optimization is computationally intensive

- optimization is iterative

- each iteration requires simulation of many statistically related circuits

- simulation of each nonlinear circuit is iterative

yield-driven design demands powerful, robust, fast optimizers and effective statistical representation of devices and subcircuits

Manufacturing Yield

manufacturing yield is simply the ratio

$$Y = N_{pass}/N_t$$

where

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

Yield Optimization Problem Formulation

centering problem with fixed tolerances

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

where $\mathbf{x}^0$ denotes the nominal design parameter vector

Pioneering Work on Statistical Design

circuit design exploiting parameter tolerances
(Karafin 1971, Pinel and Roberts 1972)

worst-case design with optimized tolerances
(Bandler 1972-1974)

optimal centering, tolerancing and tuning
(Bandler 1976)

integrated approach to microwave design with parameter tolerances, model uncertainties, mismatches and reference plane uncertainties
(Bandler 1976)

Major Approaches to Statistical Design

simplicial approximation (Director and Hachtel 1977)

updated approximations and cuts (Bandler and Abdel-Malek 1978)

outer-approximation (Polak and Sangiovanni-Vincentelli 1979)

arbitrary and discrete distributions (Abdel-Malek and Bandler 1980)

statistical exploration (Soin and Spence 1980)

stochastic approximation with Monte Carlo based optimization (Styblinski and Ruszczynski 1980)

parametric sampling (Singhal and Pinel 1981)

Process/Geometrical Approach to Statistical Design

developed for VLSI statistical design with process/geometrical parameters

identification of significant parameters in MOS VLSI (Yang, Hocevar, Cox, Machala and Chatterjee 1986)

software tools for IC yield optimization with respect to manufacturing process parameters (e.g., diffusion time and temperature) and layout mask dimensions (Styblinski and Opalski 1986)

worst-case analysis with respect to a set of statistically independent process disturbances (Nassif, Strojwas and Director 1986)

Recent Explorations in Statistical Design

yield gradient estimation for truncated probability density functions (Styblinski 1986)

theoretical relations between parametric and catastrophic yield (Maly, Strojwas and Director 1986)

profit-based statistical design (Riley and Sangiovanni-Vincentelli 1986)

maximum income approach (Opalski and Styblinski 1986)

regression model w.r.t. critical system parameters (Yu, Kang, Hajj and Trick 1987)

gradient based optimization exploiting transient sensitivity (Hocevar, Cox and Yang 1988)

Recent OSA Contributions to Statistical Design

world's first commercial, microwave oriented yield-driven design (OSA for Super-Compact 1987)

a novel one-sided ℓ_1 formulation of design centering (Bandler and Chen 1988)

efficient quadratic modeling and large scale yield optimization (Bandler, Biernacki, Chen, Renault, Song and Zhang 1988)

yield optimization of nonlinear microwave circuits (Bandler, Zhang, Song and Biernacki 1989)

FAST and IGAT gradient based yield optimization (Bandler, Zhang, Song and Biernacki 1990)

Typical statistical distributions

Yield interpretation in the parameter space

Envelope diagram for the magnitude of S_{21}
for centered design of 11 element LC filter

Yield Optimization of Nonlinear Microwave Circuits

pioneered by OSA

comprehensive treatment of yield optimization of nonlinear microwave circuits with statistically characterized devices

one-sided $_1$ circuit centering with gradient approximations

efficient harmonic balance simulation with exact Jacobians

statistical representation of nonlinear devices:

- multidimensional statistical distributions of the intrinsic device and parasitic parameters

yield enhanced from 25% to 61% for a frequency doubler design having 34 statistically toleranced parameters

Yield Optimization of the 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

bias voltages V_{GB} and V_{DB}

driving power level P_{IN}

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

tolerances assumed

uniform distributions with 3% tolerances for 6 optimization variables

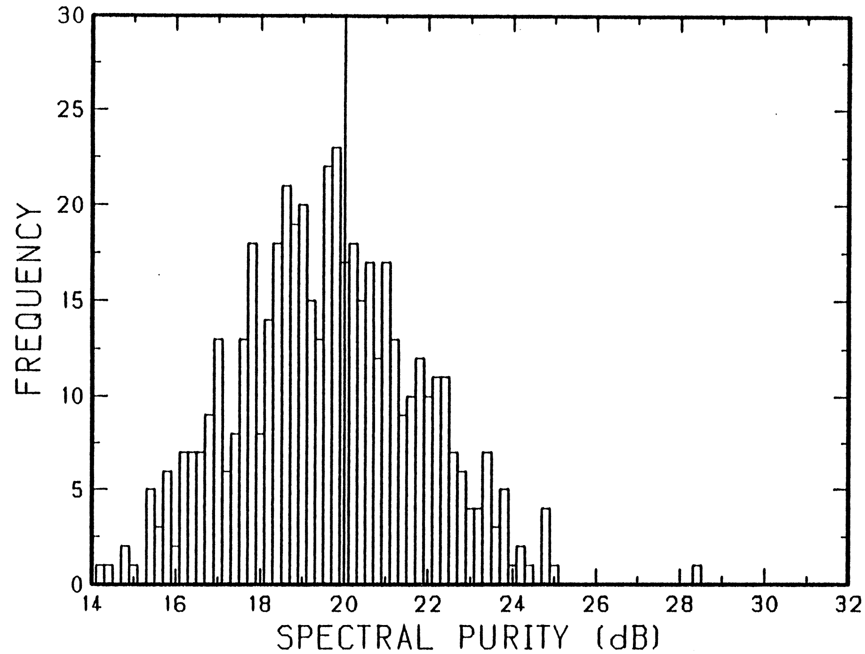
uniform distributions with 5% tolerances for 6 other elements

the large-signal FET model

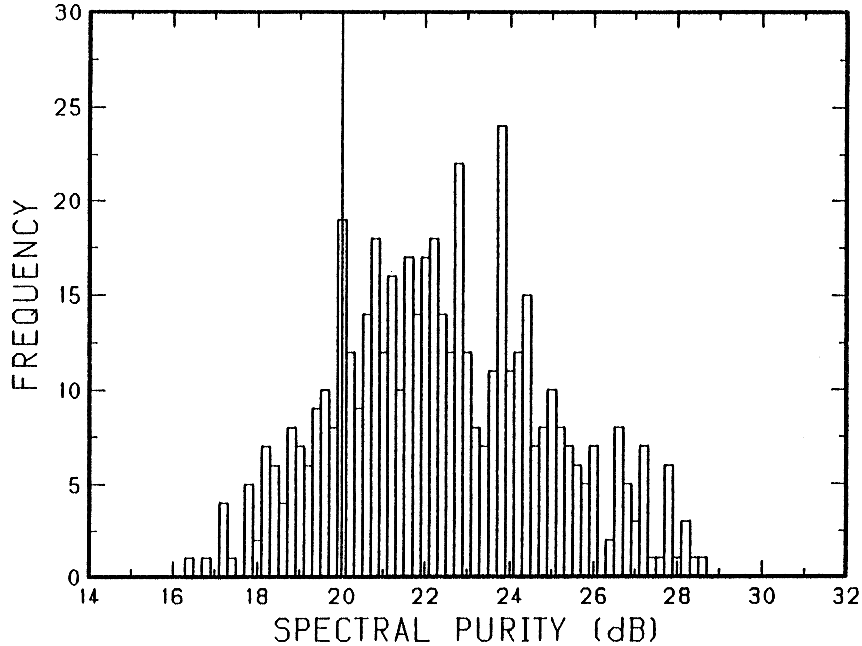
modified Materka and Kacprzak model, normal distributions and correlations assumed for 22 parameters

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

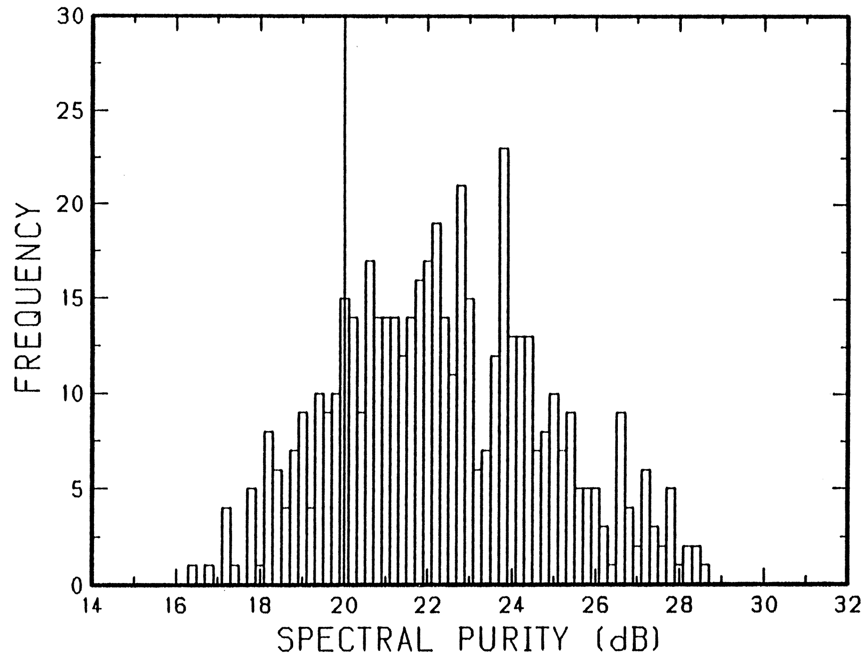
FET frequency doubler



Histogram of the spectral purity for 500 frequency doubler outcomes - before optimization



Histogram of the spectral purity for 500 frequency doubler outcomes - after optimization using IGAT



Histogram of the spectral purity for 500 frequency doubler outcomes - after optimization using FAST

Efficient Harmonic Balance Optimization

traditional perturbation (PAST): inaccurate, time-consuming Jacobian and gradient calculations

Kundert and Sangiovanni-Vincentelli and *Rizzoli et al.* suggested exact Jacobian approach

Rizzoli et al. combined both optimization and solving nonlinear equations - disadvantage - incompatibility with established yield optimization formulations

Bandler, Zhang and Biernacki (1988) developed the exact adjoint sensitivity technique (EAST) for harmonic balance

Bandler, Zhang and Biernacki (1989) developed the feasible adjoint sensitivity technique (FAST™) for harmonic balance

FAST™

a breakthrough in circuit theory

an expedient implementation of the EAST concept

unmatched speed and accuracy over perturbation

implementable in general purpose CAE architectures

combines efficiency of exact adjoint sensitivities with simplicity of conventional perturbation

concept applicable to Jacobian evaluation for fast harmonic balance simulation

the basis of the world's most powerful harmonic balance optimizer (featured in HarPE)

Statistical Modeling

variations of process and geometrical parameters in device manufacturing result in complex statistical behaviour of devices

complicated distributions and correlations of device responses or equivalent model parameters

statistical modeling provides tools to generate device random outcome responses that reflect the actual distribution of the responses

growing demand for reliable statistical models

needed for accurate yield estimation

needed in yield optimization

Increasing Complexity of Device Statistics

statistically independent variables

multidimensional distributions - correlated variables

measurement errors superimposed

multi-level distributions

Equivalent Circuit Statistical Models

equivalent model parameters are needed as the input data to popular microwave CAD software

model parameters are strongly correlated

multidimensional distributions

an approach based on measurements of the S-parameters for a sample of finished devices - *Purviance, Criss and Monteith* (1988)

Physics Based Models

models based on semiconductor device physics equations

two approaches to solving device equations

analytical models where device equations are analytically simplified or solved under certain assumptions (e.g., quasi-static assumption)

numerical models where numerical techniques are used to directly solve device equations

analytical models evaluate faster than numerical ones

Advantages of Physics Based Models

true device design: optimization to adjust physical, geometrical and process variables before device fabrication

overall circuit performance reflects geometrical dimensions, material parameters, doping profile, channel thickness, etc.

essential for meaningful statistical analysis and yield optimization

Parameter Extraction in Statistical Modeling

each set of measurements corresponding to one device outcome is converted to the corresponding parameters of the model

parameter extraction procedure leading to a reliable and unique solution must be applied

this step provides a sample of models

Statistical Estimation

the statistics of the model parameters are examined

estimates of the means, standard deviations and correlation coefficients are calculated

Introduction to HarPE™

device-oriented nonlinear/linear simulation, characterization and optimization

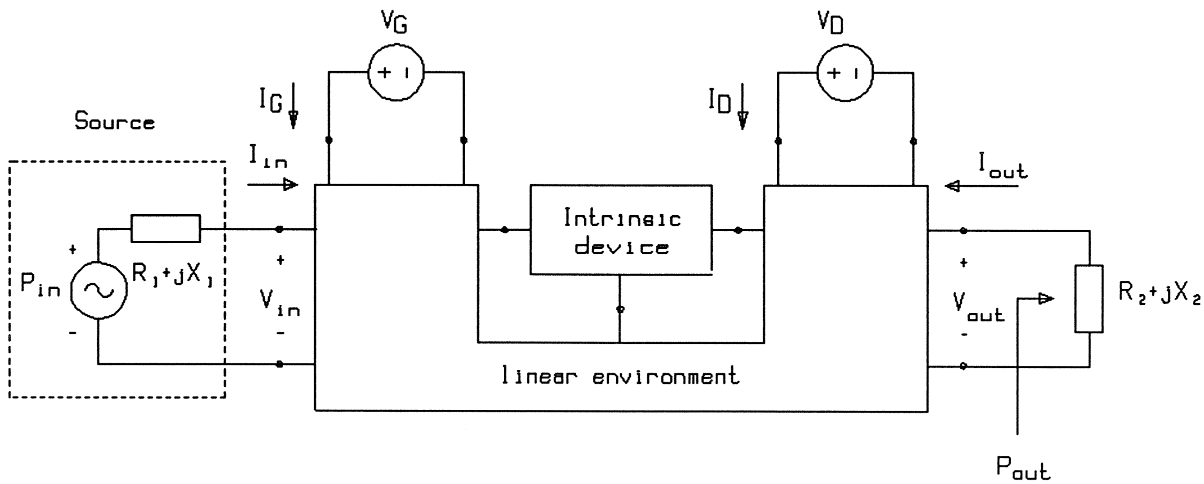
the world's first system for exploitation of harmonic data for complete and accurate device characterization

nonlinear adjoint sensitivity analysis for gradient optimization of nonlinear circuits (FAST™)

provides individualized models usable either in HarPE or in other CAD software

writing in-house modeling programs is unnecessary

statistical modeling from multi-device measurements, and Monte Carlo analysis



Schematic representation of a single-device circuit

HarPE Implementation of Physics Based Model

an analytical large-signal model based on the work of Khatibzadeh and Trew (1988)

model parameters include gate length, width, channel thickness, doping density, critical electric field, saturation velocity, built-in potential, low-field mobility, high-field diffusion coefficient

applicable to both small- and large-signal analysis

dynamically integrated into harmonic balance simulation

velocity - electric field curve is optimizable

Optimization of Physics Based Model

HarPE can optimize all parameters in the physics based model

parameter extraction allows determination of model parameters which can neither be accurately measured nor analytically derived, e.g., doping density, velocity - electric field curve

in parameter extraction excellent agreement was achieved using S-parameter measurements at 3 bias points

in design optimization of an amplifier an improvement of 12% power added efficiency was achieved using the physics based model parameters

Circuit Optimization with Physical Models

three stage power amplifier circuit

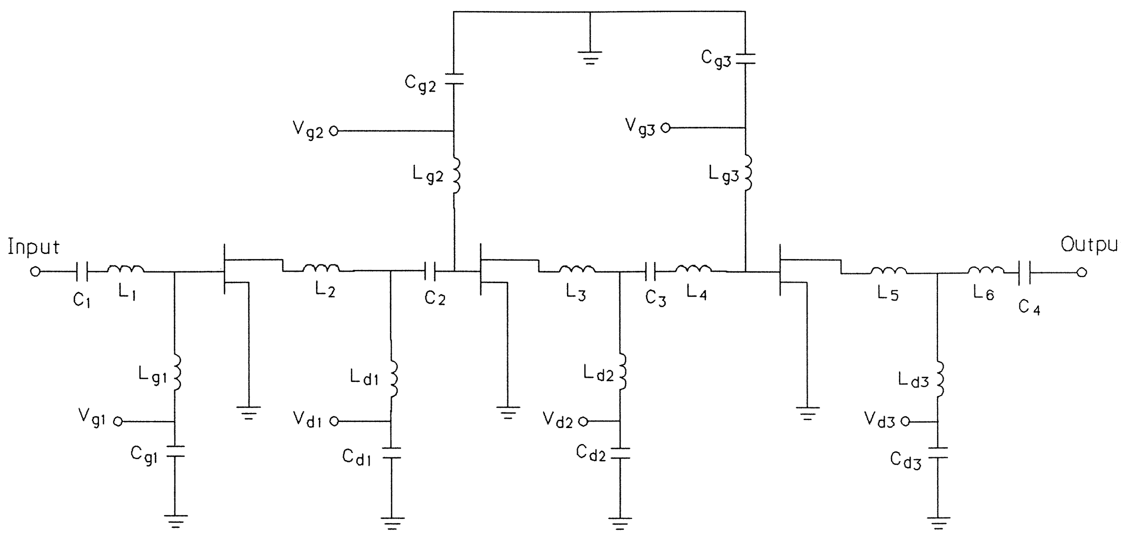
specifications are imposed on gain and power added efficiency

variables in the linear subcircuit

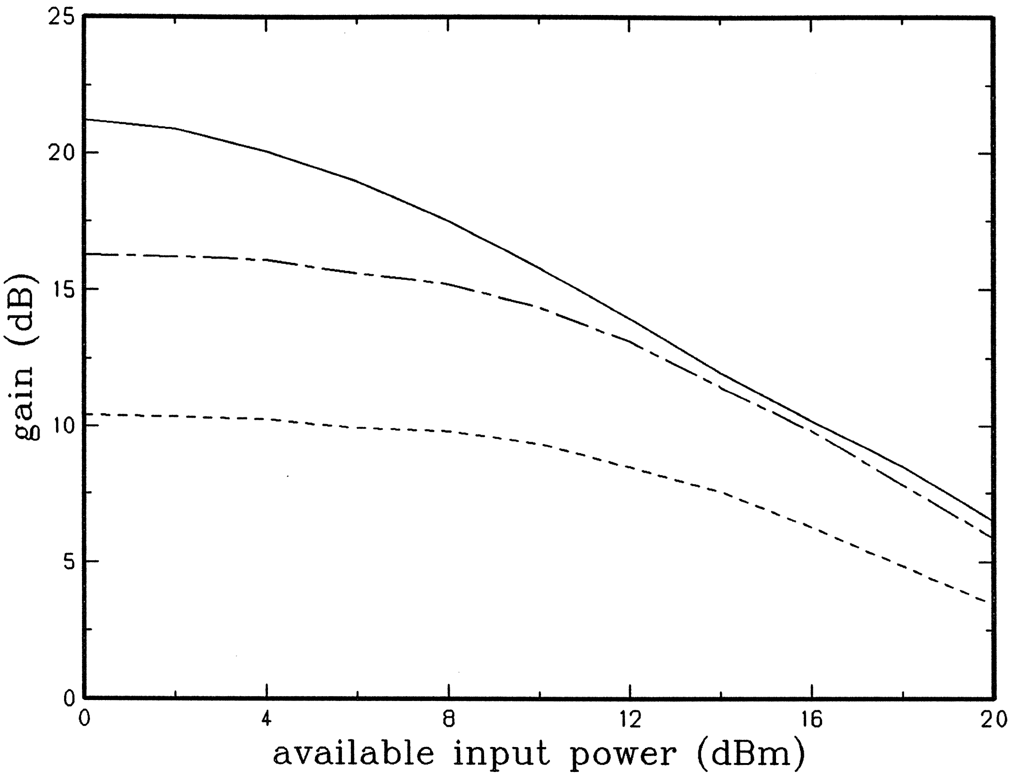
C_1, C_2, C_3, C_4, L_1, L_2, L_3, L_4, L_5, L_6

variables in the FET

L, a, W, N_d

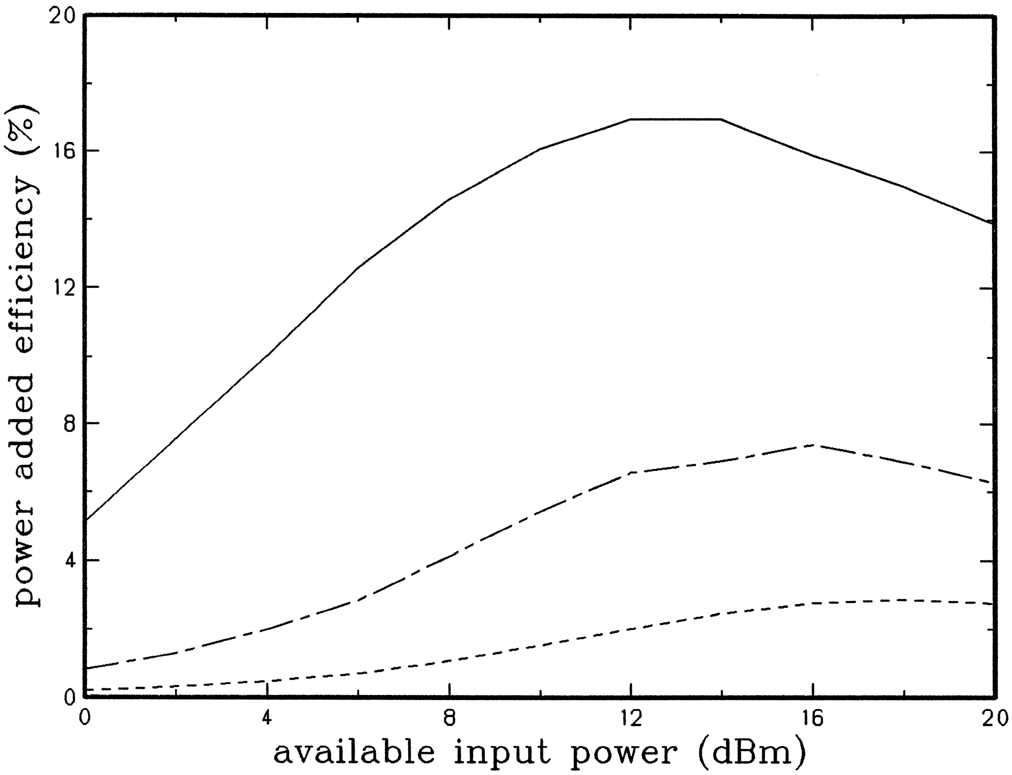


Three stage power amplifier
(Kermarrec and Rumelhard 1988)



Gain versus input power of the amplifier

-------	before optimization
— - —	after optimizing only linear elements
——	after optimizing both linear elements and FET parameters



Power added efficiency versus input power of the amplifier

------- before optimization
— - — after optimizing only linear elements
—— after optimizing both linear elements and FET parameters

Statistical Modeling

histogram of the small-signal transconductance

a small-signal equivalent circuit FET statistical model

model extracted from S-parameter measurements of 100 devices

Correlations in Statistical Models

correlation between the FET gate length and the channel delay time

a small-signal statistical equivalent circuit model extracted from 100 sets of synthetic S-parameter data generated by the physics-based model with variations on the gate length, width, etc.

Statistical Response

Monte Carlo analysis of an LC filter

200 outcomes

before yield optimization

Yield Optimization (coming soon)

statistical response of an LC filter after yield optimization

Monte Carlo analysis with 200 outcomes

yield increases from 54.5% to 78.5%

Statistical Response

Monte Carlo analysis of a FET frequency doubler

run chart of spectrum purity for 500 outcomes

before yield optimization

Yield Optimization

run chart of spectrum purity of the FET frequency doubler after yield optimization

Monte Carlo analysis with 500 outcomes

yield increases from 32.4% to 78.6%