STATISTICAL MODELING

AND YIELD OPTIMIZATION FOR (M)MICs

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STATISTICAL MODELING AND YIELD OPTIMIZATION FOR (M)MICs

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Summary

Cost-effective, yield-driven design and production of nonlinear, large-scale circuits such as (M)MICs, integrating statistical variations with physical/process/geometrical parameters are well beyond the capabilities of microwave CAE products engineered in the pre-MMIC period. OSA has recognized these limitations and is focusing its R&D on powerful, novel techniques for intensive number crunching complemented by flexible, state-of-the-art software architectures dedicated to microwave integrated circuits. This talk summarizes current advances.

Effective yield optimization requires meaningful statistical representation of devices and subcircuits. The statistics arise from unknown mismatches, environmental fluctuations, random variations of basic physical, geometrical and process parameters, etc. Two important points of view, namely, the equivalent circuit based approaches and the physical/geometrical/process based approaches to statistical modeling are discussed.

Practical properties of ℓ_1, ℓ_2, least pth and minimax formulations are being exploited by OSA. OSA pioneered yield optimization of nonlinear microwave circuits. OSA pioneered a unified theory for frequency domain simulation and sensitivity analysis of linear and nonlinear circuits, resulting in the powerful computational concept EAST (exact adjoint sensitivity analysis). An expedient implementation combining the efficiency of EAST with the simplicity of traditional perturbation has realized the breakthrough FAST™ (feasible adjoint sensitivity technique). FAST™, particularly suitable for implementation in general purpose microwave CAE programs, is a key to the power of OSA's HarPE™. The foregoing concepts and their relevance to modern (M)MIC/CAE are explained. OSA's various claims are illustrated and justified.

HarPE™ features the world's most powerful harmonic balance optimizer. Currently, HarPE™ solves device-oriented simulation, characterization and design optimization problems. HarPE's user-definable model building capability has effortlessly facilitated several state-of-the-art models, including a recent research model by Plessey. For future release, OSA has incorporated the physics based model of Khatibzadeh and Trew. OSA is also developing extensive statistical capabilities into HarPE™. Further evolutionary directions for HarPE™ will be mentioned.

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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

Milestones in Yield Optimization

Bandler begins formal exploitation of parameter tolerances in circuit optimization in 1969-70

cost-driven worst-case design with optimized tolerances (1972)

optimal centering and tolerance assignment integrated with tuning at the design stage (1974)

integrated approach to microwave design with parameter tolerances, model uncertainties, mismatches and reference plane uncertainties (1975)

yield-driven optimization using general statistical distributions (1976)

optimal tuning and alignment at the production stage (1980)

Milestones in Yield Optimization (cont'd)

foundation of multicircuit ℓ_1 yield optimization (1987)

world's first yield-driven design features introduced into commercial CAD (Super-Compact 1987)

yield optimization of large-scale microwave circuits (1988)

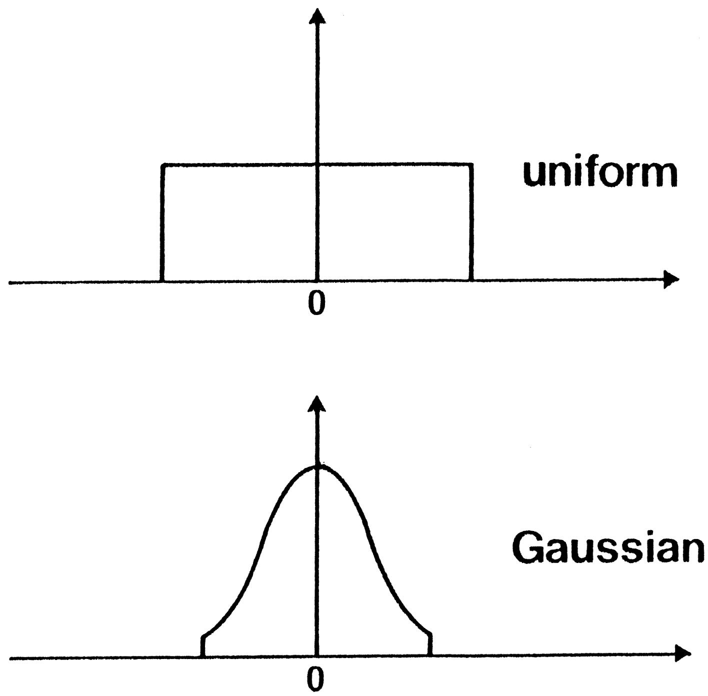
yield optimization of nonlinear circuits within the harmonic balance simulation environment (1989)

IGAT (integrated gradient approximation technique) based yield optimization of nonlinear circuits (1990)

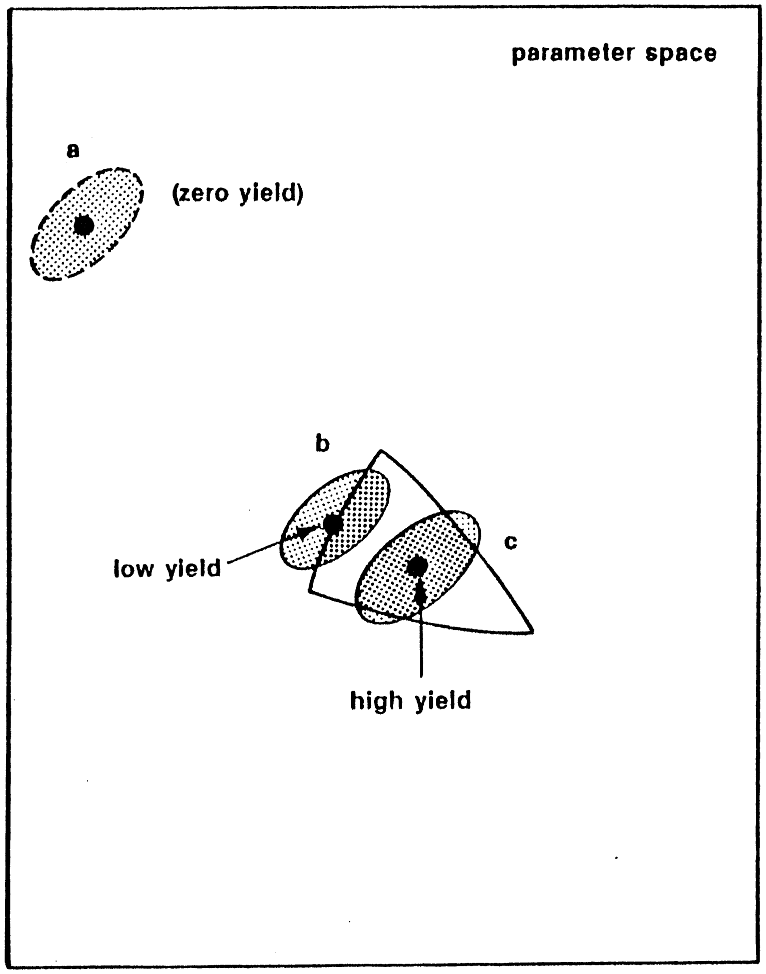
FAST™ (feasible adjoint sensitivity technique) gradient based yield optimization of nonlinear circuits (1990)

yield-driven design with dynamically integrated physics based device models (1990)

statistical modeling for HarPE™ (1990+)



Typical statistical distributions



Yield interpretation in the parameter space

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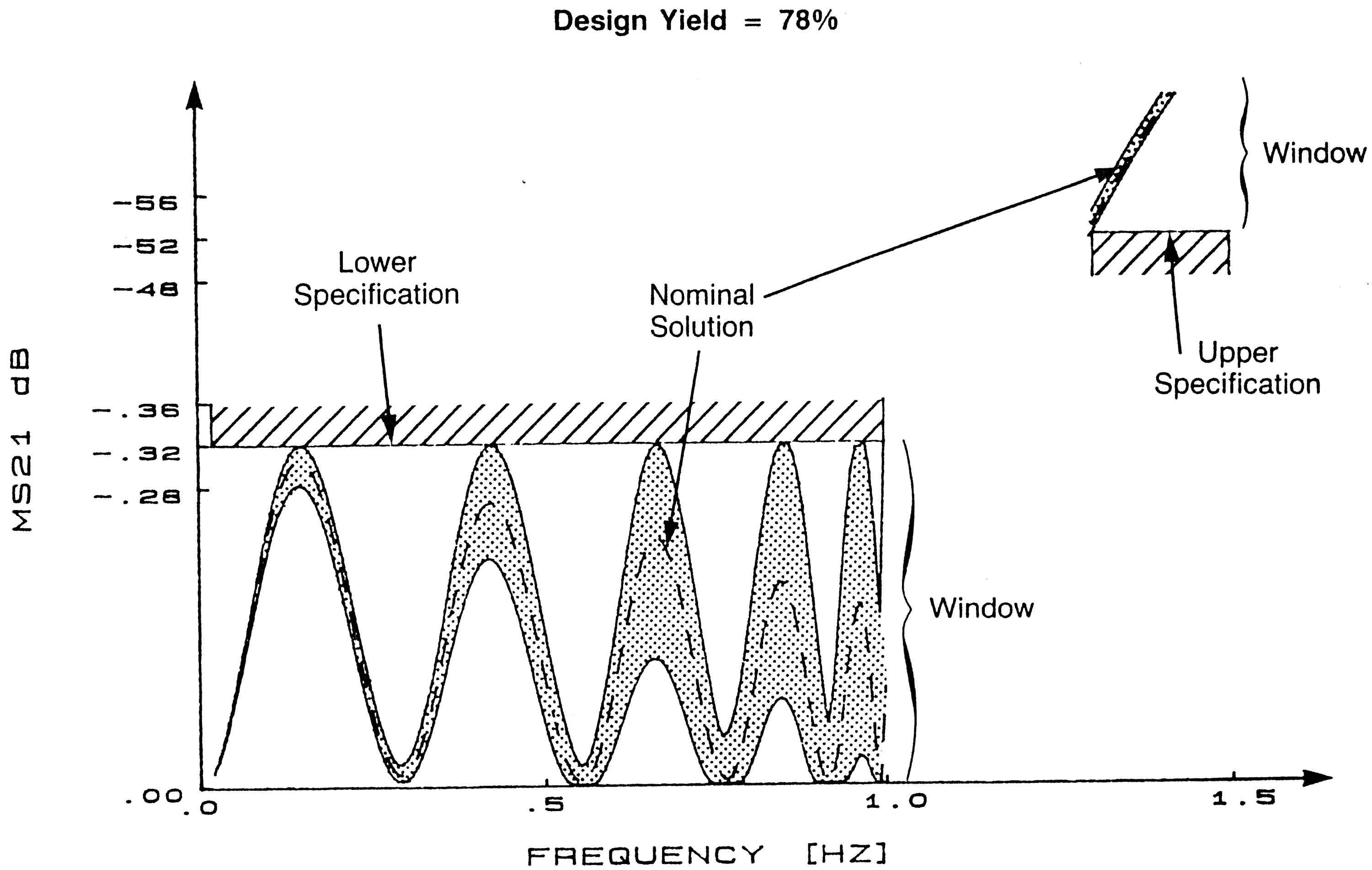


Envelope diagram for the magnitude of S_{21} for centered design of 11 element LC filter

Yield Optimization of Nonlinear Microwave Circuits

pioneered by OSA

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

one-sided ℓ_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

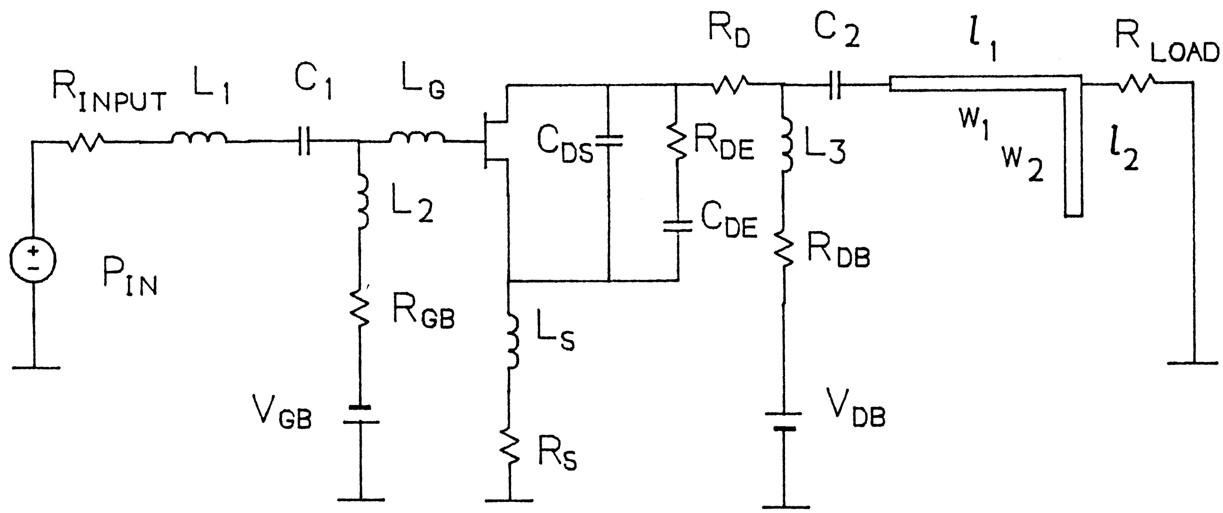
uniform distributions with 3% tolerances for 6 optimization variables

uniform distributions with 5% tolerances for 6 other elements

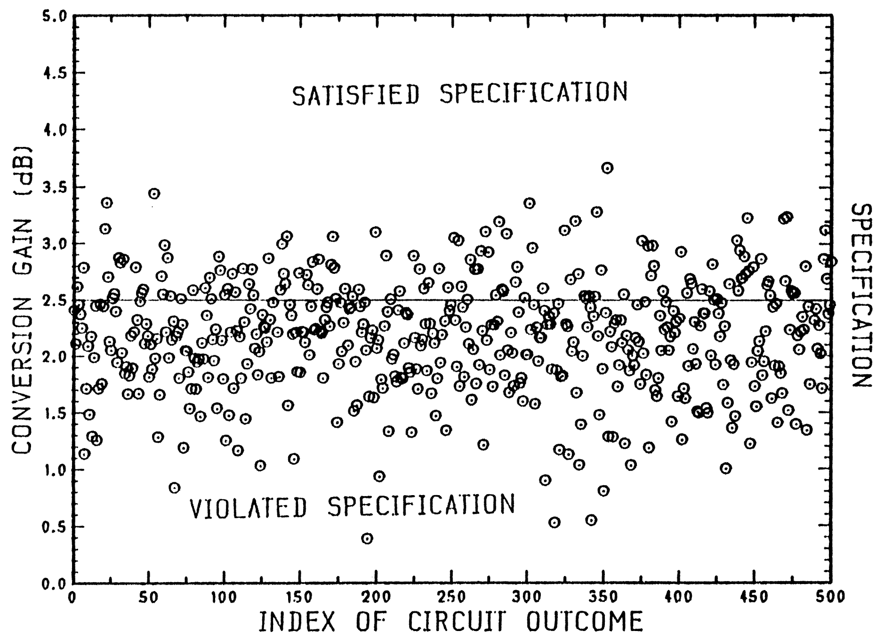
the large-signal FET model

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

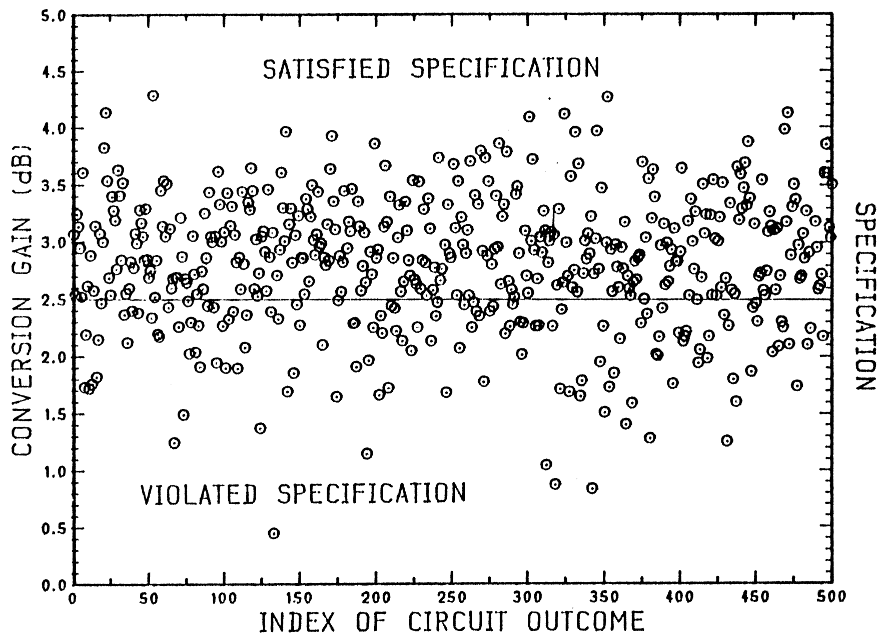
mean values, standard deviations and correlations based on information given by *Purviance et al.* (1988)



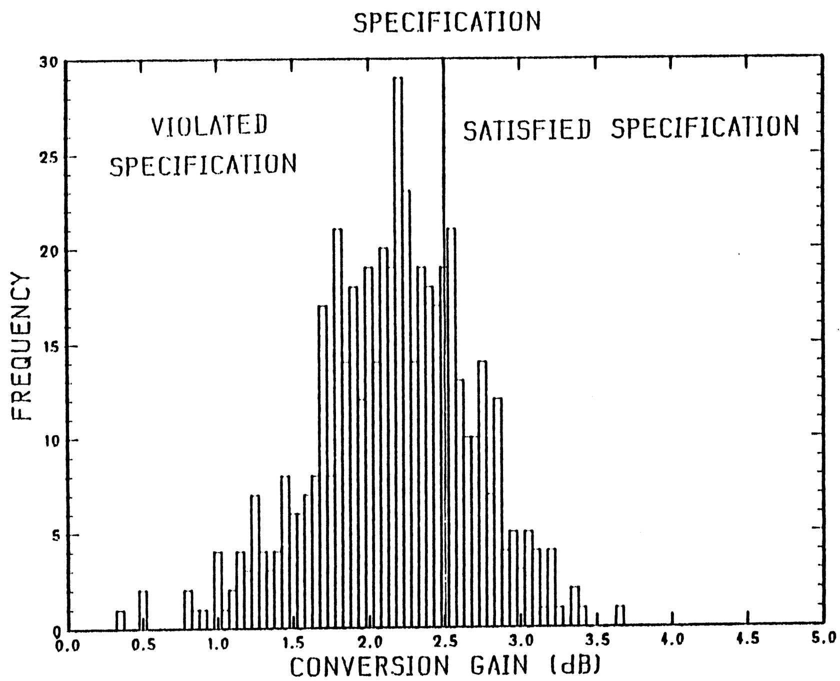
FET frequency doubler



Run chart of the conversion gain for
the frequency doubler - before optimization



Run chart of the conversion gain for
the frequency doubler - after optimization



Histogram of the conversion gains for 500 frequency doubler outcomes - before optimization

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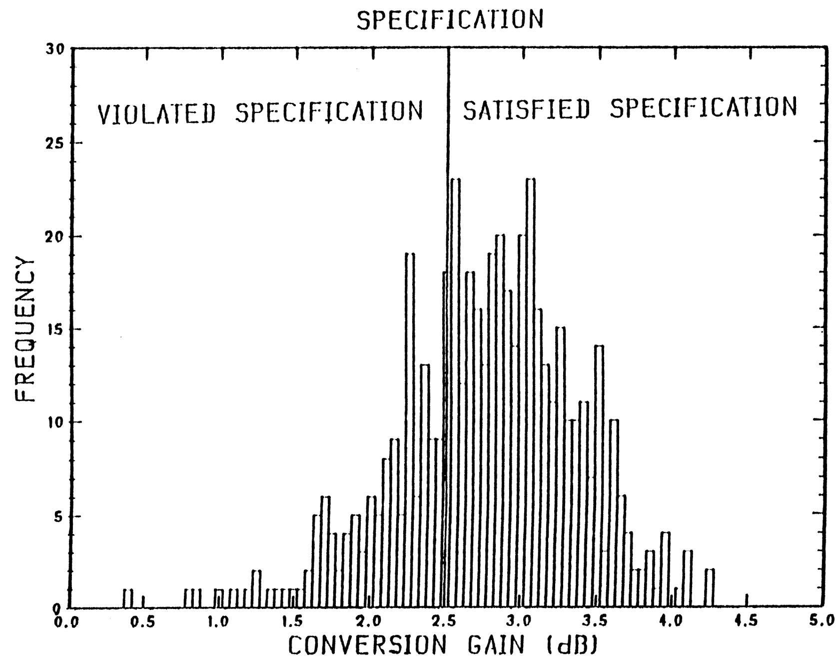


Histogram of the conversion gains for 500 frequency doubler outcomes - after optimization

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^{TM}) 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

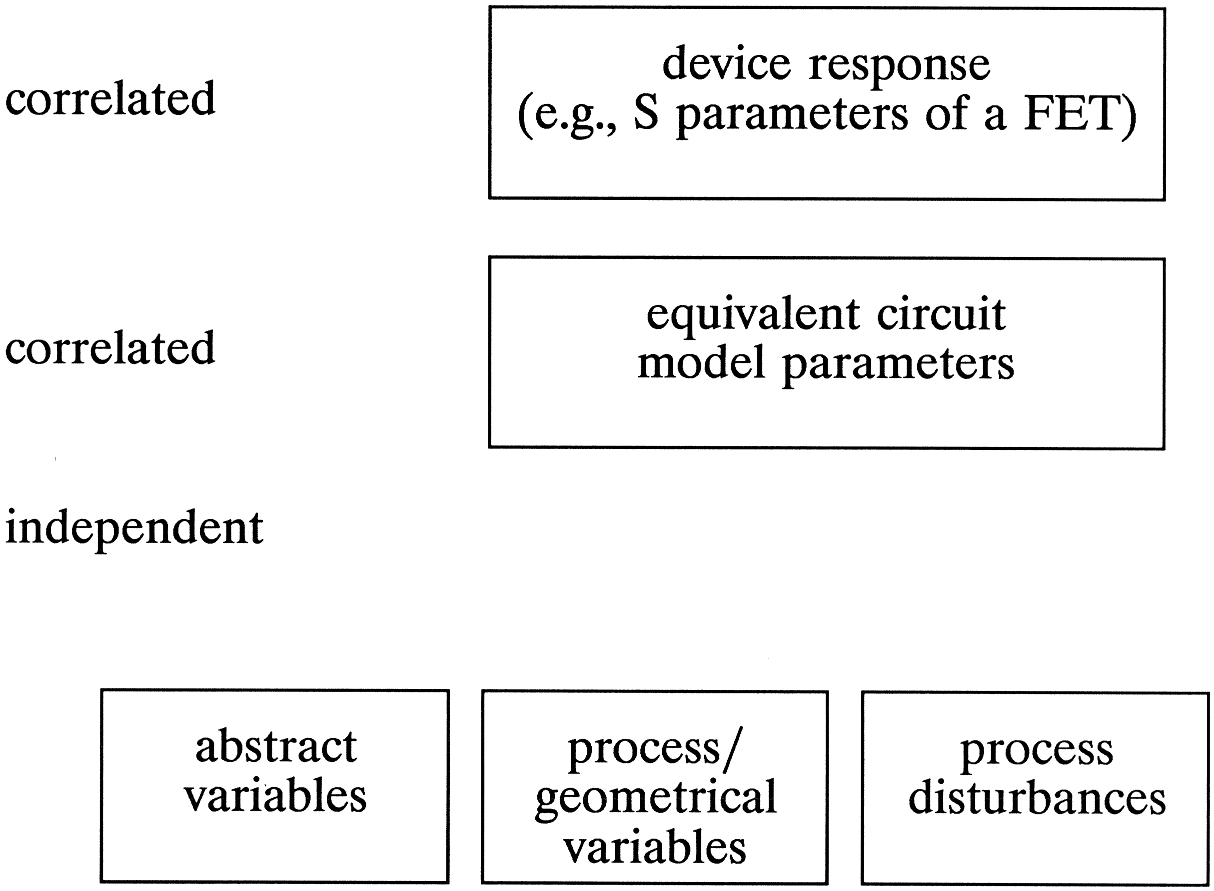
statistically independent variables

multidimensional distributions - correlated variables

measurement errors superimposed

multi-level distributions

Hierarchical Statistical Modeling



Hierarchical Treatment of Device Statistics

device statistical model includes the overall effect of device statistics, chip statistics and wafer statistics

inter-device correlations originate from chip and wafer statistics

inter-chip correlations originate from wafer statistics

device statistics

chip statistics

wafer statistics

Major Approaches to Statistical Modeling

equivalent circuit based approach

- models are generally available
- distribution functions may not be simple, for example bimodal
- parameter correlations may be complicated and meaningless
- number of statistical variables may be large

physics/geometrical/process based approach

- small number of statistically independent variables
- normal distribution generally applicable
- physical/empirical formulas required

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

Multidimensional Normal Distribution

mean values, standard deviations and correlation coefficients are sufficient to describe pdf

easy to generate outcomes

assumption of multidimensional normal distribution is often made in practice for simplicity

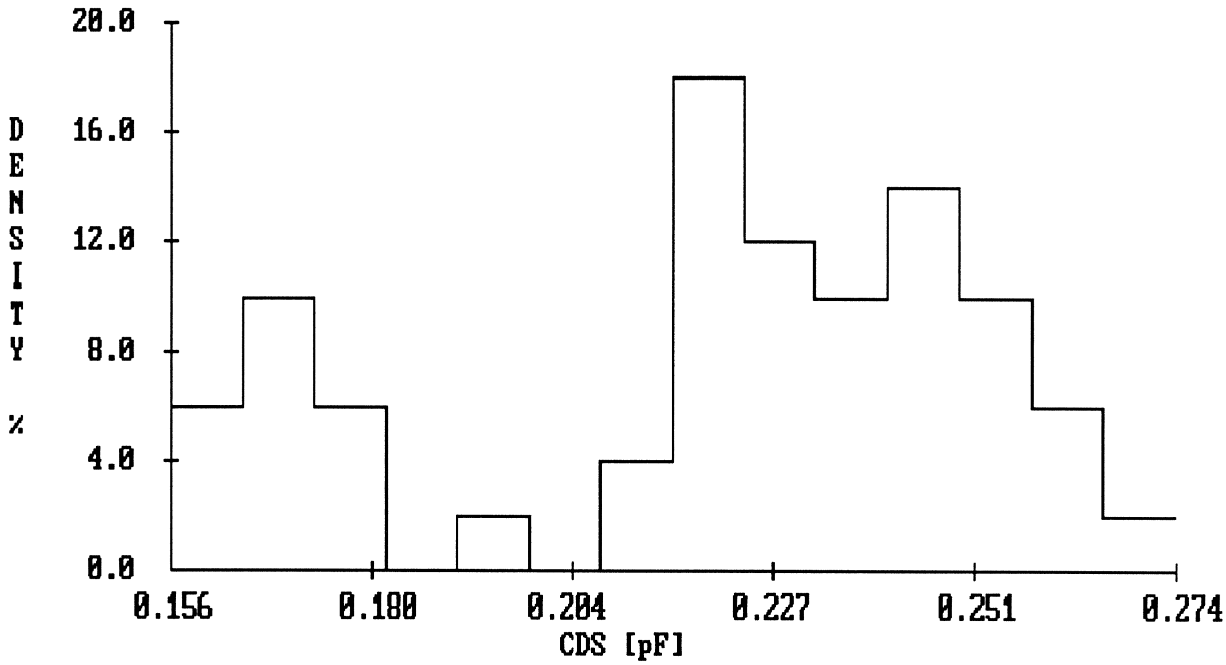
Arbitrary Multidimensional Distributions

approximation to the joint pdf

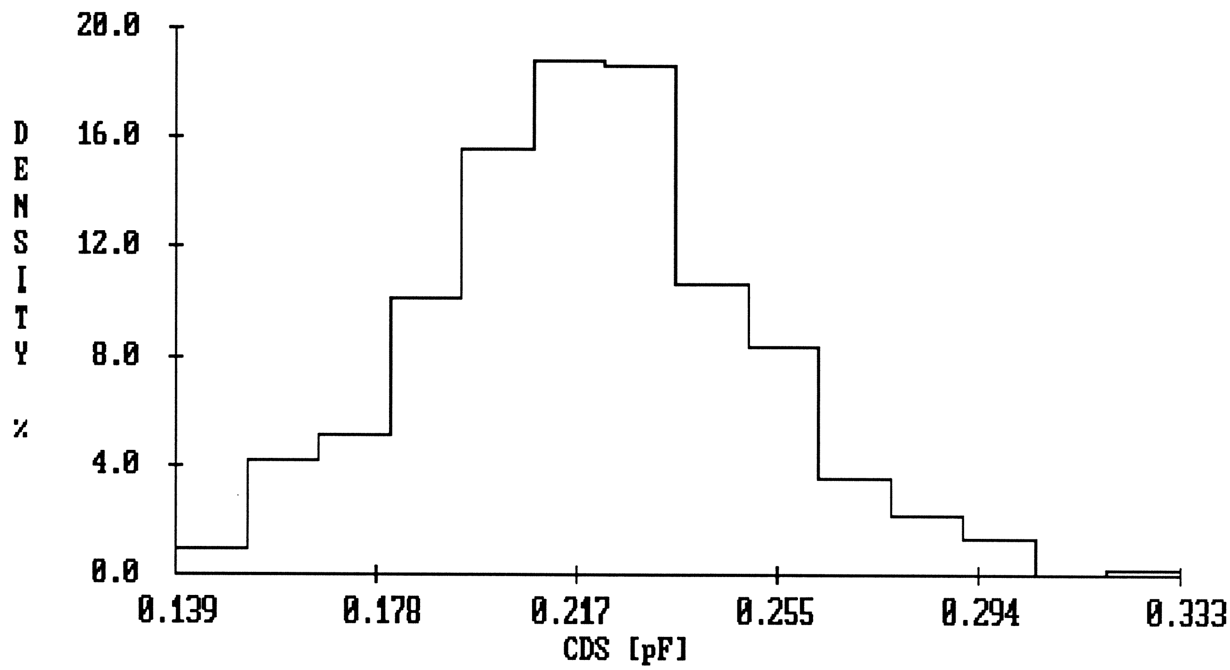
discretized pdf is a practical solution

limitations:

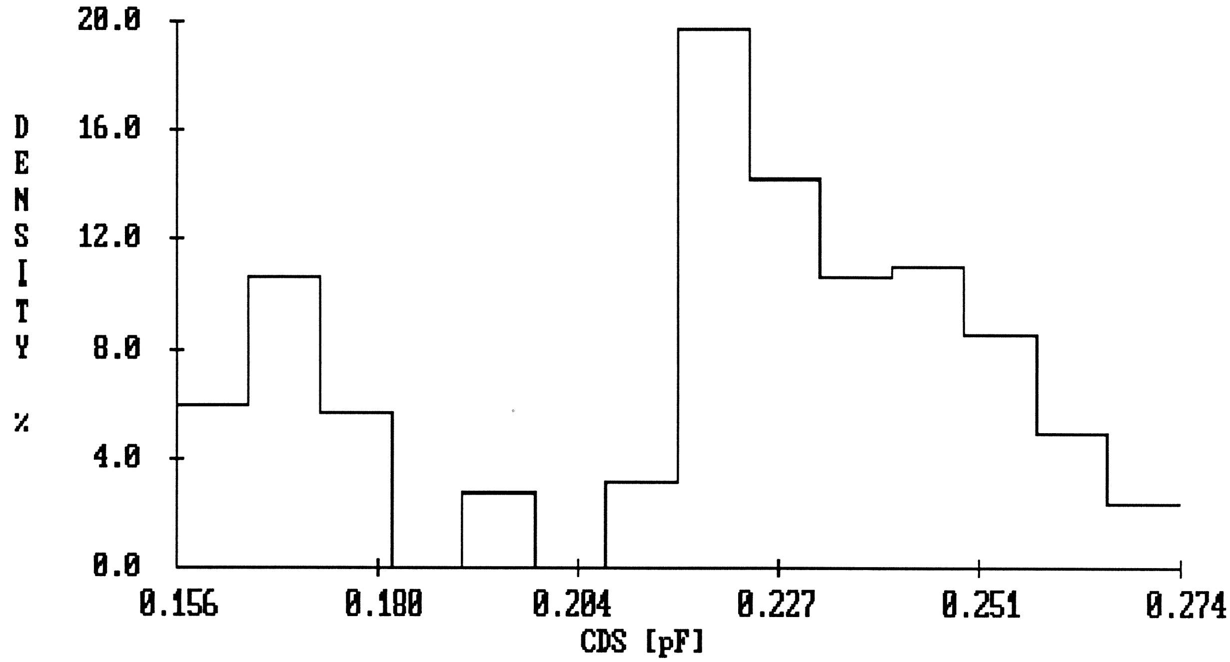
- limited size of the sample (poor approximation)
- exponential growth of the number of cells with the number of variables



Original histogram of C_{DS} obtained from 50 FETs



Regenerated histogram of C_{DS} using multidimensional normal distribution



Regenerated histogram of C_{DS} using combined discrete/normal approach

Sample Size

result of trade-off between measurement cost and statistical accuracy

decision on the size of a statistical sample can be based on relationships between the sample sizes and the confidence intervals

optimal sample sizes correspond to the knee points on the confidence curves

investigation shows that, under the assumption of a normal distribution, a reasonable sample size is between 20 and 50

Introduction to HarPE™

device-oriented nonlinear/linear simulation, characterization and optimization

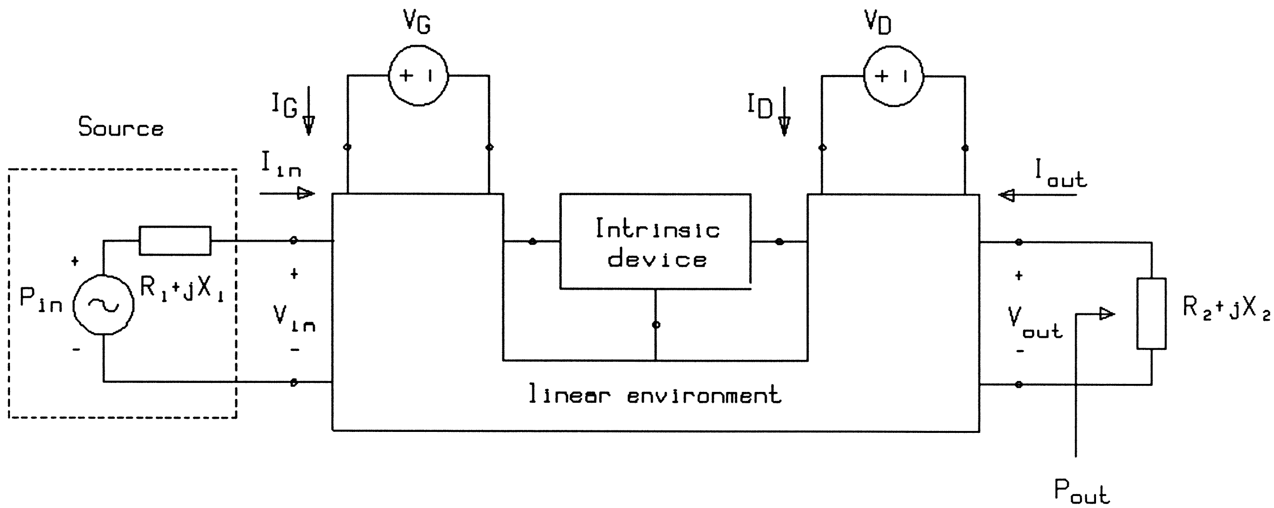
the world's first system for exploitation of harmonic data for complete and accurate device characterization

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

ensures nonlinear/linear simulations and optimization consistent with model parameter extraction

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

writing in-house modeling programs is unnecessary



Schematic representation of a single-device circuit

HarPE Built-In Models

Curtice and Ettenberg FET model

Materka and Kacprzak FET model

Raytheon (Statz et al.) FET model

Gummel and Poon bipolar models (NPN and PNP)

Measurements Processed by HarPE

power spectra

waveforms

small-signal S-parameters

DC data

HarPE Circuit File Overview

```
Expression
      GDS_MODEL = 0.004 - 0.001 * VG;     ! bias-dependent GDS
End

Model
      Extrinsic2  1 2 3 4 5
            LG: ?0.1NH?  RG: 0.0119  GDS: GDS_MODEL ...;

      FETM  1 2 3                       ! Materka FET model
            IDSS: ?0.2?  VP0: ?-4? ...  CF0: 0.023PF;

      2PORT  4 0  5 0;
End

Data
      #include "fetb_6.dat"   ! power spectrum measurements
End

Sweep
      FREQ: 6GHZ  PIN: from -15DBM to 10DBM step=5DBM
      VG: -0.673V  VD: 4V;
End

Specification
      FREQ: 6GHZ  PIN: -5DBM, 5DBM  ID0 POUT1 POUT2 POUT3;
End
```

User-Defined Linear Environment in HarPE

```
! parasitics
SRL  @int_gate   @gate  R=4.063  L=.338NH;
SRL  @int_drain  @drain  R=0.01  L=.254NH;
SRL  @int_source @ground  R=2.49  L=.08NH;

! bias circuits
SRL  @gate_bias  @gate  R=10  L=1000NH;
SRL  @drain_bias @drain  R=10  L=1000NH;

! input/output circuits
CAP  @input  @gate  C=1000PF;
CAP  @output @drain  C=1000PF;

! intrinsic FET, Raytheon model
FETR  @int_gate  @int_drain  @int_source  TAU: 3PS ...;

2BIASPORT @gate_bias @ground @drain_bias @ground;
2PORT  @input @ground  @output @ground;
```

Flexible HarPE Data Format

```
PARAMETER  VG=-0.372V  VD=2V  FREQ=6GHZ;
FORMAT  PIN(DBM)  POUT1(DBM)  POUT2(DBM)  POUT3(DBM)  ID0(MA);
          +10.0      +15.1        +2.4        -5.7         38.9
            0.0       +9.6       -19.5       -27.3         44.3
          -10.0        0.0       -42.7       -60.1         44.9
```

```
PARAMETER VG=0V  VD=4V;
FORMAT  FREQ(GHZ) MS11 PS11 MS21 PS21 MS12 PS12 MS22 PS22;
  2.0  0.9546  -46.72  4.0405  145.54  0.0291  62.95  0.6010  -21.43
  3.0  0.9392  -66.98  3.6149  129.27  0.0388  52.47  0.5808  -32.82
  4.0  0.8944  -83.24  3.3323  118.50  0.0458  42.58  0.5718  -39.93
```

```
PARAMETER  QUIET  VG=-0.673V  VD=4V  FREQ=6GHZ;
FORMAT  PIN(DBM)  POUT1(DBM)  TEMP(C);
          +10.0      +18.1        22.0
           +5.0      +13.9        22.0
```

Import Black-Box Data to HarPE as Subcircuits

```
Import
  PARAMETER NAME: SubcircuitA;
  FORMAT  FREQ RY11(/KOH) IY11(/KOH) RY12(/KOH) IY12(/KOH)
               RY21(/KOH) IY21(/KOH) RY22(/KOH) IY22(/KOH);
  1.2GHZ  2.926  -521.4  -2.726  522.1  -2.726  522.1  2.726  -522.1
       ...
End

Model
  ...
  2PORDATA  2  5  3  DATA=SubcircuitA;
  ...
End
```

User-Defined Model in HarPE

Curtice cubic model implemented as a user-defined model

```
! user-defined model parameters
A0: 0.15  A1: 0.15;  A2: -0.02;  A3: -0.02;
GAMMA: 1;  BETA: 0.03;  VDS0: 2;

! cubic model for drain current
V1 = VGS_TAU * (1 + BETA * (VDS0 - VDS_T));
CONDITION1 = POS(VDS_T) + ZERO(VDS_T);      ! VDS >= 0
IDS_CUBIC = CONDITION1 * (A0 + A1 * V1 + A2 * V1^2 + A3 * V1^3)
                                  * tanh( GAMMA * VDS_T);
IDS_MODEL = POS(IDS_CUBIC) * IDS_CUBIC;     ! pinchoff
```

other models, including a recent research model provided by Plessey Research Caswell, have been implemented and successfully verified

User-Created Response Function

```
Power_Ratio1 = POUTW1 / PINW;
Power_Ratio2 = POUTW2 / PINW;
```

Predefined Labels in HarPE

PI	constant 3.141592654
FREQ	frequency or harmonic frequency
FFREQ	fundamental frequency
VD	drain (collector) bias voltage
VG	gate (base) bias voltage
VDS_T	intrinsic drain-source instantaneous voltage
VGS_T	intrinsic gate-source instantaneous voltage
VGG_T	intrinsic internal gate instantaneous voltage
VGS_TAU	intrinsic gate-source voltage delayed by TAU
PIN	input power in dBm
PINW	input power in Watts
ID0	DC component of drain (collector) current
POUTk	output power at the kth harmonic, in dBm
POUTWk	output power at the kth harmonic, in Watts
MSij	magnitude of S-parameters
PSij	phase of S-parameters in degrees
RSij	real part of S-parameters
ISij	imaginary part of S-parameters
ID	DC drain (collector) current

Mathematical Functions Supported by HarPE

EXP, LOG, LOG10, SQRT, ABS, SIN, COS, TAN, ASIN
ACOS, ATAN, SINH, COSH, TANH

Conditional Expression

if (expression1 > 0)	expression2
else if (expression1 = 0)	expression3
else	expression4

can be implemented as

POS(expression1) * expression2 +
ZERO(expression1) * expression3 +
NEG(expression1) * expression4 ;

Device Modeling

simulation of linear/nonlinear circuits requires accurate linear/nonlinear device models

device model parameter extraction is crucial for microwave CAD such as the design of power amplifiers, frequency doublers, mixers, etc.

device model parameter values must be supplied to CAD software

major deficiencies in parameter extraction techniques are nonuniqueness, wild solution values

local (small-signal) models

global models - DC, small-signal, large-signal, time domain

physics-based models

FET Parameter Extraction Results

device is excited under practical (large-signal) working conditions; measurement data from Texas Instruments:

> power spectrum measurements at two bias points, three fundamental frequencies, and input power level from -10dBm to 10dBm

parameters are extracted by optimizing the model response to match the spectrum measurements

30 bias-point, input-power and fundamental-frequency combinations

30 simultaneous nonlinear circuit simulations

20 optimization variables

113 error functions

2.3 hours of CPU time on Apollo DN3500 without floating point accelerator; 40 minutes on Sun SPARCstation 1

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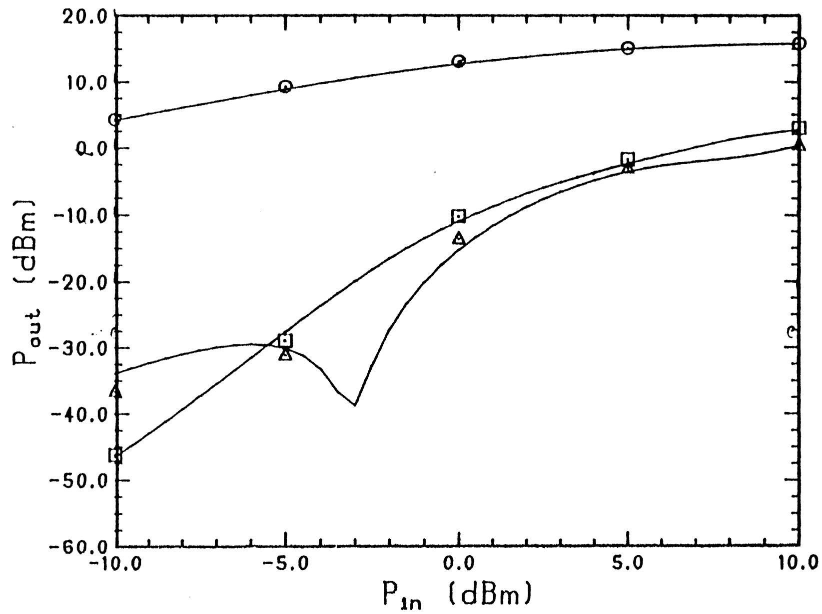

— Materka model response

○ measurement at fundamental frequency

Δ measurement at second harmonic

□ measurement at third harmonic

Spectrum match for the Materka model at f_1 = 0.2 GHz

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

HarPE™ Version 1.3 Highlights

fast, reliable and consistent large- and small-signal device simulation

accurate characterization from large-signal, small-signal and DC measurements

design optimization with user-defined responses and goals using expressions, including window specifications

state-of-the-art ℓ_1, least-squares and minimax optimizers

user-defined device models and response functions

graphical display of spectra, power and frequency sweeps, waveforms, DC IV curves, small-signal model parameters, Smith chart, polar plot, stability factor and maximum available gain, and user-defined responses

menu-driven, window-driven, mouse-driven

direct data import from Cascade Microtech measurement system