# OSA's CURRENT RESEARCH PROJECTS

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*Optimization Systems Associates Inc.*

# OSA's CURRENT RESEARCH PROJECTS


Optimization Systems Associates Inc.
Dundas, Ontario, Canada


January 1989

Optimization Systems Associates Inc.

## OSA's Current Research Projects

large-signal FET parameter extraction using harmonic measurements and harmonic balance simulation environment

yield optimization of nonlinear circuits with statistically characterized devices and within harmonic balance environment

practical, high speed gradient computation for harmonic balance simulators (FAST)

confidence levels of estimated statistical parameters

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**Large-Signal FET Parameter Extraction Using Harmonics**

a novel approach to large-signal nonlinear parameter extraction of GaAs MESFET devices measured under harmonic conditions

powerful nonlinear adjoint-based optimization

simultaneous processing of multi-bias, multi-power-input, multi-fundamental-frequency excitations and multi-harmonic measurements to uniquely extract the parameters of the intrinsic FET

successfully tested with 111 error functions and 20 model parameters

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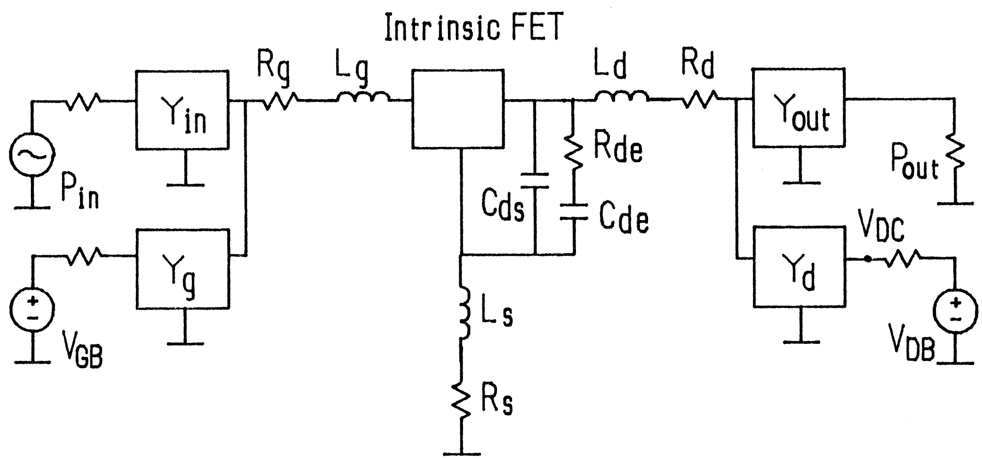
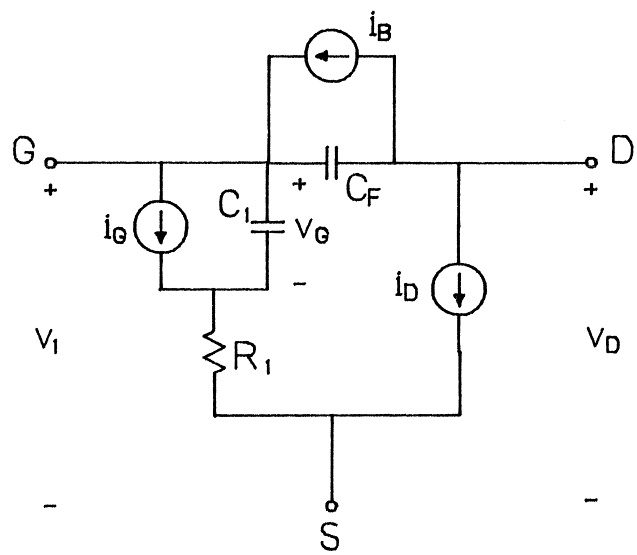



Circuit setup for large-signal multi-harmonic FET measurement




Intrinsic part of the modified Materka and Kacprzak FET model

## LINEAR PARASITIC PARAMETER VALUES OF THE FET MODEL USED IN ALL NUMERICAL TESTS

| Parameter | Value | Unit |
|---|---|---|
| $R_g$ | 0.0119 | Ω |
| $L_g$ | 0.1257 | nH |
| $R_s$ | 0.3740 | Ω |
| $L_s$ | 0.0107 | nH |
| $R_d$ | 0.0006 | Ω |
| $L_d$ | 0.0719 | nH |
| $C_{ds}$ | 0.1927 | pF |
| $R_{de}$ | 440 | Ω |
| $C_{de}$ | 1.5 | pF |

## CPU TIME WITH AND WITHOUT NONLINEAR ADJOINT GRADIENT CALCULATIONS IN TEST 1

| | Without Adjoint Ana.* | | With Adjoint Ana. | |
|---|---|---|---|---|
| | CPU** (sec.) | Obj. fun. value | CPU** (sec.) | Obj. fun. value |
| Starting point 1 | 1800 | $1.158\times10^{-3}$ | 230 | $1.013\times10^{-3}$ |
| | 2600 | $2.235\times10^{-4}$ | 260 | $1.734\times10^{-4}$ |
| Starting point 2 | 2600 | $1.366\times10^{-3}$ | 200 | $1.115\times10^{-3}$ |
| | 2900 | $5.479\times10^{-4}$ | 220 | $4.894\times10^{-4}$ |

* The gradient is estimated by perturbations at every other iteration.
** Fortran program run on a VAX 8650.

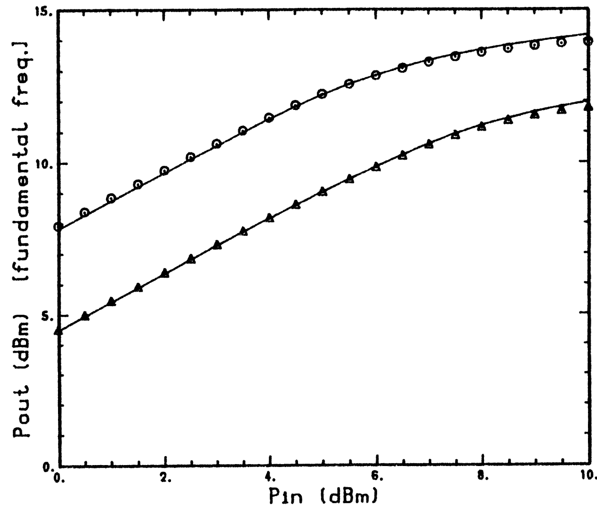
PARAMETERS OF THE CURTICE MODEL USED IN TEST 3

| Parameter | Value | Unit |
|---|---|---|
| $\beta_2$ | 0.04062 | 1/V |
| $A_0$ | 0.05185 | A |
| $A_1$ | 0.04036 | A/V |
| $A_2$ | -0.009478 | $A/V^2$ |
| $A_3$ | -0.009058 | $A/V^3$ |
| $\gamma$ | 1.608 | 1/V |
| $V_{DS0}$ | 4.0 | V |
| $I_S$ | $1.05\times10^{-9}$ | A |
| N | 1.0 | - |
| $C_{GS0}$ | 1.1 | pF |
| $C_{GD0}$ | 1.25 | pF |
| $F_C$ | 0.5 | - |
| $G_{MIN}$ | 0.0 | $1/\Omega$ |
| $V_{BI}$ | 0.7 | V |
| $V_{BR}$ | 20 | V |
| $\tau$ | 5.0 | ps |

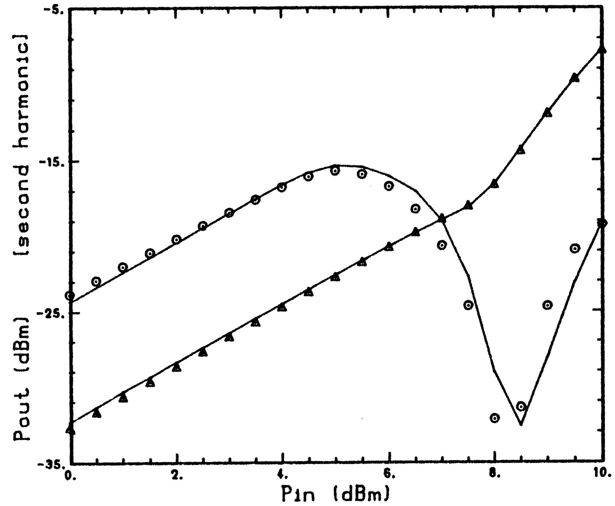
INPUT LEVELS USED WITH DIFFERENT FUNDAMENTAL FREQUENCIES AND DIFFERENT BIASES IN TEST 3

| ($V_{GB}$, $V_{DB}$) | $P_{in}$ (dBm) | | | |
|---|---|---|---|---|
| | $f_1$=0.5GHZ | $f_1$=1.0GHZ | $f_1$=1.5GHZ | $f_1$=2.0GHZ |
| (-0.3, 3) | 0, 4 | 0, 4 | 0, 4 | 0, 4 |
| (-0.3, 7) | 0, 4 | 0, 4 | 0, 4 | 0, 4 |
| (-1.0, 3) | 0 | 0 | 0 | 0 |
| (-1.0, 7) | 0 | 0, 4 | 0, 4 | 0 |
| (-0.5, 3) | -- | 8 | 8 | -- |
| (-0.5, 7) | 8 | 8 | 8 | 8 |

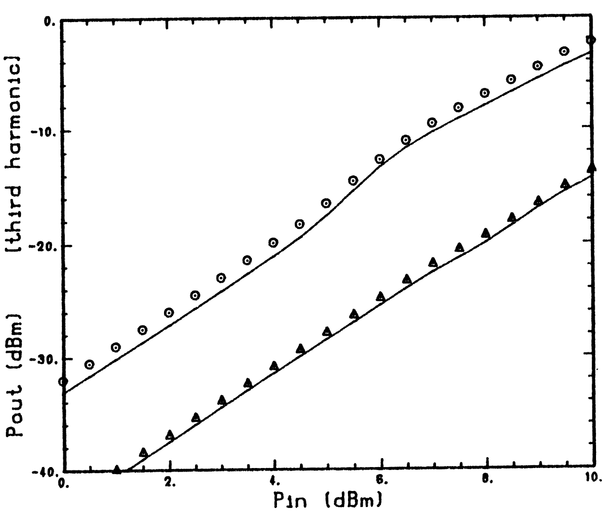
$f_1$ denotes the fundamental frequency



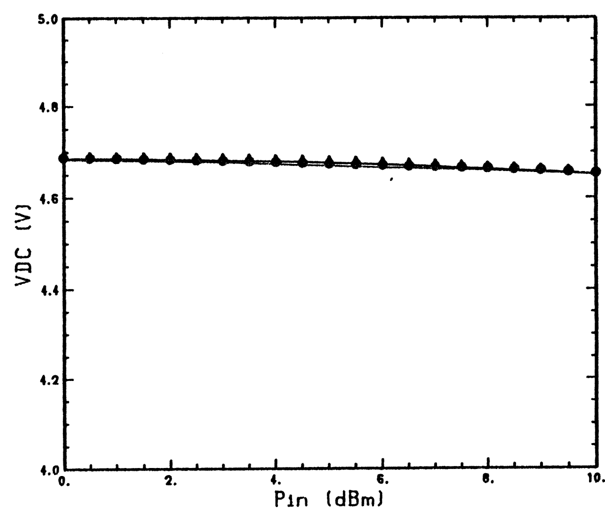

(a)




(b)

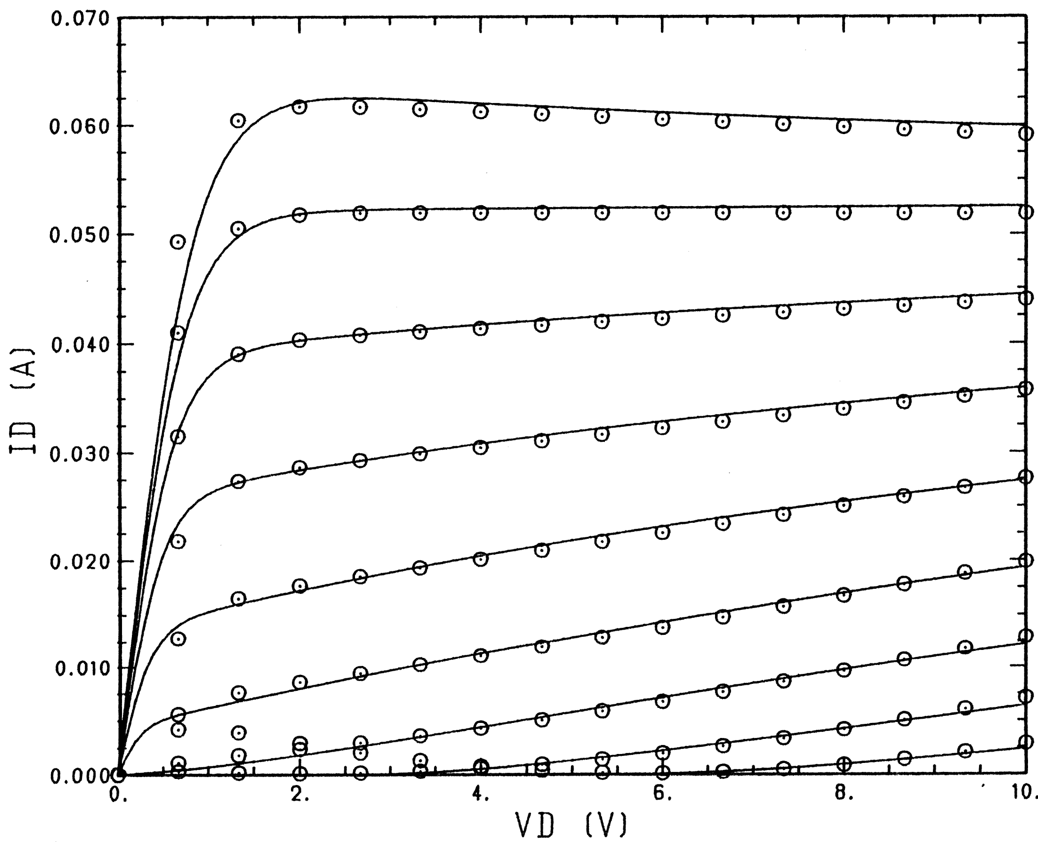



(c)




(d)

Agreement between the (Materka) model response and the simulated measurements (using the Curtice model) at $V_{GB}$=-0.5 and $V_{DB}$=5 in Test 3. Solid lines represent the (Materka) computed model response. Circles denote the simulated measurements at fundamental frequency 0.5GHZ and triangles the simulated measurements at fundamental frequency 1.0GHZ. (a) Fundamental component, (b) second harmonic component, (c) third harmonic component, and (d) DC component.




Agreement between the DC characteristics of the modified Materka and Kacprzak model and the simulated measurements (from the Curtice model) in Test 3. $V_G$ is from −1.75V to 0.25V in steps of 0.25V, and $V_D$ is from 0 to 10V. (Curtice uses $V_{in}$ and $V_{out}$, respectively.) Solid lines represent the (Materka) model, and the circles represent the measurements.

## Yield Optimization of Nonlinear Circuits with Statistically Characterized Devices

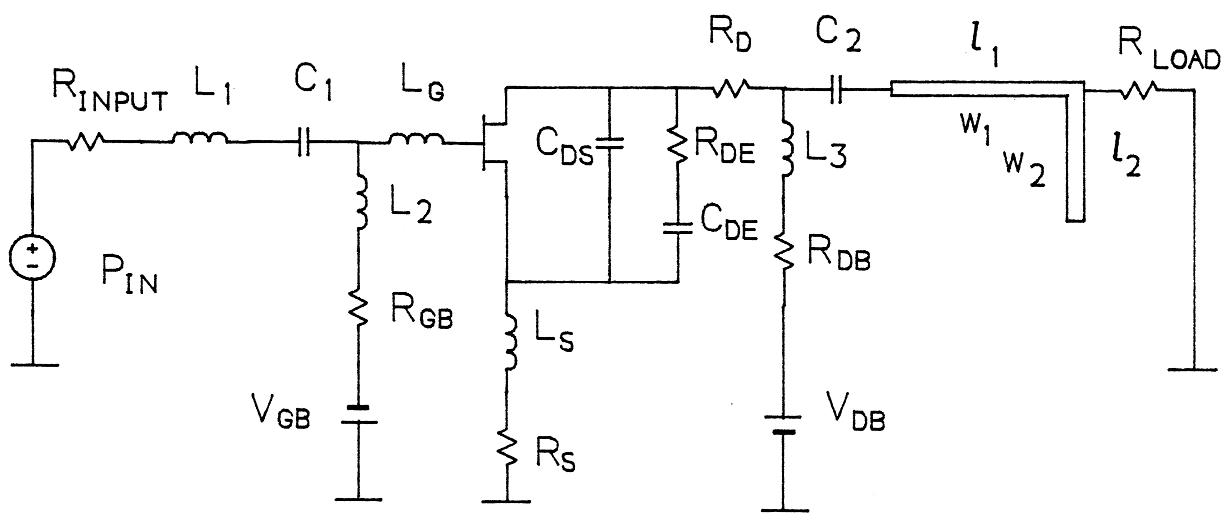
comprehensive treatment of yield optimization of nonlinear microwave circuits with statistically characterized devices

one-sided $l_1$ circuit centering with gradient approximations

efficient harmonic balance simulation with exact Jacobians

multidimensional statistical distributions of the intrinsic and parasitic parameters of FETs fully accommodated

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




Circuit diagram of the FET microwave frequency doubler example.

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ASSUMED STATISTICAL DISTRIBUTIONS FOR THE FREQUENCY DOUBLER

| Element and FET Parameter | Nominal Value | Type of Distribution | Relative Tolerance or Standard Deviation |
|---|---|---|---|
| $V_{GB}$ | optimized | uniform | 3% |
| $V_{DB}$ | optimized | uniform | 3% |
| $P_{IN}$ | optimized | uniform | 3% |
| $l_1$ | optimized | uniform | 3% |
| $l_2$ | optimized | uniform | 3% |
| $L_1$ | optimized | uniform | 3% |
| $L_2$ | 15nH | uniform | 5% |
| $L_3$ | 15nH | uniform | 5% |
| $C_1$ | 20pF | uniform | 5% |
| $C_2$ | 20pF | uniform | 5% |
| $w_1$ | $0.1\times10^{-3}$m | uniform | 5% |
| $w_2$ | $0.635\times10^{-3}$m | uniform | 5% |
| $L_G$ | 0.16nH | normal | 5% |
| $R_D$ | 2.153Ω | normal | 3% |
| $L_S$ | 0.07nH | normal | 5% |
| $R_S$ | 1.144Ω | normal | 5% |
| $R_{DE}$ | 440Ω | normal | 14% |
| $C_{DE}$ | 1.15pF | normal | 3% |
| $C_{DS}$ | 0.12pF | normal | 4.5% |
| $I_{DSS}$ | $6.0\times10^{-2}$ | normal | 5% |
| $V_{p0}$ | -1.906 | normal | 0.65% |
| $\gamma$ | $-15.\times10^{-2}$ | normal | 0.65% |
| E | 1.8 | normal | 0.65% |
| $S_l$ | $0.676\times10^{-1}$ | normal | 0.65% |
| $K_G$ | 1.1 | normal | 0.65% |
| $\tau$ | 7.0pS | normal | 6% |
| $S_S$ | $1.666\times10^{-3}$ | normal | 0.65% |
| $I_{G0}$ | $0.713\times10^{-5}$ | normal | 3% |
| $\alpha_G$ | 38.46 | normal | 3% |
| $I_{B0}$ | $-0.713\times10^{-5}$ | normal | 3% |
| $\alpha_B$ | -38.46 | normal | 3% |
| $R_{10}$ | 3.5Ω | normal | 8% |
| $C_{10}$ | 0.42pF | normal | 4.16% |
| $C_{F0}$ | 0.02pF | normal | 6.64% |

The following parameters are considered as deterministic:
$K_E = 0.0$, $K_R = 1.111$, $K_1 = 1.282$, $C_{1S} = 0.0$, and $K_F = 1.282$.

$V_{GB}$ and $V_{DB}$ are bias voltages, and $P_{IN}$ is the driving power level.

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FET MODEL PARAMETER CORRELATIONS

| | $L_G$ | $R_S$ | $L_S$ | $R_{DE}$ | $C_{DS}$ | $g_m$ | $\tau$ | $R_{IN}$ | $C_{GS}$ | $C_{GD}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $L_G$ | 1.00 | -0.16 | 0.11 | -0.22 | -0.20 | 0.15 | 0.06 | 0.15 | 0.25 | 0.04 |
| $R_S$ | -0.16 | 1.00 | -0.28 | 0.02 | 0.06 | -0.09 | -0.16 | 0.12 | -0.24 | 0.26 |
| $L_S$ | 0.11 | -0.28 | 1.00 | 0.11 | -0.26 | 0.53 | 0.41 | -0.52 | 0.78 | -0.12 |
| $R_{DE}$ | -0.22 | 0.02 | 0.11 | 1.00 | -0.44 | 0.03 | 0.04 | -0.54 | 0.02 | -0.14 |
| $C_{DS}$ | -0.20 | 0.06 | -0.26 | -0.44 | 1.00 | -0.13 | -0.14 | 0.23 | -0.24 | -0.04 |
| $g_m$ | 0.15 | -0.09 | 0.53 | 0.03 | -0.13 | 1.00 | -0.08 | -0.26 | 0.78 | 0.38 |
| $\tau$ | 0.06 | -0.16 | 0.41 | 0.04 | -0.14 | -0.08 | 1.00 | -0.19 | 0.27 | -0.46 |
| $R_{IN}$ | 0.15 | 0.12 | -0.52 | -0.54 | 0.23 | -0.26 | -0.19 | 1.00 | -0.35 | 0.05 |
| $C_{GS}$ | 0.25 | -0.24 | 0.78 | 0.02 | -0.24 | 0.78 | 0.27 | -0.35 | 1.00 | 0.15 |
| $C_{GD}$ | 0.04 | 0.26 | -0.12 | -0.14 | -0.04 | 0.38 | -0.46 | 0.05 | 0.15 | 1.00 |

Certain modifications have been made to adjust these small-signal parameter correlations to be consistent with the large-signal FET model.

YIELD OPTIMIZATION OF THE FET FREQUENCY DOUBLER

| Variable | Starting Point | Nominal Design | Solution I | Solution II |
|---|---|---|---|---|
| $P_{IN}$ | $2.0000\times10^{-3}$* | $2.0000\times10^{-3}$ | $2.5000\times10^{-3}$ | $2.4219\times10^{-3}$ |
| $V_{GB}$ | -1.9060* | -1.9060 | -1.9010 | -1.9011 |
| $V_{DB}$ | 5.0000* | 5.0000 | 4.9950 | 4.9949 |
| $L_1$ | 1.0000 | 5.4620 | 5.4670 | 5.4670 |
| $l_1$ | $1.0000\times10^{-3}$ | $1.4828\times10^{-3}$ | $1.6306\times10^{-3}$ | $1.7088\times10^{-3}$ |
| $l_2$ | $5.0000\times10^{-3}$ | $5.7705\times10^{-3}$ | $5.7545\times10^{-3}$ | $5.7466\times10^{-3}$ |
| Yield | | 24.8% | 57.0% | 61.4% |
| Number of Optimization Iterations | | | 11 | 8 |
| Number of Function Evaluations | | | 41 | 26 |

* Not considered as variables in nominal design.

Variable Definitions:
$P_{IN}$ Driving power level in watts
$V_{GB}$ Gate bias in volts
$V_{DB}$ Drain bias in volts
$L_1$ Inductor in the input matching network in nH
$l_1$ Length of the microstrip section in meters
$l_2$ Length of the open-circuited microstrip stub in meters

The yield is estimated from 500 outcomes.

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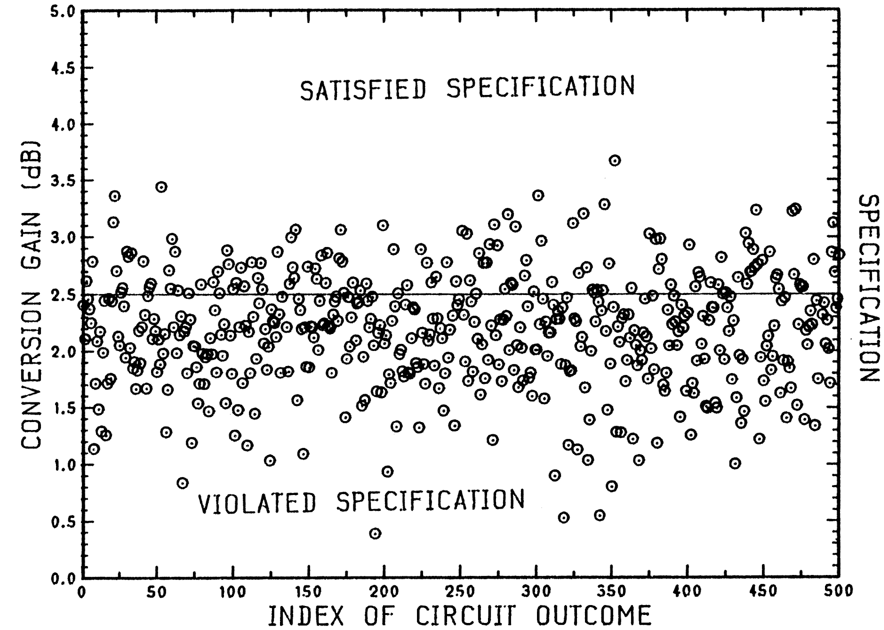
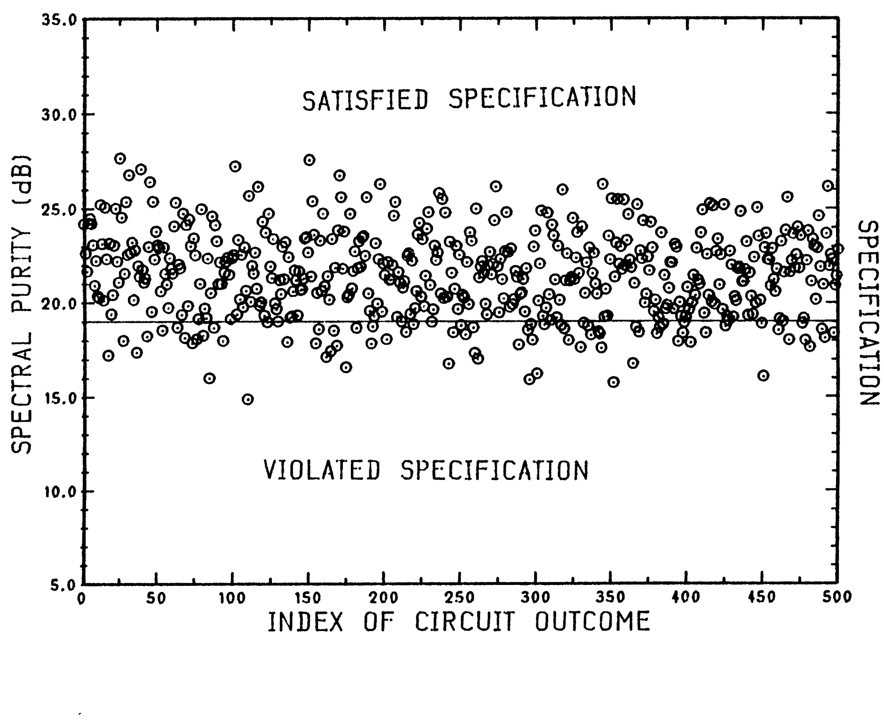
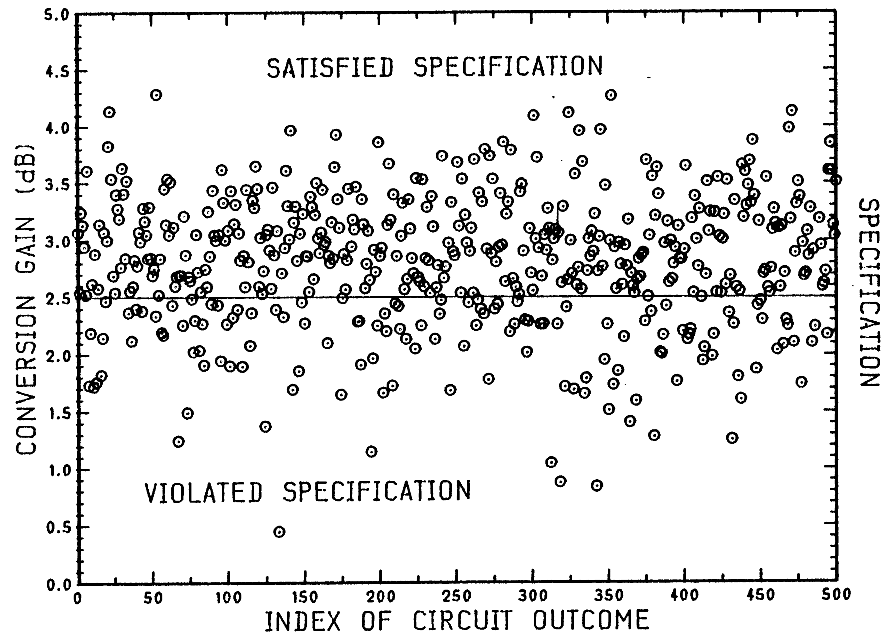


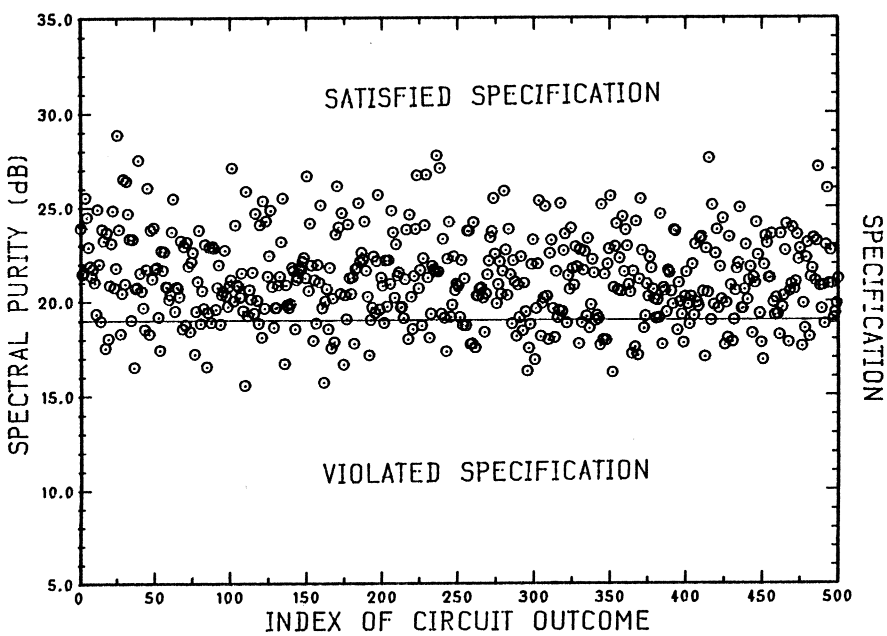

Run chart of the conversion gain for up to 500 statistical outcomes of the frequency doubler before yield optimization. The straight line shown is the performance specification.




Run chart of the spectral purity for up to 500 statistical outcomes of the frequency doubler before yield optimization. The straight line shown is the performance specification.




Run chart of the conversion gain for up to 500 statistical outcomes of the frequency doubler after yield optimization. The straight line shown is the performance specification.




Run chart of the spectral purity up to 500 statistical outcomes of the frequency doubler after yield optimization. The straight line shown is the performance specification.

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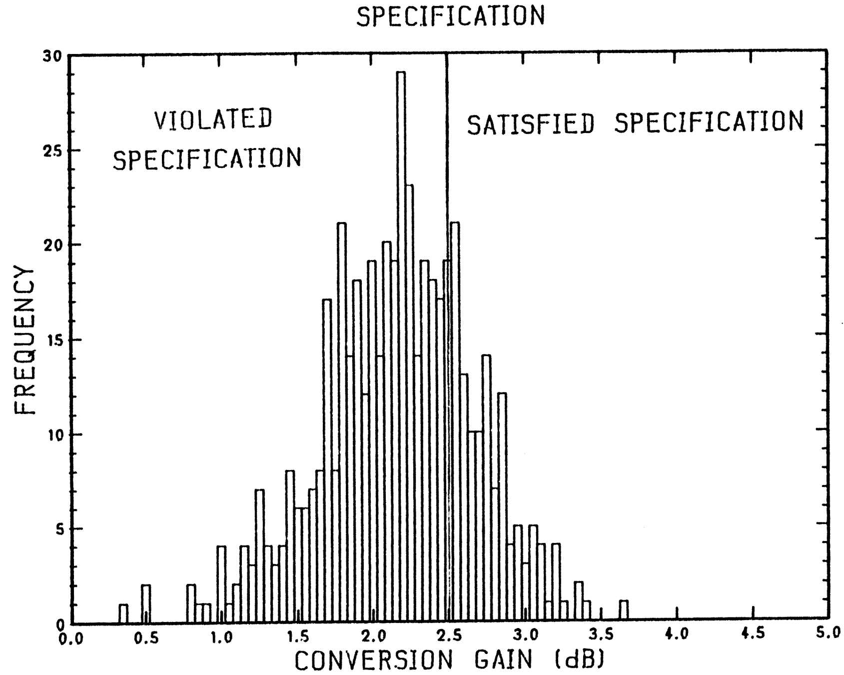
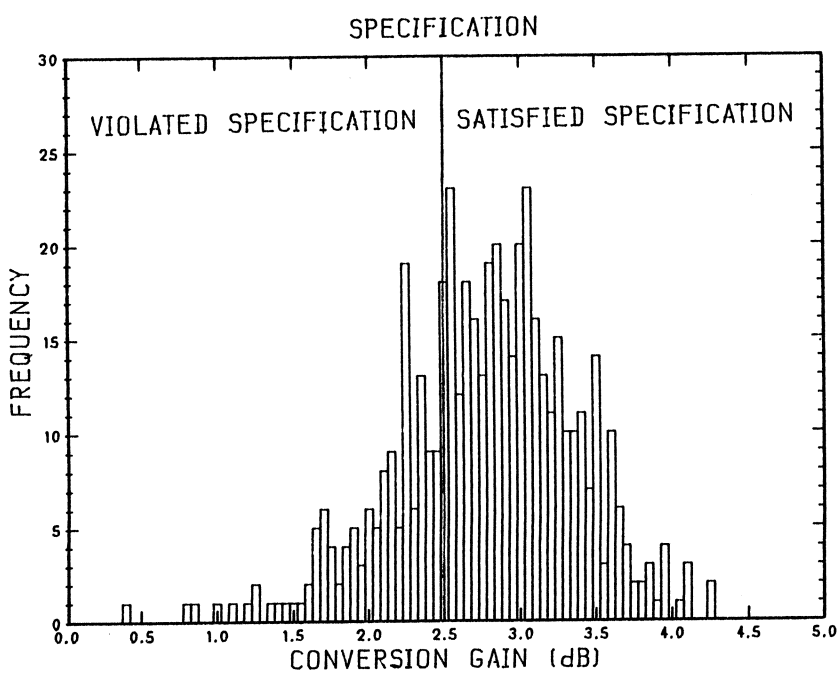



Histogram of conversion gains of the frequency doubler based on 500 statistical outcomes before yield optimization. The center of the distribution is below the specification shown by a vertical line. Most statistical outcomes violate this specification.




Histogram of conversion gains of the frequency doubler based on 500 statistical outcomes after yield optimization. The center of the distribution is above the specification shown by a vertical line. Most statistical outcomes satisfy this specification.

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**Practical, High Speed Gradient Computation for Harmonic Balance Simulators**

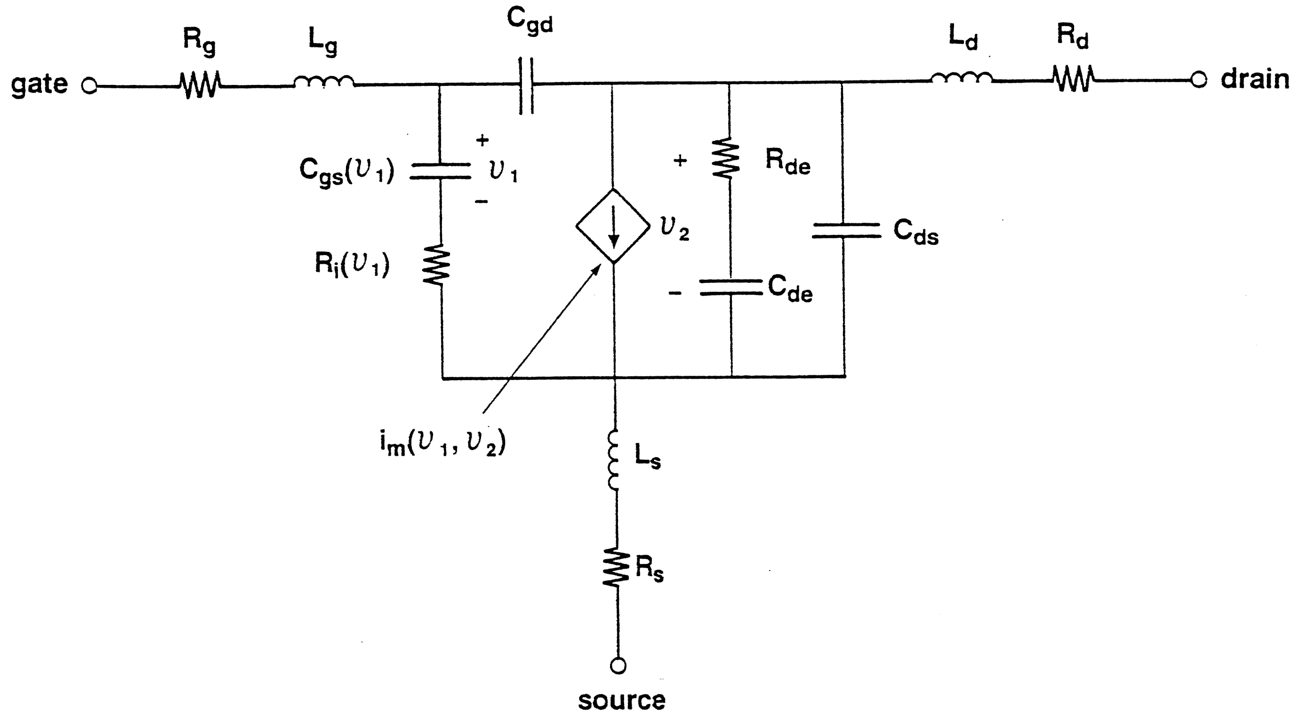
FAST (Future Adjoint Sensitivity Technique)

novel, powerful computational concept

combines efficiency of the exact adjoint sensitivity technique with the simplicity of the conventional perturbation technique

carries over to a practically implementable Jacobian for fast harmonic balance simulation

promises high speed gradient evaluation essential for yield optimization of nonlinear MMIC circuits by general purpose software




A large-signal MESFET model used for the mixer example

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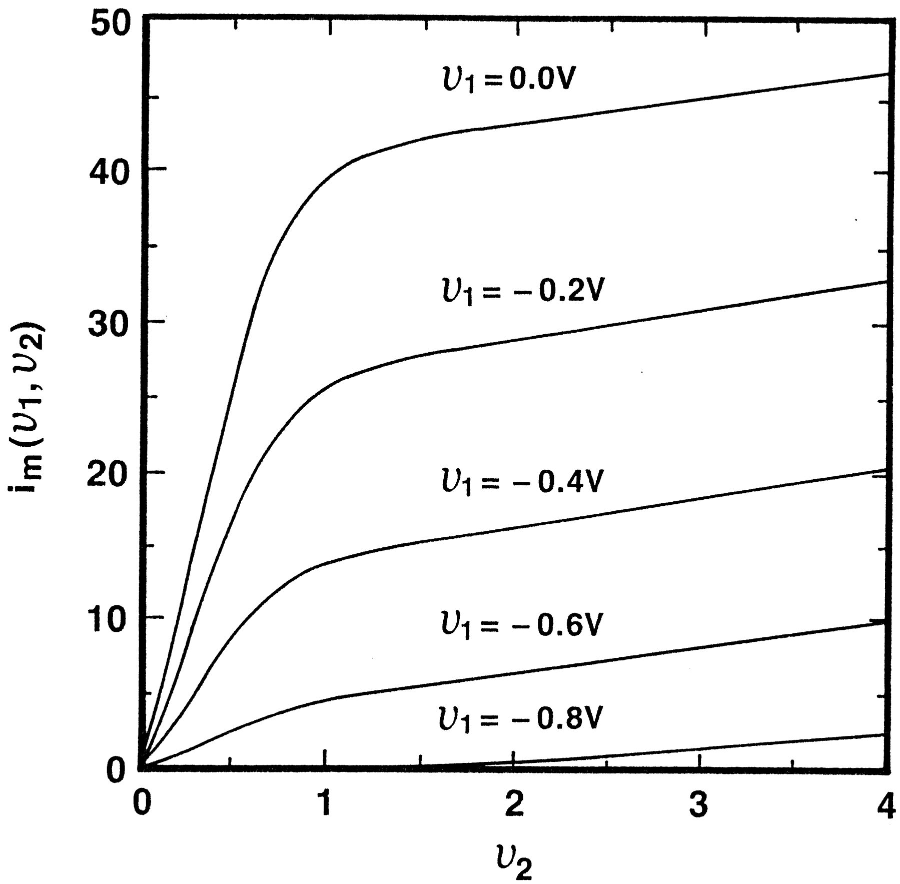


The DC characteristics of the MESFET model

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NUMERICAL VERIFICATION OF FAST FOR THE MIXER EXAMPLE

| Var. | Sensitivity from FAST | Sensitivity from EAST | Sensitivity from PAST | Difference between FAST and EAST (%) | Difference between FAST and PAST (%) |
|---|---|---|---|---|---|
| linear subnetwork | | | | | |
| $C_{ds}$ | -24.28082 | -24.28081 | -24.03669 | 0.00 | 1.01 |
| $C_{gd}$ | -32.16238 | -32.16237 | -32.33670 | 0.00 | -0.54 |
| $C_{de}$ | $-8.8\times10^{-13}$ | $1.7\times10^{-13}$ | 0 | 120.21 | 100.00 |
| $R_g$ | 10.00754 | 10.00756 | 9.89609 | -0.00 | 1.11 |
| $R_d$ | 11.71325 | 11.71327 | 11.71338 | -0.00 | -0.00 |
| $R_s$ | -4.98829 | -4.98827 | -4.98861 | 0.00 | -0.01 |
| $R_{de}$ | -0.07171 | -0.07171 | -0.07115 | 0.00 | 0.79 |
| $L_g$ | -0.30238 | -0.30238 | -0.30054 | 0.00 | 0.61 |
| $L_d$ | -0.87824 | -0.87824 | -0.87247 | 0.00 | 0.66 |
| $L_s$ | -0.33527 | -0.33527 | -0.33191 | 0.00 | 1.00 |
| nonlinear subnetwork* | | | | | |
| $C_{gs0}$ | -5.43110 | -5.43110 | -5.38265 | 0.00 | 0.89 |
| $\tau$ | 1.52983 | 1.52984 | 1.56057 | -0.00 | -2.01 |
| $V_{\phi}$ | -20.84224 | -20.84223 | -20.84308 | 0.00 | -0.00 |
| $V_{p0}$ | -14.62206 | -14.62206 | -14.62469 | 0.00 | -0.02 |
| $V_{dss}$ | 0.30209 | 0.30209 | 0.30210 | -0.00 | -0.00 |
| $I_{dsp}$ | 9.39335 | 9.39335 | 9.39338 | -0.00 | -0.00 |
| bias and driving sources | | | | | |
| $V_{GS}$ | -4.94402 | -4.94402 | -4.94271 | -0.00 | 0.03 |
| $V_{DS}$ | -0.67424 | -0.67424 | -0.67429 | 0.00 | -0.01 |
| $P_{LO}$ | 2.02886 | 2.02885 | 2.02882 | 0.00 | 0.00 |
| $P_{RF}$ | -0.09073 | -0.09072 | -0.09077 | 0.01 | -0.05 |

NUMERICAL VERIFICATION OF FAST FOR THE MIXER EXAMPLE

| Var. | Sensitivity from FAST | Sensitivity from EAST | Sensitivity from PAST | Difference between FAST and EAST (%) | Difference between FAST and PAST (%) |
|---|---|---|---|---|---|
| terminations+ | | | | | |
| $R_g(f_{LO})$ | 8.83598 | 8.83596 | 8.76244 | 0.00 | 0.83 |
| $X_g(f_{LO})$ | 2.20500 | 2.20496 | 2.16567 | 0.00 | 1.78 |
| $R_g(f_{RF})$ | 0.71282 | 0.71281 | 0.70568 | 0.00 | 1.00 |
| $X_g(f_{RF})$ | 0.46410 | 0.46409 | 0.45702 | 0.00 | 1.53 |
| $R_d(f_{IF})$ | 0.65950 | 0.65950 | 0.65272 | -0.00 | 1.03 |
| $X_d(f_{IF})$ | 0.09024 | 0.09024 | 0.09207 | -0.00 | -2.02 |

* Nonlinear elements are characterized by

$$C_{gs}(v_1) = C_{gs0} / \sqrt{1 - v_1/V_\phi} ,$$

$$R_i(v_1)C_{gs}(v_1) = \tau$$

$V_\phi$, $V_{p0}$, $V_{dss}$ and $I_{dsp}$ are parameters in the function $i_m(v_1, v_2)$.

\+ R and X represent the real and the imaginary parts of the terminating impedances, respectively. Subscripts g and d represent the gate and the drain terminations, respectively.

## Confidence Levels of Estimated Statistical Parameters

Suppose x represents the true value of mean, or standard deviation or correlation coefficient of the device statistics

Let X represent the estimation of x from statistical samples

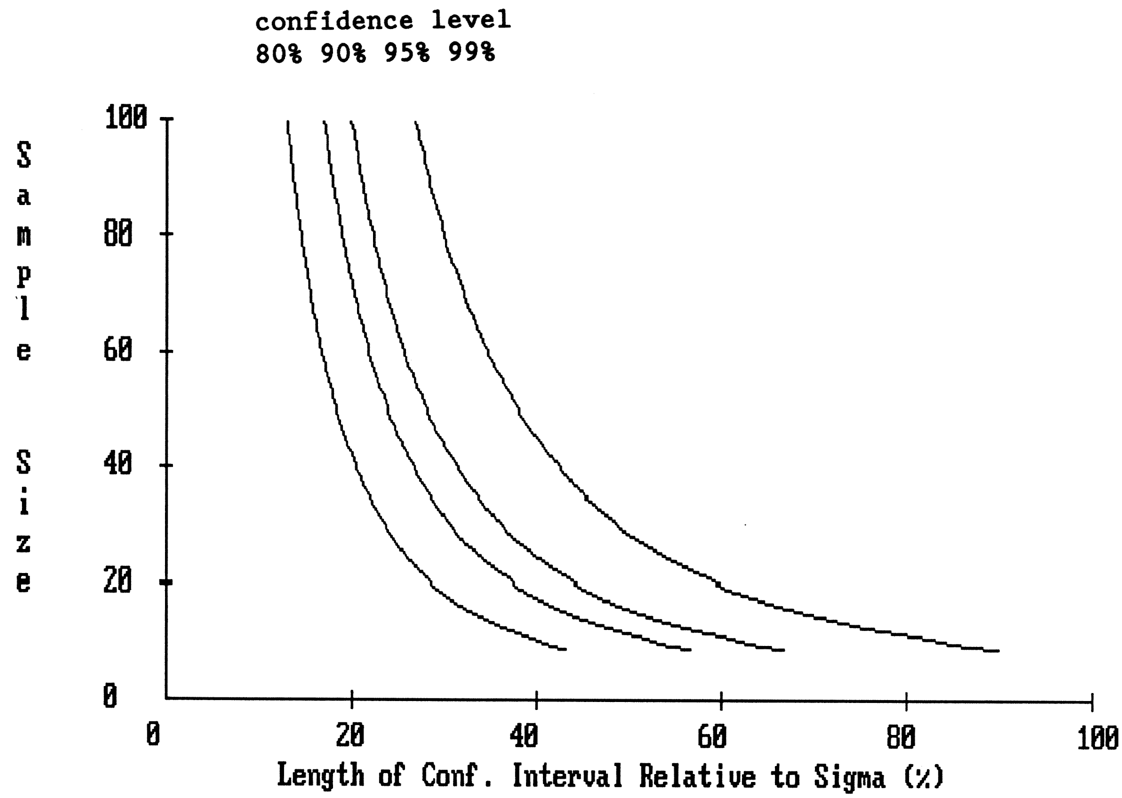
The confidence level (e.g., 90%) is the probability of x falling into the confidence interval

$$X - DX_{lower} < x < X + DX_{upper}$$

$DX_{lower}$ and $DX_{upper}$ define the size of confidence interval and are computed from

t distribution if x represents mean value
chi-square distribution if x represents std. deviation
normal distribution if x represents correlation coef.

The sample size is plotted against the average value of $DX_{lower}$ and $DX_{upper}$




SAMPLE SIZE VS. ACCURACY OF MEAN VALUE

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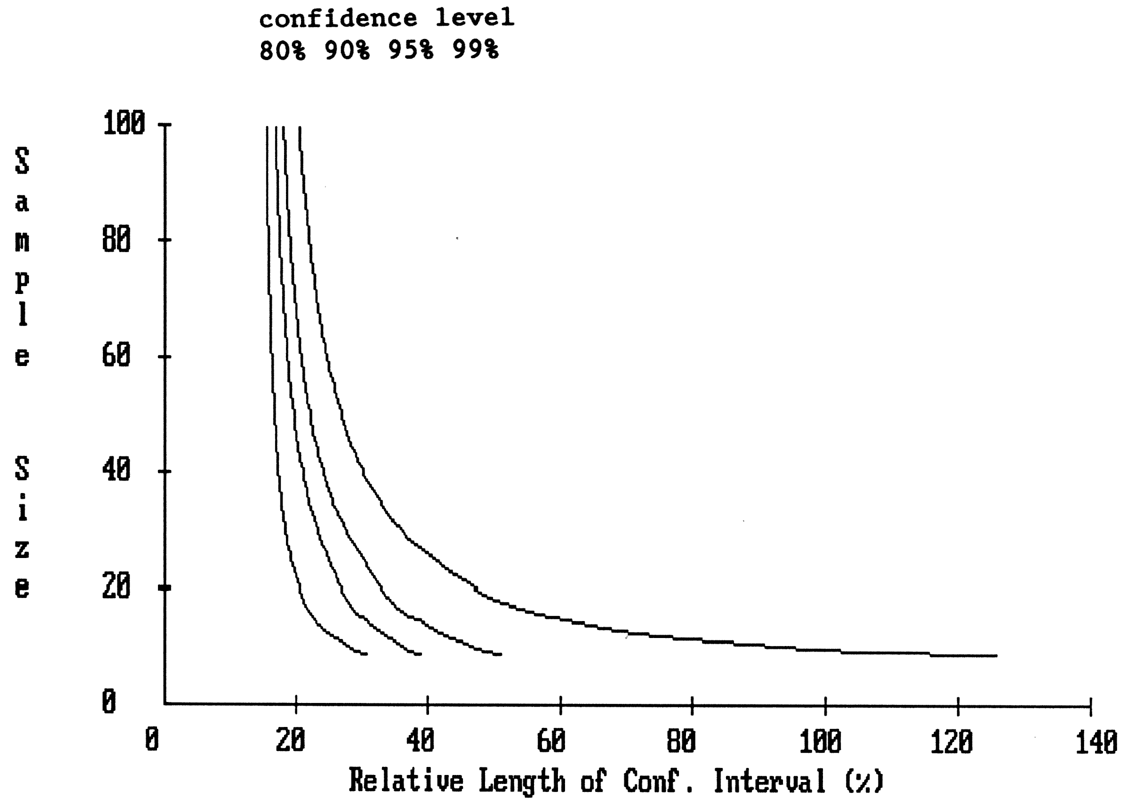
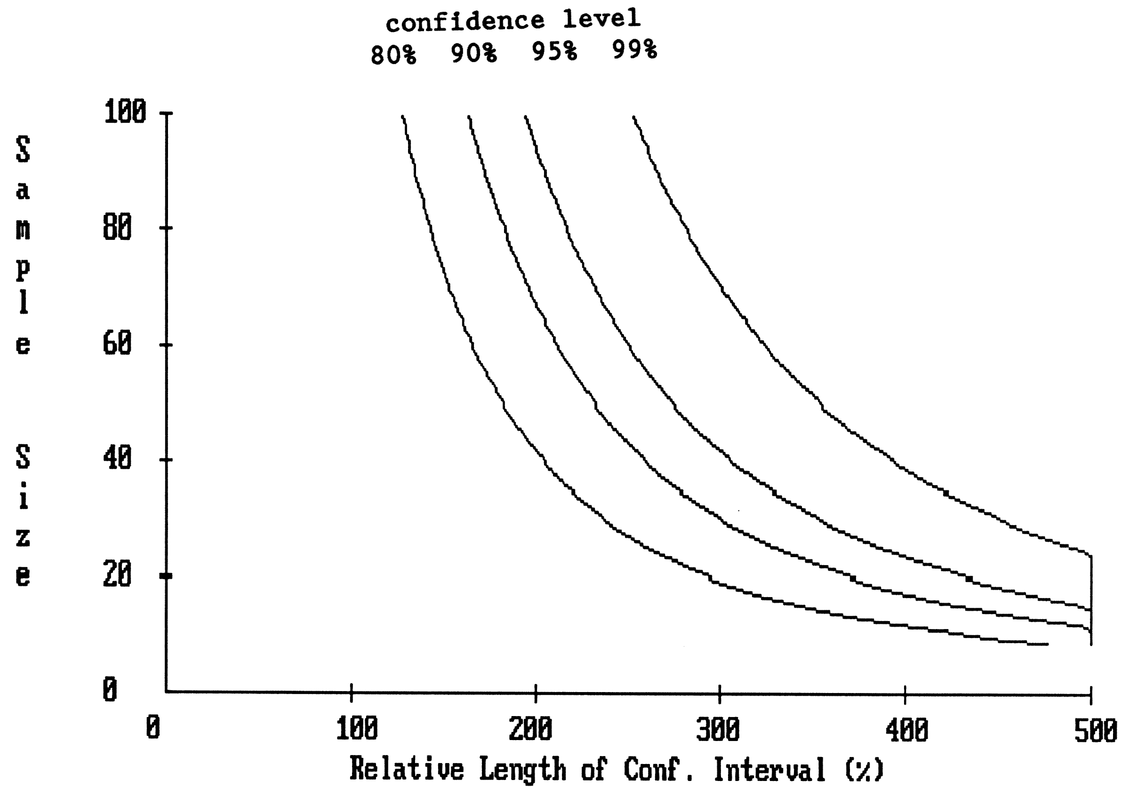



SAMPLE SIZE VS. ACCURACY OF STD DEVIATION




SAMPLE SIZE VS. ACCURACY OF CORRELATION COEF .1

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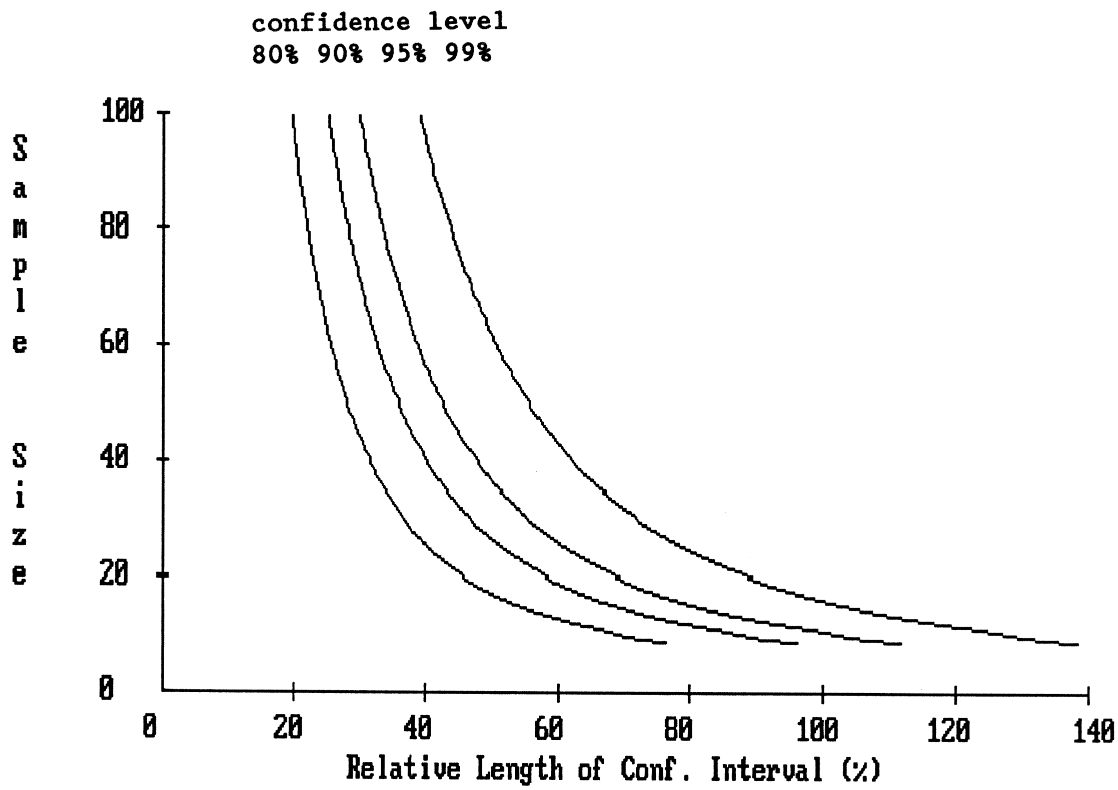


SAMPLE SIZE VS. ACCURACY OF CORRELATION COEF .5

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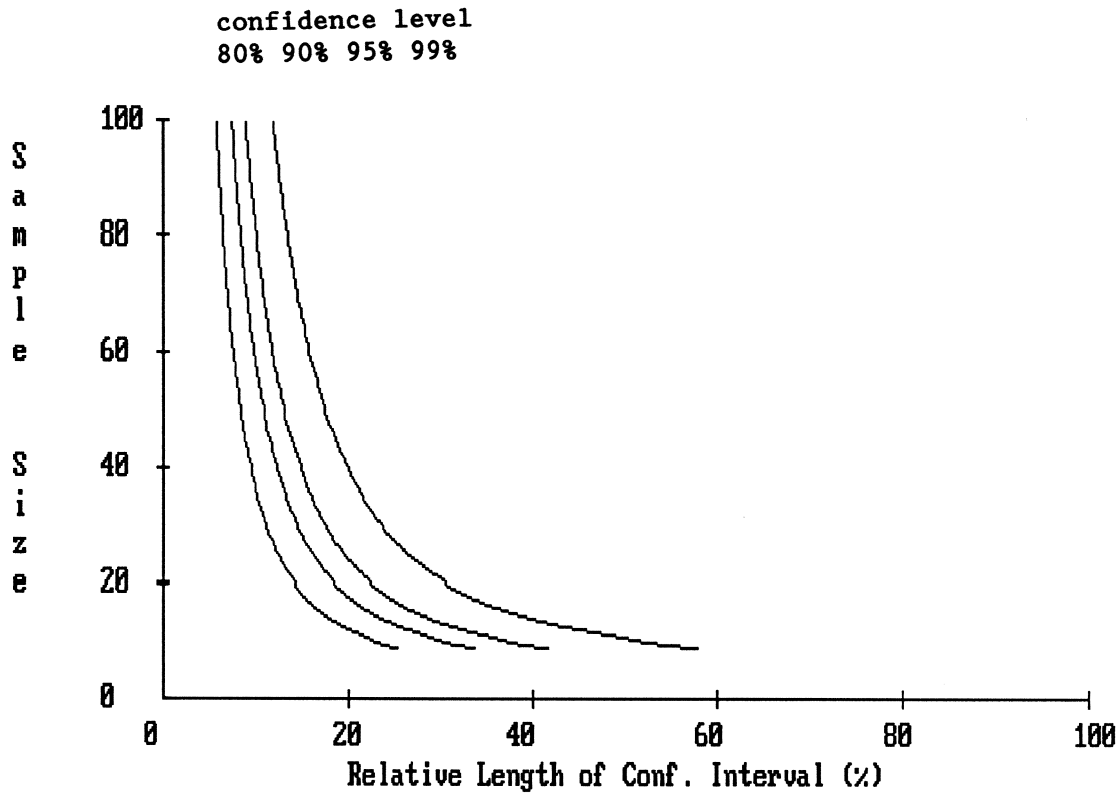


SAMPLE SIZE VS. ACCURACY OF CORRELATION COEF .8