EFFICIENT LARGE-SIGNAL FET PARAMETER EXTRACTION USING HARMONICS

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Introduction

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

FET model parameter values must be supplied to CAD software

conventional methods for parameter extraction are based on DC and small-signal measurement data fitting

Our New Approach — Spectrum Data Fitting

the FET device is excited under practical (large-signal) working conditions

the spectrum measurements are taken at different bias, input power and fundamental frequency combinations

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

this is the first true nonlinear large-signal FET model parameter extraction approach

Notation

measurements on device under test

$$S_j = \begin{bmatrix} S_j(0) \\ S_j(\omega_1) \\ \vdots \\ S_j(\omega_H) \end{bmatrix}$$

model responses

$$F_j(\phi) = \begin{bmatrix} F_j(\phi, 0) \\ F_j(\phi, \omega_1) \\ \vdots \\ F_j(\phi, \omega_H) \end{bmatrix}$$

j indicates the *j*th bias-input-frequency combination

$\omega_k = k\omega$, k=1, 2, ..., H

ϕ is the model parameter vector to be determined

Parameter Extraction by Optimization

$$\min_{\phi} \sum_{j=1}^{M} \left\{ w_{jdc} \,|\, F_j(\phi,0) - S_j(0) \,|^{p} + \sum_{k=1}^{H} w_{jk} \,|\, F_j(\phi,\omega_k) - S_j(\omega_k) \,|^{p} \right\}$$

w_{jdc} and w_{jk} are weighting factors

p=1 or 2 corresponds to ℓ_1 or ℓ_2 optimization

Special Remarks

model response calculation involves frequency domain nonlinear circuit simulation

gradient calculation needs sensitivity analysis of nonlinear circuits w.r.t. ϕ

Implementation

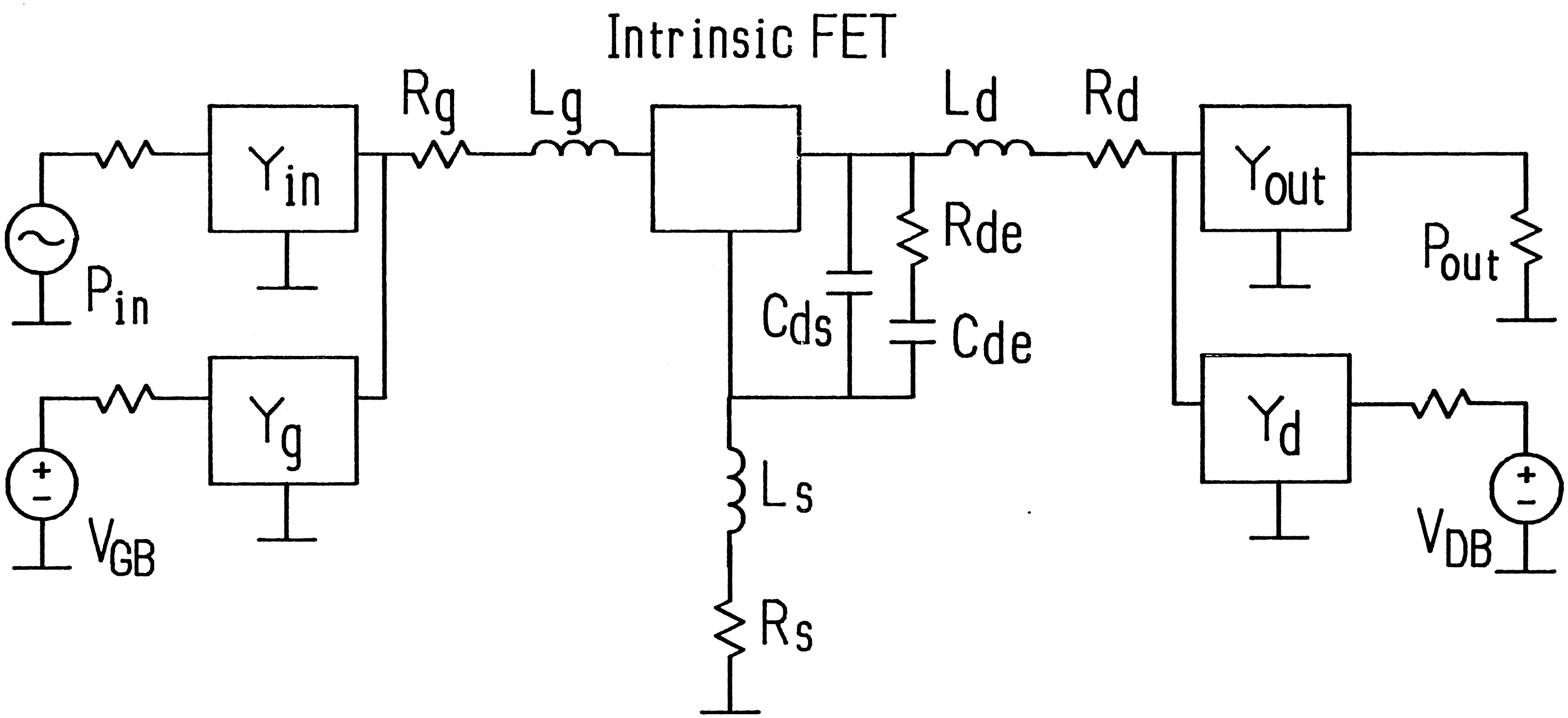
harmonic balance simulation technique for nonlinear circuit simulation in the frequency domain

nonlinear adjoint sensitivity analysis for gradient computation of nonlinear circuit responses

state-of-the-art ℓ_1 and ℓ_2 optimization

Circuit Setup for FET Model Parameter Extraction

Circuit Setup for FET Model Parameter Extraction



Modified Materka and Kacprzak Large-Signal FET Model

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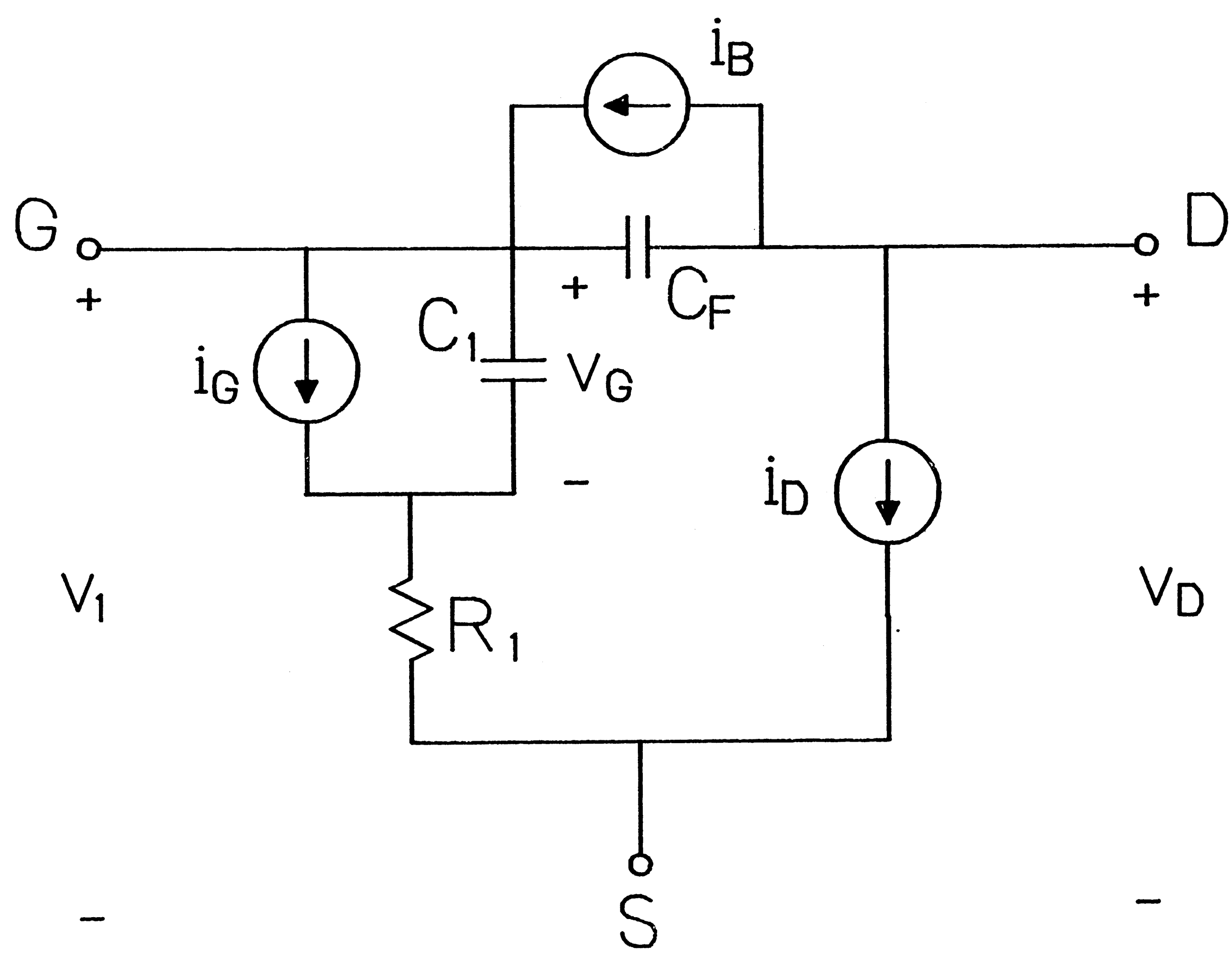


Three Numerical Experiments

(1) test of the robustness of the proposed approach

(2) fitting the Materka model to the Curtice model

(3) processing measurement data from Texas Instruments

Test of the Robustness of the Proposed Approach

the model is simulated at an assumed solution

using simulated measurement data, our parameter extraction converges to the known solution exactly

adding noise to the simulated data, the parameter extraction converges to the known solution almost exactly

there are 20 optimization variables and 64 error functions

about 13 CPU second/iteration on a VAX 8650 computer

typically 20-30 iterations or 250-400 CPU seconds in total

Fitting to the Curtice Model

simulated data is derived from the Curtice large-signal FET model

after optimization, the harmonic powers and DC responses computed from the Materka model match the simulated data perfectly

there are 20 optimization variables and 111 error functions

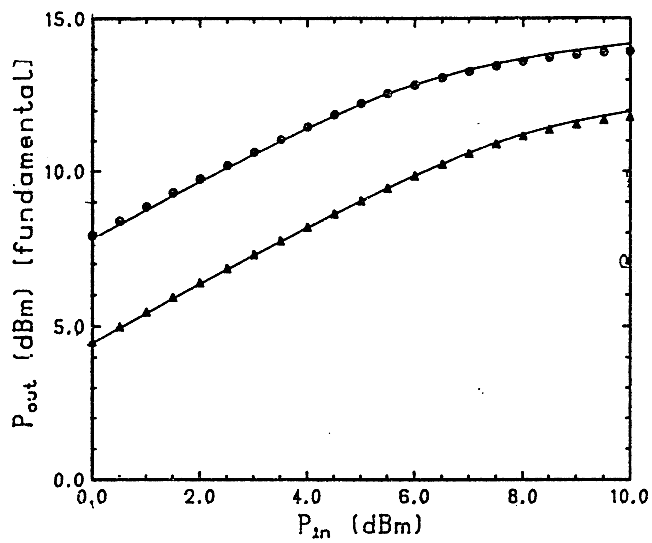
about 24 CPU sec/iteration on a VAX 8650 computer

typically 20-30 iterations or 500-750 CPU seconds in total

Fundamental Harmonic Match at V_{GB}*=-0.5V and* V_{DB}*=5.0V*

— Materka model response
○ simulated data at 0.5GHz fundamental frequency
Δ simulated data at 1.5GHz fundamental frequency

Fundamental Harmonic Match at V_{GB}=-0.5V and V_{DB}=5.0V



— Materka model response

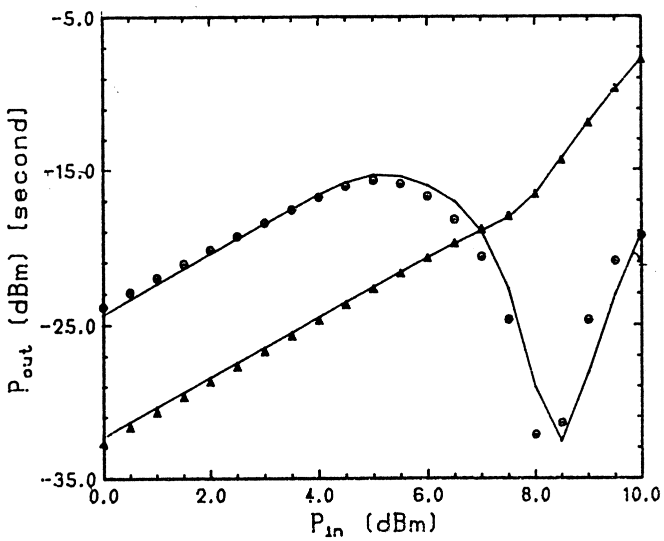
○ simulated data at 0.5GHz fundamental frequency

Δ simulated data at 1.5GHz fundamental frequency

Second Harmonic Match

— Materka model response
○ simulated data at 0.5GHz fundamental frequency
Δ simulated data at 1.5GHz fundamental frequency

Second Harmonic Match



— Materka model response

O simulated data at 0.5GHz fundamental frequency

Δ simulated data at 1.5GHz fundamental frequency

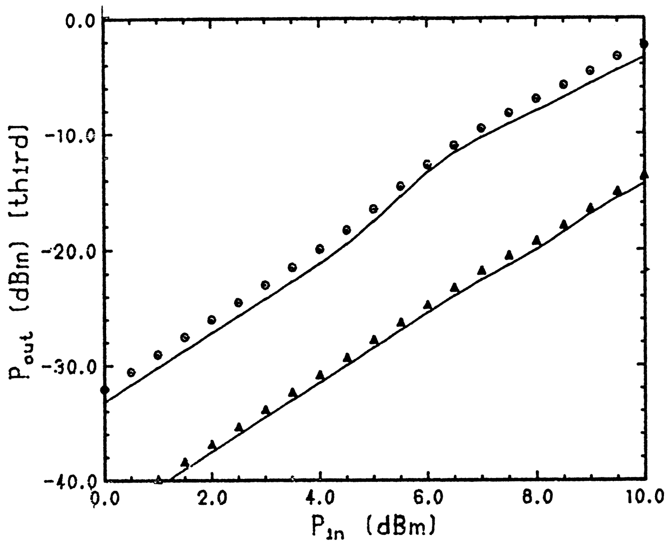
Third Harmonic Match

— Materka model response

○ simulated data at 0.5GHz fundamental frequency

Δ simulated data at 1.5GHz fundamental frequency

Third Harmonic Match



— Materka model response

O simulated data at 0.5GHz fundamental frequency

Δ simulated data at 1.5GHz fundamental frequency

Processing Measurement Data from Texas Instruments

small-signal S-parameter data is used to determine extrinsic linear parameters of the model

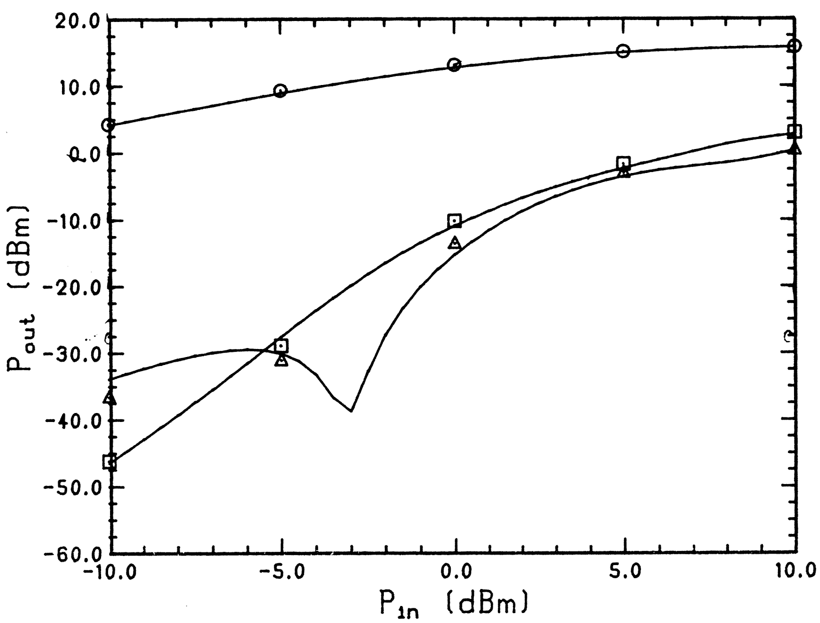
spectrum measurement data at two bias points, three fundamental frequencies, and input power level from -15dBm to 10dBm is used to extract the nonlinear intrinsic model parameters

there are 20 variables and 113 error functions

Spectrum Match at V_{GB}*=-0.373V,* V_{DB}*=2.0V and* f_1*=0.2GHz*

— Materka model response
○ measurement at fundamental frequency
△ measurement at second harmonic
□ measurement at third harmonic

Spectrum Match at V_{GB}=-0.373V, V_{DB}=2.0V and f_1=0.2GHz



— Materka model response

○ measurement at fundamental frequency

△ measurement at second harmonic

□ measurement at third harmonic

Spectrum Match at V_{GB}*=-0.673V,* V_{DB}*=4.0V and* f_1*=6GHz*

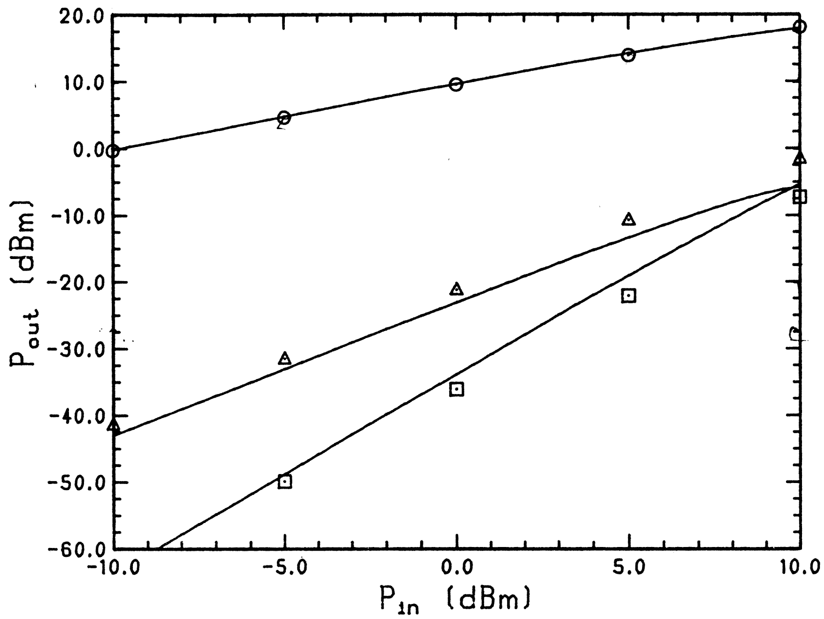
— Materka model response

○ measurement at fundamental frequency

△ measurement at second harmonic

□ measurement at third harmonic

Spectrum Match at V_{GB}=-0.673V, V_{DB}=4.0V and f_1=6GHz



— Materka model response
○ measurement at fundamental frequency
△ measurement at second harmonic
□ measurement at third harmonic

Results on the Apollo Platform

real measurement data from Texas Instruments

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

30 simultaneous nonlinear circuit simulations

20 optimization variables

2.3 hours of CPU time on Apollo DN3500 without floating point accelerator

Conclusions

our approach directly exploits FET nonlinear behaviour

powerful nonlinear adjoint sensitivity analysis is integrated into optimization

we use multi-bias, multi-power-input, multi-fundamental-

frequency excitations and multi-harmonic data

nonlinear large-signal model parameters are effectively identified

our technique has been implemented into a user-friendly program called HarPE

Model Characteristics

$$i_D = F[v_G(t - \tau), v_D(t)] \left(1 + S_S \frac{v_D}{I_{DSS}}\right)$$

$$F(v_G, v_D) = I_{DSS} \left[1 - \frac{v_G}{V_{p0} + \gamma v_D} \right]^{(E+K_E v_G)} \cdot \tanh \left[\frac{S_1 v_D}{I_{DSS}(1 - K_G v_G)} \right]$$

$$i_G = I_{G0} \left[\exp(\alpha_G v_G) - 1\right]$$

$$i_B = I_{B0} \exp[\alpha_B(v_D - v_1 - V_{BC})]$$

$$\begin{cases} R_1 = R_{10}(1 - K_R v_G) \\ R_1 = 0 \quad \text{if } K_R v_G \geq 1 \end{cases}$$

$$\begin{cases} C_1 = C_{10}(1 - K_1 v_G)^{-1/2} + C_{1S} \\ C_1 = C_{10}\sqrt{5} + C_{1S} \quad \text{if } K_1 v_G \geq 0.8 \end{cases}$$

$$\begin{cases} C_F = C_{F0}[1 - K_F(v_1 - v_D)]^{-1/2} \\ C_F = C_{F0}\sqrt{5} \quad \text{if } K_F(v_1 - v_D) \geq 0.8 \end{cases}$$

Parameters to be Determined

$$\phi = [I_{DSS}\ V_{P0}\ \gamma\ E\ K_E\ S_1\ K_G\ \tau\ S_s\ I_{G0}\ \alpha_G\ I_{B0}\ \alpha_B$$
$$R_{10}\ K_R\ C_{10}\ K_1\ C_{1S}\ C_{F0}\ K_F]^T$$

INPUT LEVELS USED WITH DIFFERENT FUNDAMENTAL FREQUENCIES AND DIFFERENT BIAS POINTS

(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

Sequential Parameter Extraction

use DC I-V curve fitting to determine some model parameters

fix those parameters and identify the rest by matching small-signal measurement data

Integrated DC/Small-Signal Parameter Extraction

take into account the relationship between the DC and small-signal parameters

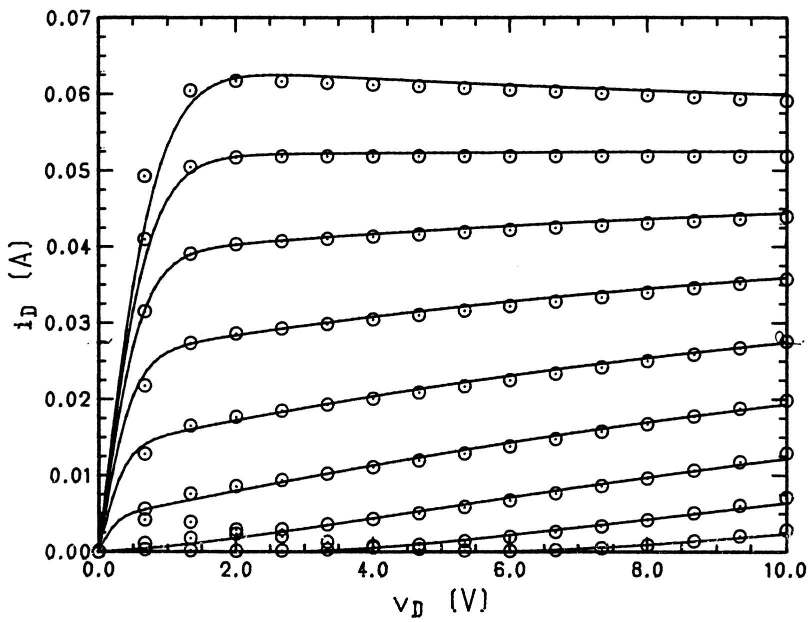
use multi-bias and multi-frequency measurements

combine DC and small-signal data matching into one optimization problem

Drain-to-Source DC I-V Curve Match

— Materka model
○ simulated data (Curtice model)

Drain-to-Source DC I-V Curve Match



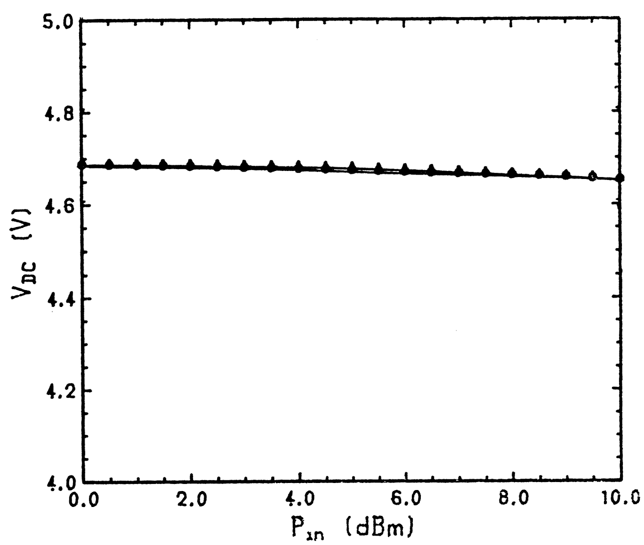
— Materka model

○ simulated data (Curtice model)

DC Response Match

— Materka model response
○ simulated data at 0.5GHz fundamental frequency
Δ simulated data at 1.5GHz fundamental frequency

DC Response Match



— Materka model response

○ simulated data at 0.5GHz fundamental frequency

Δ simulated data at 1.5GHz fundamental frequency

DC I-V Curve

DC I-V Curve