An Accurate Nonlinear MOSFET Model for Intermodulation Distortion Analysis

Breandán Ó hAnnaidh, *Student Member, IEEE,* and Thomas J. Brazil, *Fellow, IEEE*

***Abstract*—A compact charge-conservative nonlinear equivalent circuit model for metal–oxide–semiconductor field-effect transistors is comprehensively verified in terms of its ability to predict intermodulation distortion. The model is valid for the dc, small-signal, and large-signal simulation of high frequency circuits over a wide range of bias conditions and is globally fully continuous. Simulations made using the model, following parameter extraction, are validated by comparisons with experimental data. Using harmonic balance methods, intermodulation distortion for weak and large-signal two-tone tests and more realistic wide-band code-division-multiple-access signals is successfully predicted for a range of bias points.**

***Index Terms*—Advanced design system (ADS), intermodulation distortion (IMD), metal–oxide–semiconductor field-effect transistors (MOSFETs), wide-band code-division-multiple-access (WCDMA).**

I. Introduction

THE importance of the ability of a high frequency device model to predict intermodulation distortion has been well documented and there is much in the literature regarding intermodulation distortion (IMD) prediction for metal–semiconductor field-effect transistors (MESFETs) and pseudomorphic high-electron mobility transistors (pHEMTs) [1]–[3]. The aim of this paper is to report on the predictive capabilities in terms of intermodulation distortion of a charge-conservative, nonlinear, equivalent circuit model of RF metal–oxide–semiconductor field-effect transistors (MOSFETs) [4]. The model's predictive capabilities in weak-signal analysis has previously been assessed [5]. This paper extends the analysis, through harmonic balance methods, to large-signals, using both two-tone and wide-band code-division-multiple-access (WCDMA) signals, and determines the model's overall performance.

Based on the I_{ds} model function (*COBRA*) [6], as well as a new charge formulation together with traditional extraction techniques, we show that the IMD characteristics can be predicted very well in the case of MOSFET processes. The model is implemented in Agilent's Advanced Design System (ADS) and harmonic balance methods are used for simulations. The capacitances are derived from a single nonlinear gate charge expression that ensures charge conservation. The model parameters were extracted for a MOSFET with $L_g = 0.18$ μm, and $W_g = 100$ μm and verified with both small-signal and large-signal measurements at different bias conditions.

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The authors are with the Department of Electronic and Electrical Engineering, University College Dublin, Dublin 4, Ireland (e-mail: breandan.ohannaidh@ucd.ie).

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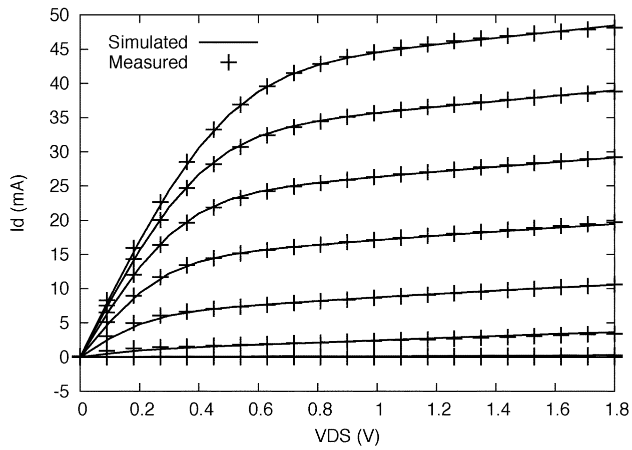

Fig. 1. DC characteristics for $V_{\text{GS}} = 0$ to 1.6 V in steps of 0.2 V.

Following verification of the model's ability to predict weak-signal IMD from results of two-tone tests carried out on the device, we compare large-signal two-tone measurements to the simulations over a wide range of bias points. We also compare simulation results to measurements of complex distortion due to WCDMA signals of relatively high input powers applied to the device.

II. Model Verification

Equation (1) gives the drain current equation we have implemented in the model for RF MOSFET devices and is an adapted version of the COBRA model [6] developed for MESFET and pHEMT devices

$$I_{\text{ds}}(V_{\text{gs}}, V_{\text{ds}}) = \beta V_{\text{eff}}^{\frac{\lambda}{1+\mu \cdot V_{\text{ds}}^2 + \xi \cdot V_{\text{eff}}}} \tanh\left[\alpha V_{\text{ds}}(1+\zeta V_{\text{eff}})\right]$$
$$V_{eff} = \frac{1}{2}\left(V_{\text{gst}} + \sqrt{V_{\text{gst}}^2 + \delta^2}\right)$$
$$V_{\text{gst}} = V_{\text{gs}} - \beta_r V_{TO} + \gamma V_{\text{ds}}. \quad (1)$$

In (1), V_{TO} is the pinchoff voltage and α, β, β_r, γ, δ, λ, μ, ξ, and ζ are model parameters. The model is continuous over the entire bias plane and its derivatives are continuous, which is important for a good representation of the intermodulation characteristics [1].

The nonlinear capacitance expressions $C_{\text{gs}}(V_{\text{gs}}, V_{\text{gd}})$ and $C_{\text{gd}}(V_{\text{gs}}, V_{\text{gd}})$ are determined from the derivatives, with respect to V_{gs} and V_{gd}, of a single gate charge expression, $Q(V_{\text{gs}}, V_{\text{gd}})$, given in [4]. The model is charge conservative if (2) is satisfied for the single gate charge function [7]–[9]

$$\frac{\partial C_{\text{gd}}}{\partial V_{\text{gs}}} = \frac{\partial^2 Q}{\partial V_{\text{gs}} \partial V_{\text{gd}}} = \frac{\partial^2 Q}{\partial V_{\text{gd}} \partial V_{\text{gs}}} = \frac{\partial C_{\text{gs}}}{\partial V_{\text{gd}}} \quad (2)$$

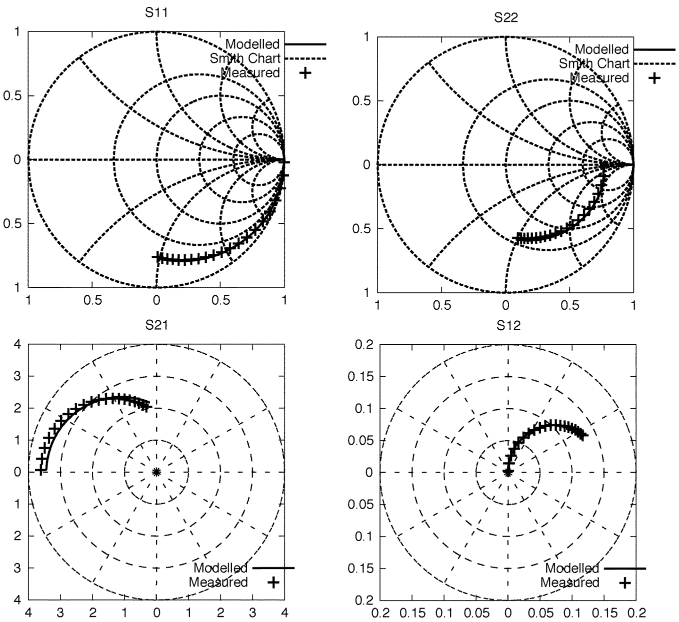

Fig. 2. S-parameter measurements and simulations for $V_{\rm DS} = 1.0$ V and $V_{\rm GS} = 0.8$ V from 0.5 to 10 GHz.

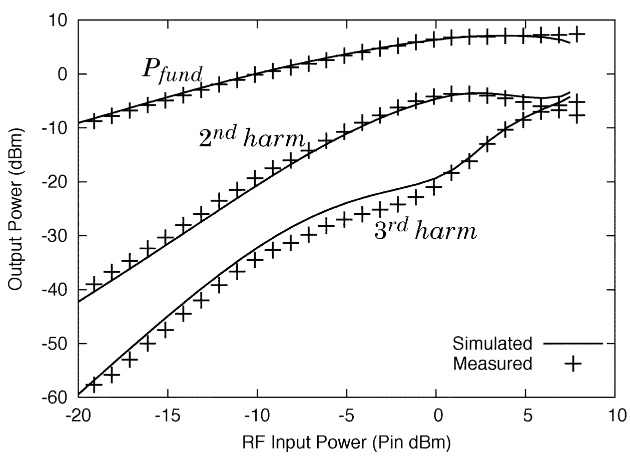

Fig. 3. One-tone power measurements against ADS simulations for the extracted model at $V_{\rm DS} = 0.8$ V and $V_{GS} = 1.2$ V.

Bias dependent S-parameter measurements and dc-measurements from an on-wafer MOSFET ($L_g = 0.18$ μm, $W_g = 100$ μm) were used for the extraction of the model parameters. The intrinsic elements were calculated after de-embedding of the parasitics from measured S-parameters from 0.5 to 10 GHz [10]. Using in-house software, the parameters were extracted using an optimization procedure by fitting the model equations on the measured dc and ac data. The results can be seen in Figs. 1 and 2.

In order to validate the model, following implementation in the ADS environment, single-tone measurements were carried out with a microwave power $P_{\rm in}$ applied at the input of the on-wafer device using a 50-Ω generator. The first to third harmonics of the output power $P_{\rm out}$ dissipated by the 50-Ω output load were measured. Fig. 3 shows excellent agreement between simulated and experimental results to the third harmonic for a bias of $V_{\rm DS} = 0.8$ V and $V_{\rm GS} = 1.2$ V. This kind of agreement is typical of that we observed for dc bias points covering most of the bias plane in Fig. 1.

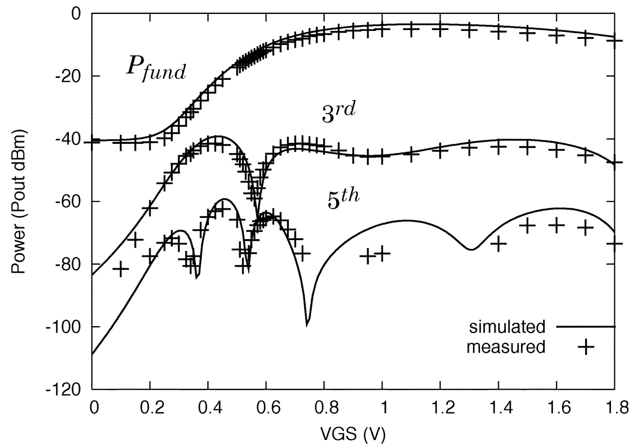

Fig. 4. Characteristics of intermodulation distortion products against swept gate-source voltage for weak-signal two-tone tests at $V_{\rm DS} = 1.0$ V and $P_{\rm in} = -15$ dBm.

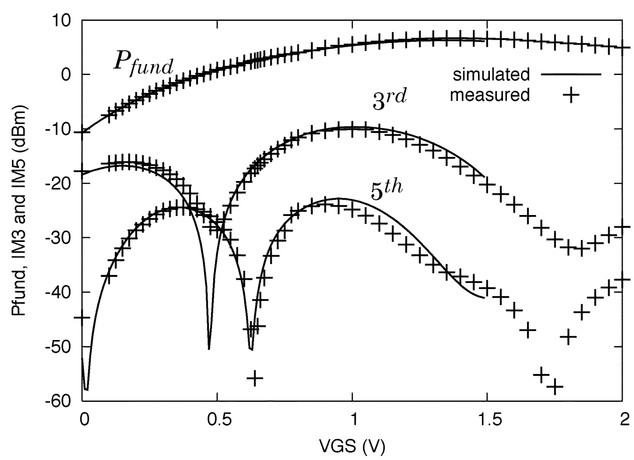

Fig. 5. Characteristics of intermodulation distortion products against swept gate-source voltage for two-tone tests at $V_{\rm DS} = 1.2$ V and $P_{\rm in} = -2$ dBm.

III. IMD

In [5], the behavior of the derivatives of the I/V model are related to a series of weak-signal two-tone measurements, for swept $V_{\rm GS}$. A series of alternating lobes in the I/V derivatives are due to the highly nonlinear effects seen around turn-on [2], [11] and can be related to the number of sweet-spots [12] present in the results obtained for the two-tone measurements presented in Fig. 4. A -15-dBm input signal was used with a tone spacing of 200 kHz, centered on 2 GHz. We measured the output power, third and fifth order IMD against swept V_{GS}, with $V_{\rm ds} = 1.0$ V and the close agreement between the measurements and simulations up to the fifth oder is quite apparent. Measurements below the apparatus noise floor are not included and result in gaps in the fifth order IMD.

Having established the model's ability to accurately predict IMD behavior in the case of two-tone weak-signal experiments, we sought to evaluate its ability to predict IMD using larger signals. A -2-dBm input signal was used with a tone spacing of 1 MHz, centered on 2 GHz. We measured the output power, third and fifth-order IMD against swept $V_{\rm GS}$, with $V_{\rm DS} = 1.2$ V.

The results shown in Fig. 5 cannot alone be predicted by the I/V derivatives with respect to V_{GS} because we no longer have small perturbations of $V_{\rm ds}$, as is the case for weak-signals [5].

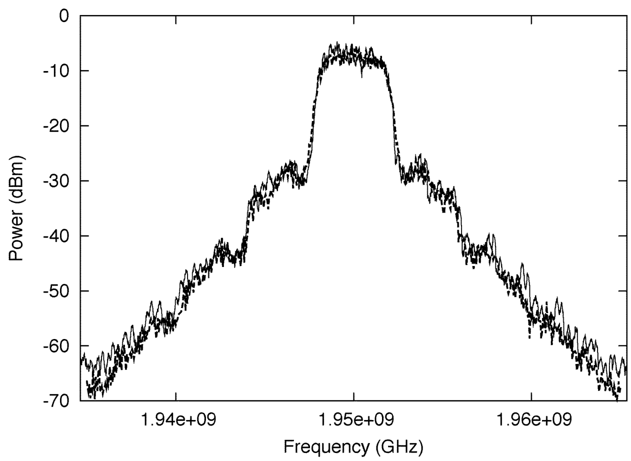

Fig. 6. Measured and simulated frequency spectra of a WCDMA signal of $P_{\rm in} = +4$ dBm at $V_{\rm DS} = 1.0$ V, $V_{\rm GS} = 0.8$ V.

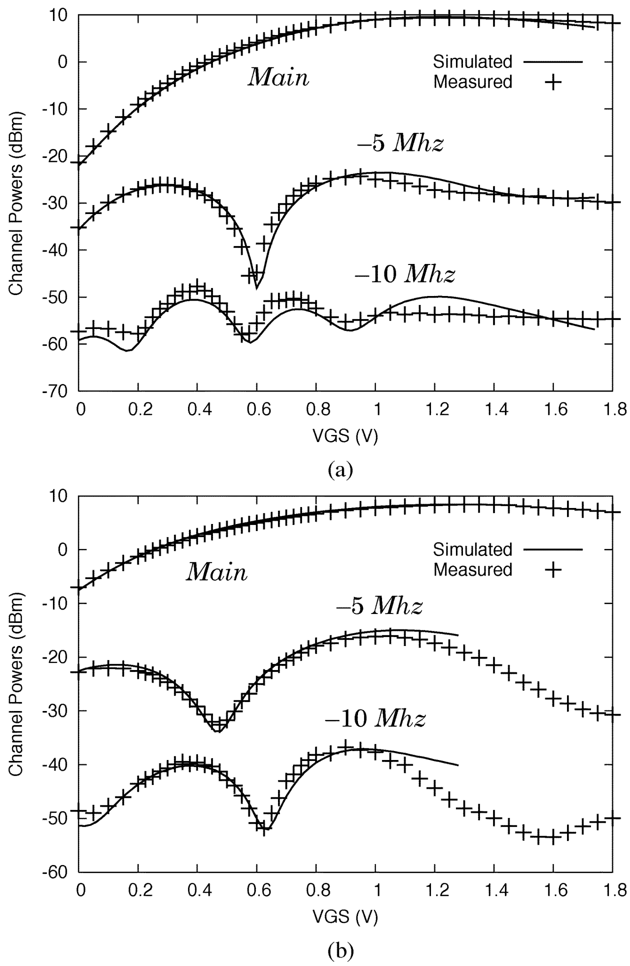

Fig. 7. Simulations versus measurements of the main and lower channel powers for swept $V_{\rm GS}$, for a WCDMA signal of high input power applied to the MOSFET at (a) $V_{\rm DS} = 1.6$ V, $P_{\rm in} = -2$ dBm, and (b) $V_{\rm DS} = 1.0$ V, $P_{\rm pin} = +2$ dBm.

Nonetheless, the model simulates very accurately the IMD behavior of the MOSFET, up to the fifth order, for these larger signals. The simulations were carried out to the ninth order but can be carried out to higher orders. At higher input power levels, convergence properties of ADS became problematic for similar reasons to those leading to simulation failure for $V_{GS} > 1.5$ V in Fig. 5.

With these highly accurate results for IMD for large-signal two-tone tests, we sought to determine the model's ability to predict more complex distortion characteristics using WCDMA signals of high input power. Using an Agilent E4438C ESG, we generated a Third Generation Partnership Project (3-GPP) WCDMA signal excitation with a 3.84-Mchip/s chip rate at 2 GHz, with input levels of −2, 0, 2, and 4 dBm and swept $V_{\rm GS}$ with $V_{\rm DS} = 1.6$, 1.2, and 1.0 V. The frequency spectra showing simulations compared to measurements for a particular bias point can be seen in Fig. 6. A comparison of measurements and simulations for the main channel power and first and second lower adjacent channel powers for swept $V_{\rm GS}$ at different $V_{\rm DS}$ and input power levels is presented in Fig. 7 showing excellent agreement. Again, the behavior of the channel powers against $V_{\rm GS}$ is notable.

IV. Conclusion

A charge-conservative compact nonlinear equivalent circuit model for RF MOSFETs has been verified in terms of its accuracy in predicting intermodulation distortion. The nonlinear drain current and charge expressions are globally continuous both in themselves and to arbitrary orders of differentiation. Measurements and simulations of intermodulation distortion products of weak and large-signal two-tone tests are in excellent agreement, as are the results for the complex distortion due to WCDMA signals of high input power.

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