Improved Prediction of the Intermodulation Distortion Characteristics of MESFETs and PHEMTs Via a Robust Nonlinear Device Model

Vicentiu I. Cojocaru and Thomas J. Brazil

Department of Electronic and Electrical Engineering
University College Dublin, Ireland.

ABSTRACT

The paper investigates the intermodulation distortion (IMD) prediction capabilities of the *COBRA* model [1] by analysing the first, second and third order derivatives of the drain *I/V* model and the gate *Q/V* model. The model is extracted simply from DC and small-signal S-parameter data, without the need for complex low-frequency (VHF) measurements of harmonic output levels under low-load conditions, as proposed in previous studies. The computed main *I/V* characteristic and its derivatives are shown to be continuous over the entire bias plane, and are proven to give better results than other models available. Results of two-tone large signal tests for the case of a 0.2µm PHEMT process are presented, showing excellent agreement between simulated and experimental third and fifth intermodulation products.

INTRODUCTION

Good prediction of IMD characteristics and spurious-response levels of MESFET and PHEMT devices is becoming increasingly important for microwave/RF circuit designers, especially in applications such as FET mixers and amplifiers. At the same time, modelling these characteristics represents one of the most difficult challenges for device modellers. Recently it has been demonstrated [2][3][4] that there is a direct connection between the capability of a FET model to predict those characteristics and the model's ability to reproduce the behaviour of the derivatives of the main *I/V* and *Q/V* characteristics. These two nonlinear characteristics can be expressed via Taylor series expansions as follows:

$$I_{ds}(V_{gs},V_{ds}) = I_{ds}(V_{GS},V_{DS}) + \frac{\partial I_{ds}}{\partial V_{gs}} v_{gs} + \frac{\partial I_{ds}}{\partial V_{ds}} v_{ds} + \frac{\partial^2 I_{ds}}{\partial V_{gs}^2} v_{gs}^2 + \frac{\partial^2 I_{ds}}{\partial V_{gs} \partial V_{ds}} v_{gs} \cdot v_{ds} + \frac{\partial^2 I_{ds}}{\partial V_{ds}^2} v_{ds}^2 + \ldots = \tag{1}$$

$$= I_{ds}(V_{GS}, V_{DS}) + Gm \cdot v_{gs} + Gds \cdot v_{ds} + Gm2 \cdot v_{gs}^2 + Gmd \cdot v_{gs} \cdot v_{ds} + Gd2 \cdot v_{ds}^2 + \ldots$$

where $I_{ds}(V_{GS}, V_{DS})$ is the DC current, $v_{gs} = V_{gs} - V_{GS}$ and $v_{ds} = V_{ds} - V_{DS}$, and *Gm2, Gmd,…,Gd3* are the second and third order coefficients that can be identified with the corresponding partial derivatives. Similarly we have:

$$Q_g(V_{gs},V_{ds}) = Q_g(V_{GS},V_{DS}) + \frac{\partial Q_g}{\partial V_{gs}} v_{gs} + \frac{\partial Q_g}{\partial V_{ds}} v_{ds} + \frac{\partial^2 Q_g}{\partial V_{gs}^2} v_{gs}^2 + \frac{\partial^2 Q_g}{\partial V_{gs} \partial V_{ds}} v_{gs} \cdot v_{ds} + \frac{\partial^2 Q_g}{\partial V_{ds}^2} v_{ds}^2 + \ldots \tag{2}$$

In [2] and [4], experimental methodologies are described for the extraction of the second and third order coefficients in (1), based on low-frequency (VHF) RF measurements of harmonic output levels under low-load conditions. More recently, Garcia *et al*. [5] presented another method based on harmonic measurements, for the extraction of the second and third order coefficients in (2). These experimental methodologies are very useful for providing the basic data for the actual model extraction process. Regarding the *I/V* characteristic, Maas *et al*. [2] proposes a novel drain current model along with a fitting procedure based upon simultaneous fitting for the gate-voltage portion of the model, to the measured *Ids* characteristics and its derivatives. Peng *et al*. [6], have shown that in the case of gate FET mixers, second and third order *Gds* terms have a negligible impact on the overall model performance in comparison with the corresponding *Gm* terms. They propose an empirical Gaussian function for *Gm2*, while *Gm* and *Gm3* are derived from *Gm2* by simple integration and differentiation with respect to *Vgs*.

In this study we demonstrate how by using the robust general-purpose *COBRA* model, we could still obtain very good IMD predictions for both MESFET and PHEMT devices, without the need for the complex and expensive harmonic measurements and extraction routines required by the techniques described above. Also, we show how *COBRA* model compares favourably with some of the better available equivalent circuit FET models.

IMD PREDICTION CAPABILITIES OF *COBRA*

Although the model extraction methodologies described above are accurate and reliable, they nevertheless require quite complex measurement equipment and extraction routines, which are not often available in practice to the regular device modeller. However, these extraction methods provide some very useful information regarding the type of behaviour it should be expected for the *I/V* and *Q/V* derivatives from a model with good IMD prediction capabilities. As shown in [3], most of the existing FET models, although they can predict relatively well the *I/V* characteristics, they fail to a large extent to reproduce the corresponding derivatives. We will show here how by using a novel *Ids* model function (*COBRA*) and traditional extraction techniques (using the *COMET* extraction tool) [1], we can still predict very well the IMD characteristics in the case of both PHEMT and MESFET processes.

The DC model function describes very well the FET behaviour all around the bias spectrum: linear, knee and the saturation regions; reverse bias region; it can describe also soft breakdown and mild second knee behaviour; it converges smoothly towards zero, when V_{gs} drops below pinch-off; has the ability to follow the negative slope seen in real FETs in the saturation region at high values of the gate voltage, due to electron traps and self heating effects. The equation for the drain current model is:

$$I_{ds}(V_{GS},V_{DS}) = \beta \cdot V_{eff}^{\frac{\lambda}{1+\mu \cdot V_{DS}^2+\xi \cdot V_{eff}}} \cdot \tanh\left[\alpha V_{DS} \cdot (1+\zeta \cdot V_{eff})\right]$$
$$V_{eff} = \frac{1}{2} \cdot \left(V_{gst} + \sqrt{V_{gst}^2+\delta^2}\right)$$
$$V_{gst} = V_{GS} - (1+\beta_r^2) V_{T0} + \gamma \cdot V_{DS} \qquad (3)$$

where V_{T0} is the pinch-off voltage and $\alpha, \beta, \beta_r, \gamma, \delta, \lambda, \mu, \xi, \zeta$, are model parameters. β_r is a dimensionless parameter, numerically equal with β (when I_{ds} is expressed in Amperes). The model function is continuous over the entire bias plane and its derivatives are also continuous. In Figure 1.a we compare measured and modelled (*COBRA*) DC characteristics for a 0.2x120μm PHEMT device from Philips. In Figure 1.b, the same data are compared with a modified Materka model. We chose this model because it gave the best fit among all the other traditional FET models available. It should be noticed from the start that one important shortcoming of the Materka model (and indeed of most of the other models available) is the restricted bias range over which the main model function and its derivatives are defined and continuous, which represents a great disadvantage in many applications. However, it is very hard to see significant differences between the two DC models just by looking at the two data-fits in Fig. 1, within the normal operating regions. But things are looking quite different when the derivatives of the main model function are analysed and compared. For the two extracted models we calculated the first, second and third derivatives with respect to *Vgs*, and the results are presented in Fig. 2 (*COBRA*) and Fig. 3 (Materka). By simple comparison with the results shown in [3][4][6], it is clear that the *COBRA* model predictions are very similar with what it is expected. All derivatives are seen to be continuous over the entire bias plane.

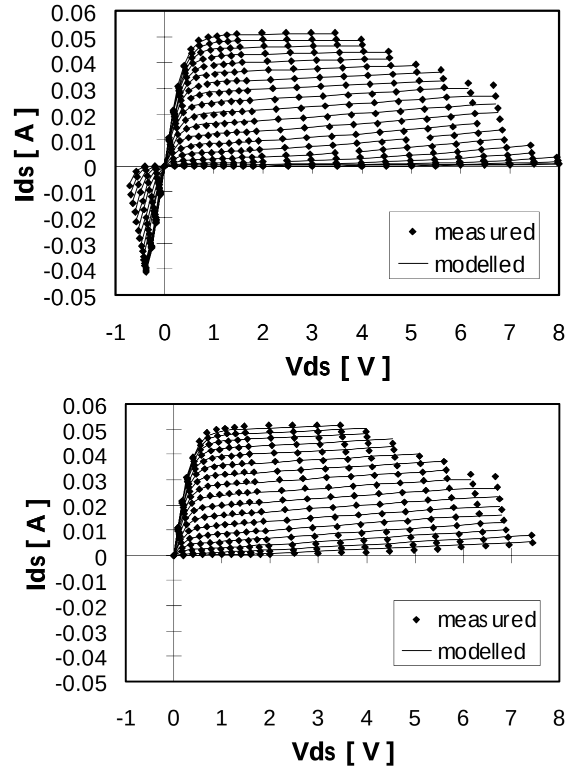

Figure 1. Measured vs. modelled *I/V* characteristics for a 0.2x120μm PHEMT: **(a)** *COBRA* (*Vgs=-1.4V to +0.6V; Vpo=-1.0V*); **(b)** Modified Materka (*Vgs=-1.0V to +0.6V*).

As far as the Materka model is concerned (and similar for most of the traditional FET models), a first observation concerns the effect of the limited bias-range where the main model-function is valid. This brings significant distortions, especially in the bias region around pinch-off, for all the *I/V* derivatives. Also there is less accurate description of the second and third order derivatives even within the normal operating bias region.

A similar study has been performed on the *Q/V* characteristics, and the corresponding computed derivatives of the *COBRA Q/V* model compare well with those extracted from harmonic measurements for similar devices and presented in [4]. Another strength of the *COBRA* model in comparison to other models, which enhances among other things its IMD prediction capabilities, is given by the consistent account of DC/AC dispersion effects as described in detail in [1][7].

Finally, results of IMD tests for the case of a 0.2μm PHEMT process are presented in Fig. 4 (*COBRA*) and Fig. 5 (Materka), for four different bias conditions. They demonstrate much better IMD prediction capabilities in the case of the *COBRA* model. Similar results have been obtained in the case of a 0.5μm MESFET process.

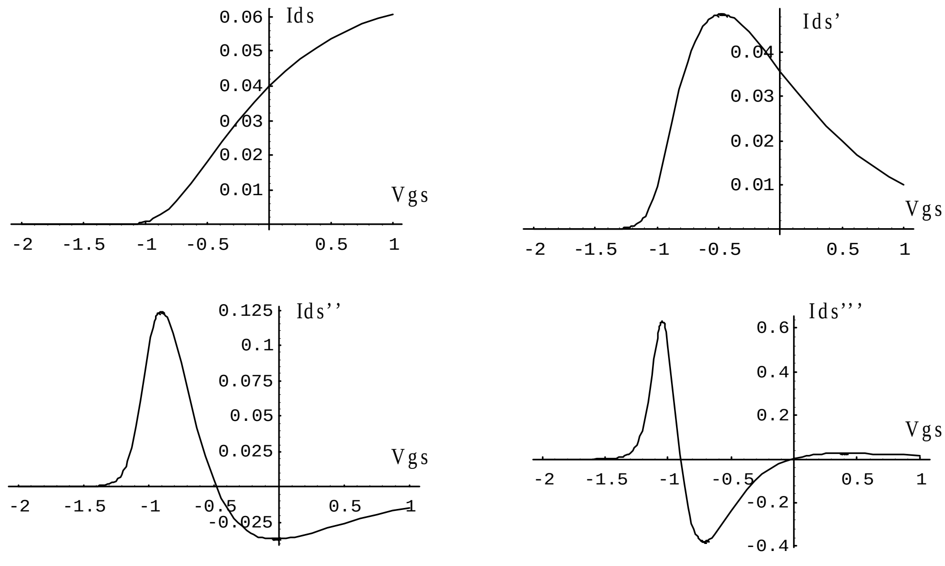

Figure 2. The calculated derivatives of the drain current function for the *COBRA* model (0.2x120µm PHEMT process with *Vpo = -1.0V; Vds = 3.0V*)

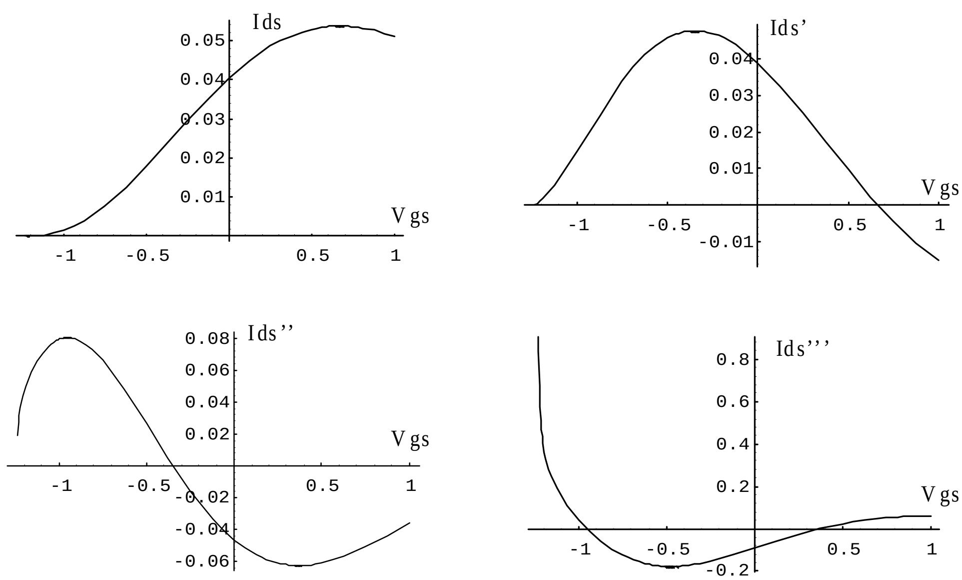

Figure 3. The calculated derivatives of the drain current function for the modified Materka model (0.2x120µm PHEMT process with *Vpo = -1.0V; Vds = 3.0V*)

CONCLUSIONS

We have demonstrated how by using the robust general-purpose *COBRA* model, we could still obtain very good IMD predictions for FET devices, without the need for the complex and expensive harmonic measurements and extraction routines required by the techniques previously used. Also, extensive test results have demonstrated how *COBRA* model IMD prediction capabilities compares favourably with some of the better available equivalent circuit FET models.

ACKNOWLEDGEMENTS

This work has been partly supported by the *ESPRIT-EDGE* project. The authors would like to thank Dr. Remy Leblanc of Philips Microwave Limeil, France, and Dr. Mike Brookbanks of GEC-Marconi, UK, for providing the FET devices used in this study.

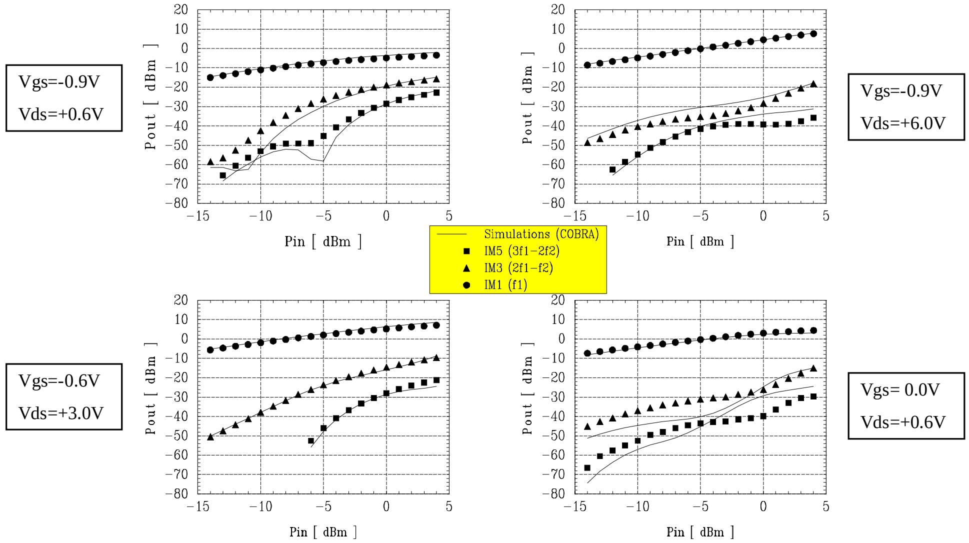

Figure 4. Results of an IMD test (*COBRA* Model) including the fundamental, third and fifth IM products for a 0.2x120µm PHEMT (*Vpo = -1.0V; f1 = 8.975 GHz, f2 = 9.015GHz*);

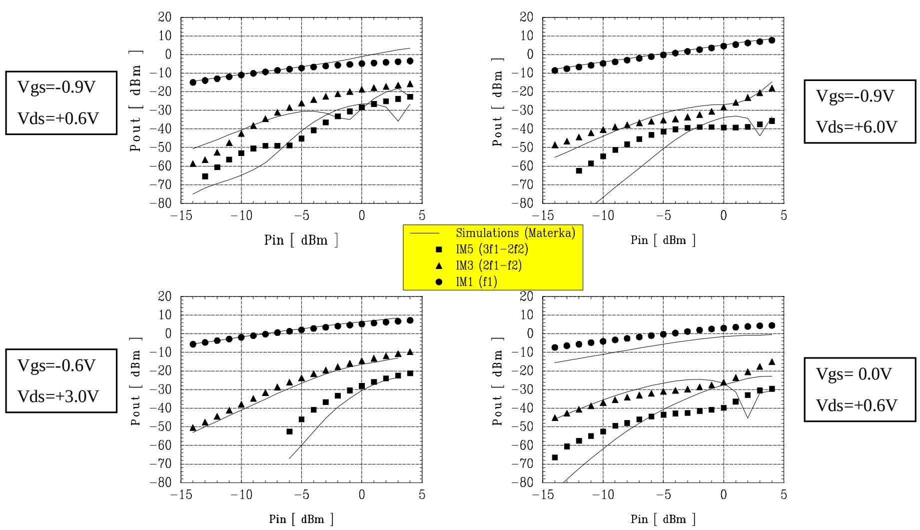

Figure 5. Results of an IMD test (Modified Materka Model) including the fundamental, third and fifth IM products for a 0.2x120µm PHEMT (*Vpo = -1.0V; f1 = 8.975 GHz, f2 = 9.015GHz*);

REFERENCES

[1] Cojocaru V.I., Brazil T.J., "A scalable general-purpose model for microwave FET's including the DC/AC dispersion effects", *IEEE Trans. on MTT*, Vol.45, No.12, December 1997.

[2] Maas S.A., Crosmun A., "Modelling the gate I/V characteristic of a GaAs MESFET for Voltera-series analysis", *IEEE Trans. on MTT*, Vol.37, No.7, pp. 1134-1136, July 1989.

[3] Maas S.A., Neilson D., "Modelling MESFET's for intermodulation analysis of mixers and amplifiers", *IEEE Trans. on MTT*, Vol. 38, pp. 1964-1971, December 1990.

[4] Pedro J.C., Perez J., "Accurate simulation of GaAs MESFET's intermodulation distortion using new drain-source current model", *IEEE Trans. on MTT*, Vol. 42, No.1, pp.25-33, January 1994.

[5] Garcia J.A., Mediavilla A., Tazon A., Garcia J.L., Pedro J.C., Accurate characterisation procedure of FET's reactive nonlinearities for intermodulation analysis", *Proc. of GAAS'97 conference*, pp. 87-90, Bologna, Italy, September 1997.

[6] Peng S., McCleer P.J., Haddad G.I., "Nonlinear Models for the intermodulation analysis of FET mixers", *IEEE Trans. on MTT*, Vol. 43, No. 5, pp. 1037-1045, May 1995.

[7] Cojocaru V.I., Brazil T.J., "Scalability of DC/AC non-linear dispersion models for microwave FET's", *IEEE MTT-S Digest*, pp. 387-390, Denver, 1997.