Experimental Evaluation of Large-Signal Modeling Assumptions Based On Vector Analysis of Bias-Dependent S-Parameter Data from MESFETs and HEMTs

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ABSTRACT

This paper presents, for the first time, a systematic experimental examination of the validity of basic large-signal modeling assumptions by subjecting measured S-parameter data versus bias from MESFETs and HEMTs to various mathematical operations of vector analysis. Several approaches are used to determine the degree to which pairs of device nonlinearities can be accurately modeled by charge-based nonlinear capacitors, voltage-controlled current sources, and higher-order elements arranged in a standard equivalent circuit topology. Implications are discussed for such circuit modeling concepts as terminal charge conservation and its extension to other state-functions.

Introduction

Practical large-signal FET models, implemented in commercial nonlinear circuit simulators, usually assume that the intrinsic device nonlinearities can be represented (at least for modest frequencies) by a parallel connection of lumped, voltage controlled current sources and charge-based, nonlinear capacitors as shown, for example, in Figure 1a. A more complete, non-quasi static model, which adds "higher order" elements (state-functions) is shown in Figure 1b. However, it is impossible to exactly fit the bias dependence of all the intrinsic Y-parameters with such models *regardless* of the functional form used for the element constitutive relations unless Equation 1 holds for vector fields, $\vec{F}_i$, formed from various pairs of measured bias-dependent functions [1,2]. Vector fields satisfying Equation (1) are called *conservative*. This paper presents several methods used to evaluate, from experimental data, the degree to which each of the vector fields $\vec{F}_i$ is conservative, and therefore the suitability of the models of Figure 1 for large-signal circuit analysis of real FET devices.

$$\oint [\vec{F}_i(V_{GS},V_{DS}) \cdot d\vec{V}] = 0 \qquad (1)$$

$$d\vec{V} = \hat{V}_{GS}\, dV_{GS} + \hat{V}_{DS}\, dV_{DS}$$

$$\vec{F}_1 = \hat{V}_{GS} \frac{Y^{meas}_{11imag}(V_{GS},V_{DS},\omega)}{\omega} + \hat{V}_{DS} \frac{Y^{meas}_{12imag}(V_{GS},V_{DS},\omega)}{\omega} \qquad (2)$$

$$\vec{F}_2 = \hat{V}_{GS} \frac{Y^{meas}_{21imag}(V_{GS},V_{DS},\omega)}{\omega} + \hat{V}_{DS} \frac{Y^{meas}_{22imag}(V_{GS},V_{DS},\omega)}{\omega} \qquad (3)$$

$$\vec{F}_3 = \hat{V}_{GS}\, Y^{meas}_{21real}(V_{GS},V_{DS},\omega > \omega_t) + \hat{V}_{DS}\, Y^{meas}_{22real}(V_{GS},V_{DS},\omega > \omega_t) \qquad (4)$$

Here $\hat{}$ means unit vector, ω_t is characteristic of the inverse thermal and trap time constants, and V_{GS} and V_{DS} are intrinsic terminal voltages.

Analysis Methods and Results

IF1

In the first approach, Equation (1) is evaluated directly from intrinsic Y-parameters which have been transformed from S-parameters and de-embedded through calculated parasitics in the usual way [3]. Each bias point in a rectangular region of (extrinsic) voltage space, together with a fixed point (V_{GS0},V_{DS0}), determines a closed rectangular contour as shown in Figure 2. The normalized values of the closed contour integrals calculated for each of the vector fields of measured data given by Equations (2)-(4) are plotted as functions of (extrinsic) bias voltages in Figures (3a)-(3c). The data comes from a 1um x 500um MESFET with 10 fingers.

The $\vec{F}_1$ field results in a very small value for the relative closed contour integral. We conclude that $\vec{F}_1$ is a conservative vector field, or equivalently, terminal charge is conserved at the gate. The $\vec{F}_2$ and $\vec{F}_3$ fields also result in small values of the closed contour integrals, but not everywhere (in bias space) as small as $\vec{F}_1$. Therefore, $\vec{F}_2$ and $\vec{F}_3$ can be said to be at least approximately conservative, or equivalently, terminal charge and high-frequency terminal current are at least approximately conserved at the drain.

The second approach presented here uses the procedure of [2] to define scalar functions, ϕ_i, by line integration of the fields of measured data $\vec{F}_i$. Provided $\nabla\phi_i$ is a good approximation to $\vec{F}_i$ for {i=1,2,3}, the ϕ_i functions can be used as constitutive relations to define the nonlinear model elements in the topology of Figure 1b. A comparison of components of the gradient of these calculated scalar fields to the components of the original vector fields, as well as the relative error in approximating $\vec{F}_i$ by $\nabla\phi_i$, is shown in Figures (4a)-(4c). The data used for this example is from a 0.25um x 240um MODFET with 8 gate fingers. In each case, $\nabla\phi_i$ is a good approximation to $\vec{F}_i$, with the best result for $\vec{F}_1$. These results are consistent with the first method.

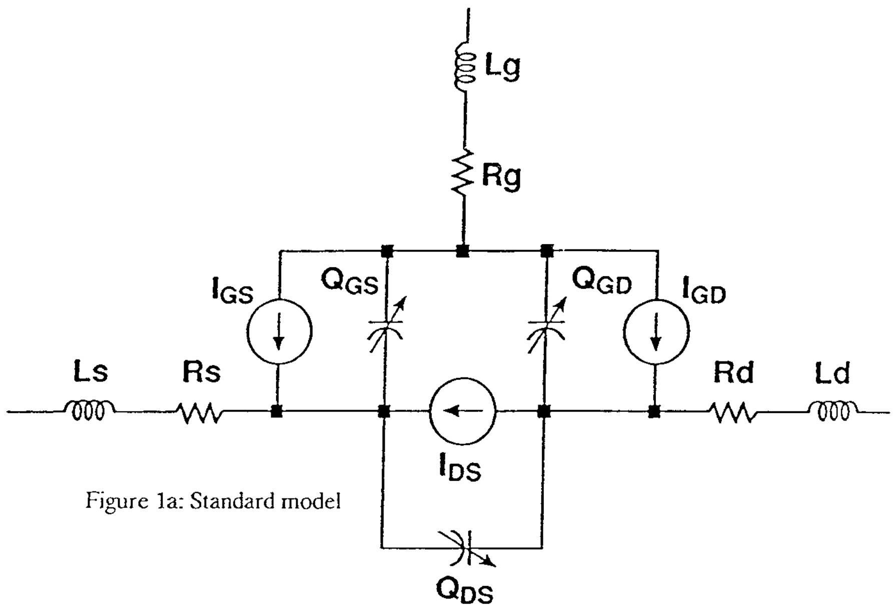

Figure 1a: Standard model

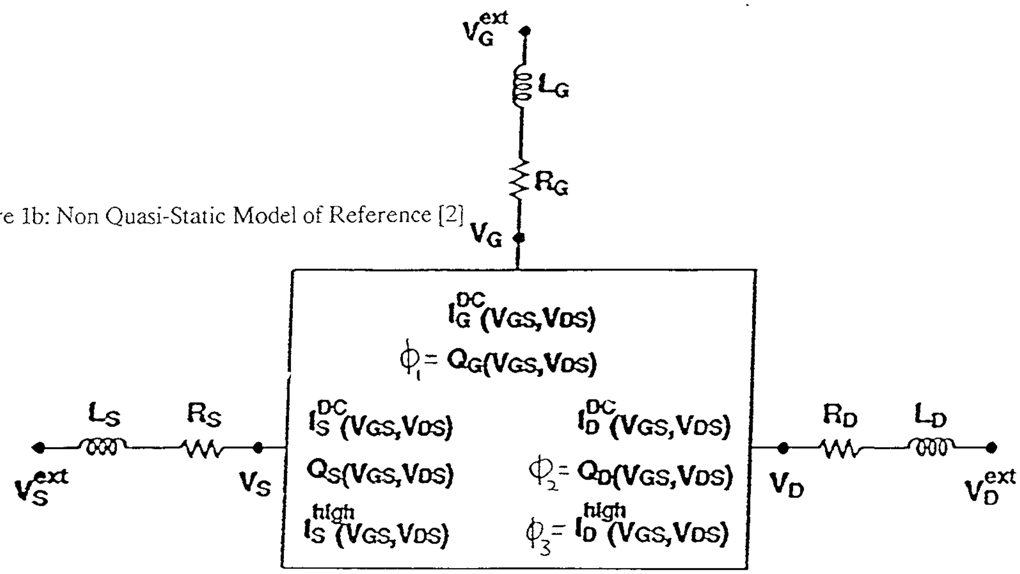

Figure 1b: Non Quasi-Static Model of Reference [2]

Figure 1: Simple Large-Signal Equivalent Circuits of a GaAs FET
("R_i" elements are neglected)

Summary and Conclusions

Various operations of vector analysis have been performed on bias-dependent S-parameter data from several types of MESFETs and HEMTs, in order to examine the validity of basic assumptions of most large-signal FET models for circuit simulation. For the range of devices tested, the circuit concept of local conservation of charge at the gate terminal is confirmed to within a high degree of precision. Local conservation of charge at the drain terminal, and local conservation of high-frequency current at the drain terminal, are at least approximately valid. This means large-signal FET models with circuit topologies similar to those of Figure 1, can accurately, if not perfectly, reproduce the detailed bias-dependence exhibited by actual MESFET and HEMT devices from a broad spectrum of processes and technologies.

References

[1] Root, D.E. and Kerwin, K.J. , 1991, "CAD for Microwave Integrated Circuits", in **Microwave Integrated Circuits**, ed. Konishi, Marcel Deckker, pp. 573-592.

[2] Root, D.E., Fan, S., and Meyer, J. "Technology Independent Non Quasi-Static FET Models by Direct Construction from Automatically Characterized Device Data" 21st *European Microwave Conference Proceedings*, Stuttgart, Germany, September, 1991 pp 927-932.

[3] Hughes, B. and Tasker, P. J. "Bias Dependence of the MODFET Intrinsic Model Element Values at Microwave Frequencies," 1989, IEEE Trans. on Electron Devices ED-36: 10 pp. 2267-2273.

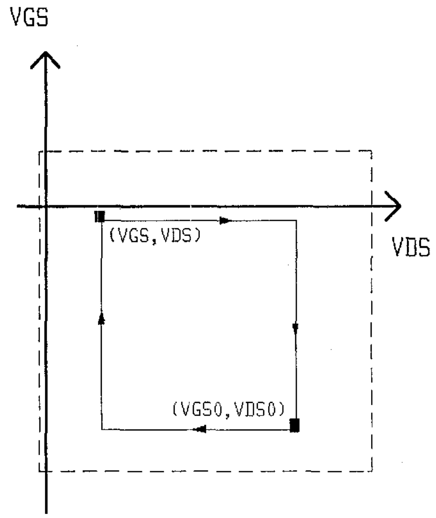

Figure 2. A typical closed path in voltage space around which the contour integrals of Equation 1 are evaluated is indicated by the thin solid line, with arrows showing the orientation for the integral. Each point, (VGS,VDS), in the plane determines a rectangular contour with respect to a fixed point (VGS0,VDS0). The contour integrals are calculated along more than 100 distinct contours, corresponding to (VGS,VDS) points distributed throughout the volume enclosed by the dashed lines.

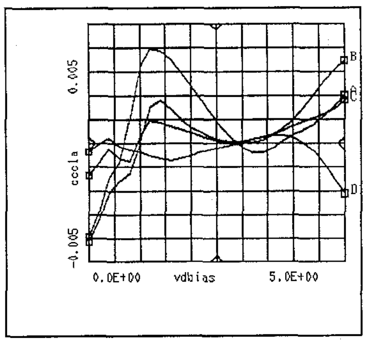

Figure 3a: normalized closed contour integral of F1 vs bias

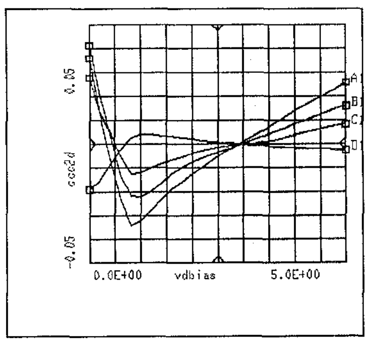

Figure 3b: normalized closed contour integral of F2 vs bias

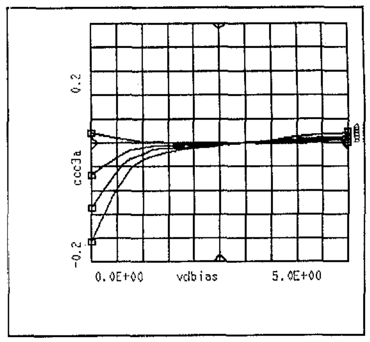

Figure 3c: normalized closed contour integral of F3 vs bias

Figure 3: Normalized values of closed contour integrals of measured vector fields (y-axis) vs drain bias (x-axis) for four different values of gate bias. Gate voltages: A: -1.5V, B: -1.0V, C: -0.5V, D: 0.0V Device: 1um x 500um MESFET with 10 gate fingers

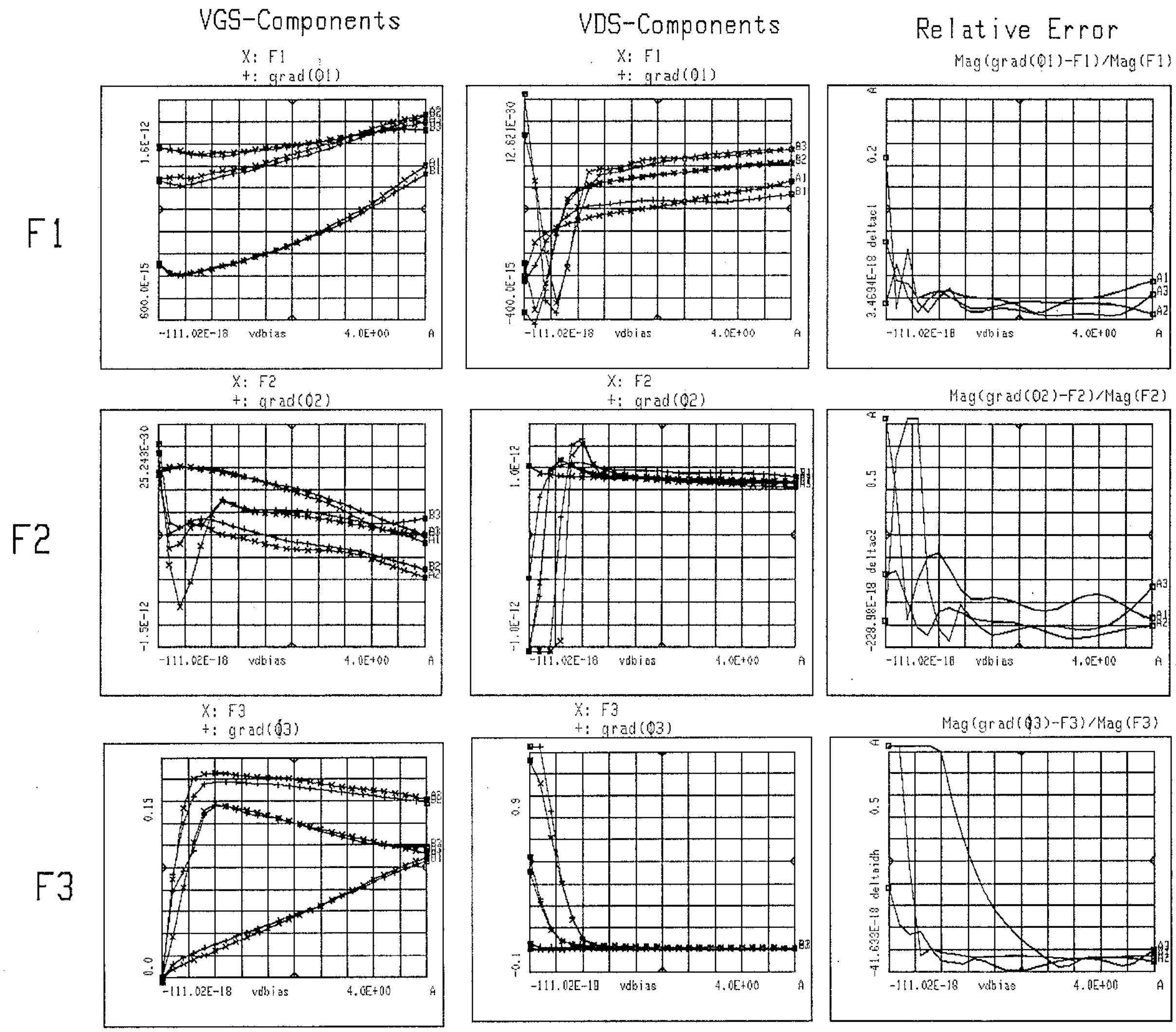

Figure 4

First two columns:
Comparison of the components of the gradients of functions Φi (calculated as in Reference [2]) to the components of the measured, vector fields, $\vec{F}i$, versus bias.

Third column:
Relative error in approximating $\vec{F}i$ by grad(Φi) versus bias.

The gate voltages are A: -1.0V, B: -0.5V, C: 0.0V
The device is a 0.25um x 240um MODFET with 8 gate fingers