Small-Signal Operation-Based Simplified Verification of Non-Linear Models for Millimeter-Wave Electron Devices

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Abstract **— Large-signal modeling of electron devices for nonlinear MMIC design is a fundamental topic for the microwave community. Many different non-linear modeling approaches have been proposed in the last years, and quite often circuit designers suffer from the lack of reliable comparison criteria, on the basis of which identify what model, between those available, could be the most suitable for the desired application. Moreover, similar strategies are needed even from the research groups, whose activity is devoted to the model identification and extraction, in order to quantify the degree of accuracy achievable by the modeling approach adopted. In this paper an approach to verify large-signal model accuracy will be discussed, which is simply based on the comparison between de-embedded measurements and model predictions of Y-parameters versus the bias voltages at the intrinsic device ports.**

Index Terms **— Field effect transistors, semiconductor device characterization, large-signal modeling, dispersive phenomena.**

I. INTRODUCTION

The problem of quantifying the degree of accuracy achievable by the modeling approach adopted is a real critical point [1]-[2], since many of the models, which are oriented to the design of large-signal circuits, are extracted only on the basis of DC I/V characteristics and small-signal differential parameters measured onto a grid of different bias points. Most of research laboratories do not actually have the capabilities of carrying out the set of large-signal measurements, which should be necessary in order to fully validate their models for each particular application. Large-signal measurement systems can be very expensive (e.g. active load-pull systems) and\or characterized by limited range (e.g. LSNA set-ups are not available above 50 GHz). In addition, simplified procedures, which are based on the comparison between empirical data and model predictions under small-signal operation and can be carried out directly in the software environment exploited for the model extraction (without the need for external CAD tools - e.g. HB simulations), definitely represent an important resource in order to rapidly achieve successful preliminary verification results. Thus the question is, which small-signal tests are the most suitable to investigate the accuracy achievable by a nonlinear dynamic model?

A first response could be to simply compare the model predictions to the small-signal measurements over the entire frequency and bias sweeping range. Such a "massive" approach could be misleading; in fact, by considering for example a simple class-A power amplifier design, it is evidently not true that all the bias conditions have the same impact on the accuracy of model predictions, which are of interest for such an application (e.g. PAE, power at a dB-specified compression point, etc.). Improvements can be certainly achieved by considering only, or weighting mostly, the small-signal parameters that refer to bias conditions "near" the PA load-line. Similar considerations can be made in the framework of the design of a "cold-FET" mixer, where the operation is limited to the linear region of the FET, which is typically biased with VDS= 0 V.

Once the bias sub-grid has been suitably defined, on which model predictions and measurements will be compared, the next problem to be dealt with is what kind of verification has to be used. A natural answer would be that of verifying the accurate fitting between S-parameter simulations and measurements. In practice, the choice of scattering parameters is only related to the fact that measurements with resistive terminations ensure the transistor stability, while the use of short/open loading conditions, which is associated with the direct measurement of admittance or impedance matrix, could easily lead to unstable behavior. Under many bias conditions Y-parameters could not exist at the extrinsic device ports, but they certainly exist at the intrinsic ports. In fact, an ideal Y-measurement performed at the intrinsic device implies to short (for the AC components) the input or output intrinsic ports by fixing the charge over the intrinsic device capacitances; since the capacitance charge is a state variable it is clear that under such test conditions the device can not become unstable.

In this paper an approach to verify large-signal model accuracy will be discussed, which is simply based on the comparison between de-embedded measurements and model predictions of Y-parameters versus the bias voltages at the intrinsic device ports. In particular, the direct link between the degree of accuracy shown by the model under the simple small-signal tests, which are involved within the proposed verification strategy, and the degree of accuracy shown instead under non-linear operation (such as intermodulation at millimeter-wave frequencies) will be demonstrated.

II. THE SMALL-SIGNAL VALIDATION PROCEDURE.

As well-known, at the intrinsic device ports the device can be described (at least until the non-quasi stationary effects can be neglected) by a simple G(V)-C(V) parallel, where V represents the vector of the intrinsic voltages. Under these hypotheses, a more convenient comparison can be made by taking into account Y rather than S parameters, since the first ones are intuitively more directly related to the device large-signal behavior. By assuming, for instance, a non-linear polynomial i(v) description for the device, it is well-known that third-order intermodulation (IMD) products are related to third-order derivatives of the currents with respect to the voltages, i.e. the second-order derivatives of the Y-parameters. The quality of the Y-parameters fitting versus the bias conditions is then explicitly related to the performances under large-signal operating condition, but it is important to notice that it would not be sufficient to compare models simply on the basis of the best fitting of Y-parameters, since it would be also fundamental to have a good fitting of second-order derivatives in order to obtain optimum performances. In other words, it would be useful to verify the accuracy shown by the model in reproducing concavities and convexities of the curves, which are obtained by plotting the Y-parameters versus bias.

It must be observed that the de-embedding of the parasitic networks is always useful because linear parasitic elements tend somehow to hide the non-linear phenomena, which are strictly related to the intrinsic device; therefore a good small-signal, bias-dependent fitting at the extrinsic device ports does not necessary imply good prediction accuracy under large signal operating conditions. In fact, while a good fitting of the bias-dependent G(V)-C(V) intrinsic functions evidently implies accurate predictions under non-linear operation, a good fitting of the extrinsic parameters does not guarantee the same results. In the latter case, it is only possible to state that the model shows a good extrinsic small-signal parameter fitting, but this could be easily obtained by exploiting, for instance, an arbitrary, large number of linear elements in the modeling of the parasitic network. Furthermore, when the analysis of the extrinsic S-parameters manifests an inaccurate fitting with measurements, it is not immediate to understand what kind of non-linearity the model fails to describe: either the quasi-static non-linearity strictly related to the bias-dependent G(V) intrinsic function, or the dynamic non-linearity shown by the bias-dependent C(V) intrinsic function.

A final consideration is that the strong source of device non-linearity is the low-frequency I/V device characteristic with the associated, important dispersive phenomena due to traps and self-heating.

To show the great impact of the low-frequency modeling, two different models for FET devices have been considered: the "Backgating" model [3] and the "Empirical" model [4] both exploiting, besides small signal measurements, large signal measurements carried out with a recently proposed measurement system [6]. In order to test the small-signal prediction capability of the i/v models, measurements of the PHEMT low-frequency trans- and output-conductance were carried out for different biases at 2 MHz - i.e. well above the trap cut-off - and compared with the Empirical and Backgating model predictions. Corresponding results are shown in Fig. 1.

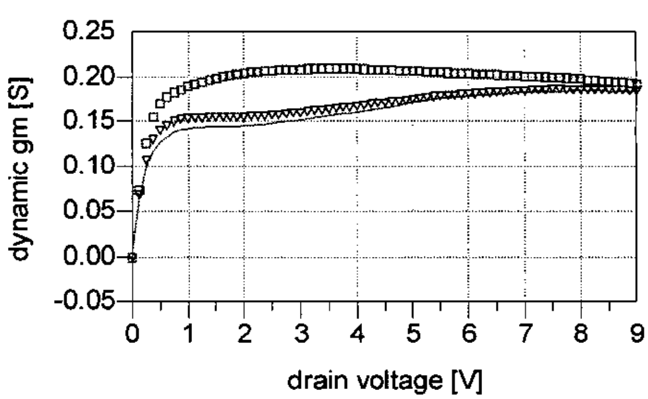

Fig. 1. Intrinsic trans-conductance of a 0.25μm Triquint GaAs PHEMT at different drain biases and Vg0= -0.55V (f = 2 MHz). Measurements (solid line) versus predictions based on Backgating (squares) and Empirical (triangles) models.

As can be seen, predictions of the Empirical model are in excellent agreement with measurements; moreover, such a model is capable to perfectly reproduce concavity and convexity of the "measured" intrinsic transconductance. Analogous results have been obtained for the output conductance.

The low-frequency drain current models extracted have been embedded in a non-quasi-static large-signal device model for millimeter-wave applications, namely the Nonlinear Discrete Convolution (NDC) model presented in [5]. In particular measurements of the third-order intermodulation product (interferer) to carrier ratio (I/C) were carried out at the frequency of 39.9 GHz (two tone displacement: 10 MHz; class-A operation: ID=60 mA, VDS=6.5 V) with the measurement system shown in Fig. 2.

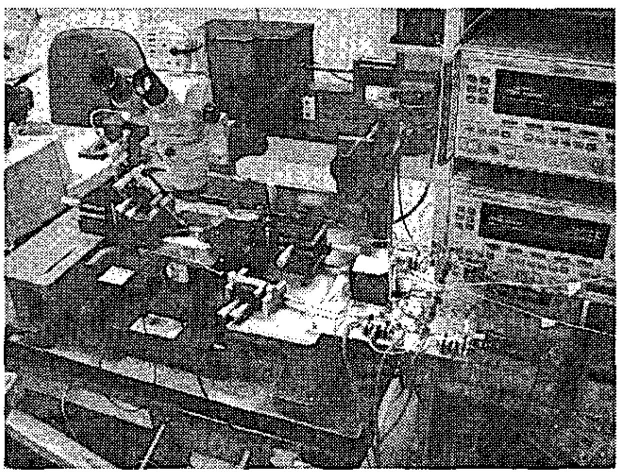

Fig. 2. The large-signal millimeter-wave measurement setup.

Simulation and measurement results are shown in Fig. 3 as a function of the output power. As can be seen, the NDC model [6] with embedded the backgating i/v model [3] is in good agreement with measurements, despite the very low level of the IMD products required by the specific application. In the same figure, also the simulation results obtained by using the Empirical model [4] are shown, in such a case, it is well evident the higher level of accuracy. Fig. 3 shows also the poor prediction capability obtained when making use of a model based on purely DC I\V characteristics.

It must be observed that a conventional bias-dependent S-parameter comparison at the extrinsic device ports does not point out any relevant difference between the two models as shown in Fig. 4 where the first derivatives with respect to the drain voltage of the S21 parameter real part computed with the different models are displayed. On the contrary, the comparison of the intrinsic Y parameters underlines an evident better prediction capability of the NDC model with embedded the "Empirical" I/V model, especially in the reproduction of the shape of the measured data as can be seen in Fig. 5 where the first derivatives with respect to the drain voltage of the Y21 parameters real part are reported.

Analogous results can be observed in Fig. 6, where the real part of the Y22 parameters are shown at the intrinsic and extrinsic device ports for a fixed bias condition versus the frequency. As can be seen only the comparison at the intrinsic device ports puts clearly in evidence that the two models simply differ for the low-frequency description; showing two curves shifted. Instead, as expected, at the extrinsic device ports linear parasitic elements tend, with their resonances, to hide the non-linear phenomena and the major difference between the two model is revealed at 70 GHz.

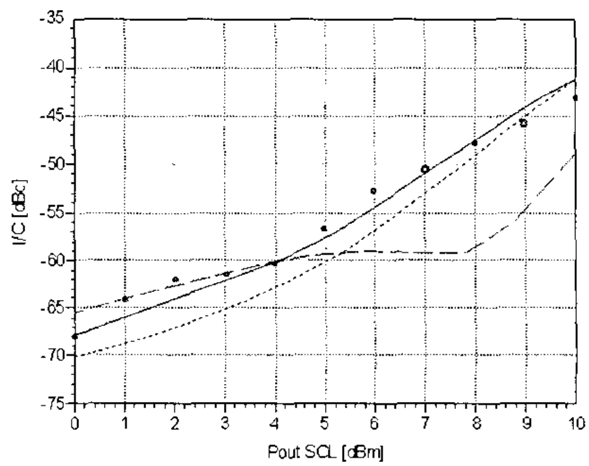

Fig. 3. Third-order intermodulation product to Carrier ratio versus output power for the considered GaAs PHEMT at 39.9 GHz. Measurements (circles) are compared to predictions based on the NDC model with embedded the Backgating (dot line), the Empirical (solid line) and the purely static I\V (dashed line) models.

IV. Conclusion

In this paper a methodology to preliminarily test the prediction accuracy of non-linear models under large-signal operating conditions has been proposed, which is based on the simple comparison of bias-dependent Y-parameters at the intrinsic device ports. In particular it has been shown as the evaluation of these parameters is directly linked to the level of large-signal model accuracy and also to what kind of non-linearity the model fails to describe.

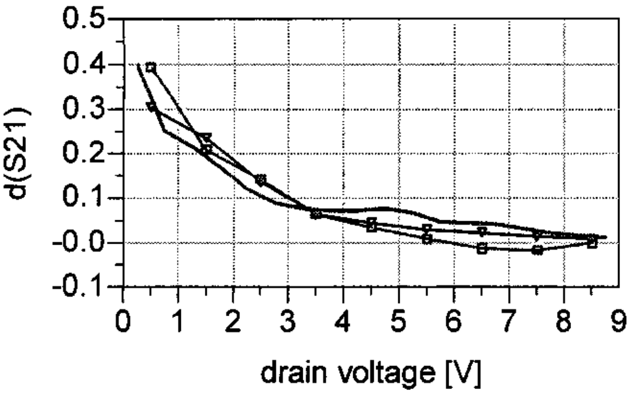

Fig. 4. Derivative of the extrinsic real part of the high-frequency S21 parameter for the 0.25 μm Triquint GaAs PHEMT considered at different drain biases and V_{g0}= -0.55V. Measurements (solid line) versus predictions based on Backgating (squares) and Empirical (triangles) models.

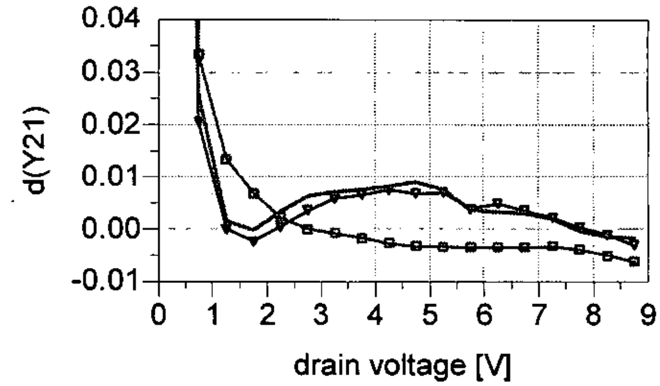

Fig. 5. Derivative of the intrinsic real part of the high-frequency Y21 parameter for the 0.25 μm Triquint GaAs PHEMT considered at different drain biases and V_{g0}= -0.55V. Measurements (solid line) versus predictions based on Backgating (squares) and Empirical (triangles) models.

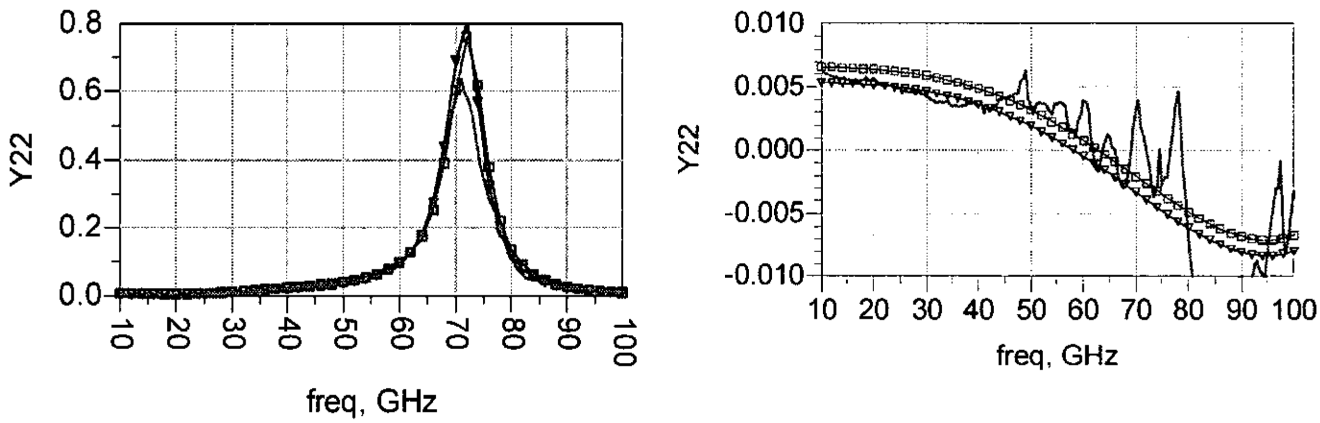

Fig. 6. Extrinsic (left) and intrinsic (right) real part of the Y22 parameter for the 0.25 μm Triquint GaAs PHEMT biased at V_{g0} = -0.55V V_{d0} = 6.5V. Measurements (solid line) versus predictions based on Backgating (squares) and Empirical (triangles) models.

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