The Construction and Evaluation of Behavioral Models for Microwave Devices Based on Time-Domain Large-Signal Measurements

D. Schreurs, J. Wood*, N. Tufillaro**, D. Usikov**, L. Barford**, D.E. Root*

K.U.Leuven, Div. ESAT-TELEMIC, Kardinaal Mercierlaan 94, B-3001 Leuven, Belgium
E-mail: dominique.schreurs@esat.kuleuven.ac.be
Fax: +32-16-321986, Phone: +32-16-321821
*Agilent Technologies, Inc., Microwave Technology Center, Santa Rosa, CA 95403, USA
**Agilent Laboratories, Palo Alto, CA 94304, USA

Abstract

We present a new procedure for creating non-linear behavioral models of microwave devices, based on techniques developed in Time-Series Analysis. We illustrate this procedure by creating a model for a HEMT device. Large-signal time-domain microwave measurements are used to generate the time-series data of the terminal currents and voltages. The dynamical model of the HEMT is defined by fitting multivariate polynomials to the terminal voltages and their higher-order derivatives. The model accurately predicts DC, small-signal, and large-signal behavior.

Introduction

The recent availability of large-signal vector network measurement systems [1] makes it possible to develop new measurement-based non-linear modeling approaches that are not limited to the use of only static (DC) and S-parameter data. Some examples of such modeling techniques include parametric equivalent-circuit model extractions [2,3], and black-box model identifications in the frequency domain [4].

In this work, we develop a *time domain* black-box modeling procedure, that is based on nonlinear system identification, using techniques developed in non-linear time-series analysis (NLTSA) [5,6]. One advantage of this technique is that the resulting model should be transportable: in other words, usable in a range of environments, and not restricted to a small domain of applicability, for example, a single bias condition. A further advantage of this time-domain technique is that it is not restricted to the modeling of only weakly nonlinear phenomena, unlike some frequency-domain methods such as Volterra Series analysis. The model is described directly by time-differential equations that are reconstructed from measured data. By this means all the observable dynamics of the device are determined. This enables the construction of a compact, accurate, and transportable dynamical model [7,8].

In this paper we illustrate the modeling procedure by constructing a model of a HEMT device. The model is validated by examining its DC, small-signal and large signal electrical behavior. The modeling techniques can also be extended to the construction of circuit and system level models.

Methodology

The approach begins by attempting to find the functional relationships between the terminal currents, and the terminal voltages and their higher order time derivatives.

In the case of a two-port device, we assume a model of the general form given by,

$$\begin{aligned} I_1(t) &= f_1\left(V_1(t), V_2(t), \dot{V}_1(t), \dot{V}_2(t), \ddot{V}_1(t), \ldots, \dot{I}_1(t), \dot{I}_2(t), \ldots\right) \\ I_2(t) &= f_2\left(V_1(t), V_2(t), \dot{V}_1(t), \dot{V}_2(t), \ddot{V}_1(t), \ldots, \dot{I}_1(t), \dot{I}_2(t), \ldots\right) \end{aligned} \quad (1)$$

The objectives of the modeling process are to determine the significant independent variables of the functions, f_1 and f_2, and to establish an efficient basis for the function approximator.

The model is built from time domain data, obtained by performing vector-corrected large-signal measurements using an *Agilent* Nonlinear Network Measurement System (NNMS) [1]. At the start of the modeling process, operating bounds for the model are established by defining the minimum and maximum gate-source (V_1) and drain-source voltage (V_2). These bounds define the operation region for which the model is to be developed and used. To enable practical identification of the device dynamics, the measured time domain data need to sample this operating region efficiently. The advantage of applying a large-signal excitation to the device instead of the conventional small signal excitation (bias-dependent S-parameters) is that the device is characterized under closer-to-use conditions. The instantaneous voltage trajectory can sample an extensive region of the device phase space, which is otherwise unreachable by conventional measurements.

This is illustrated by Figure 1, where the time domain waveform of (V_2) is plotted as function of the (V_1) time domain waveform. In this example, the device was excited by a single tone signal at the gate and by a second periodic signal of a different fundamental frequency at the drain. Hence, all the practical (V_1,V_2) area can be covered with a

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minimum number of vector-corrected large-signal measurements. This can be achieved by suitable variation of the parameters of the measurement system: DC bias, input powers, input frequencies, etc.

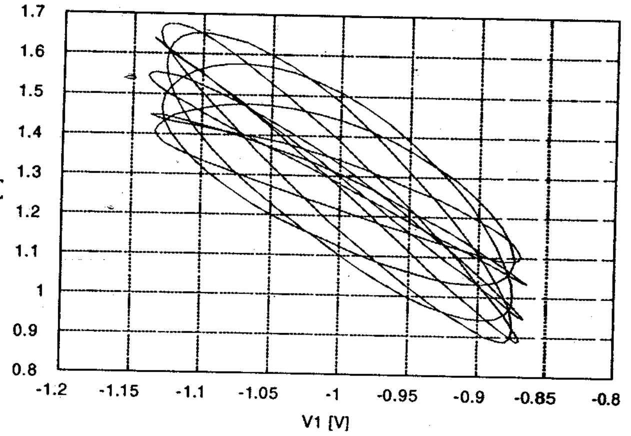

Figure 1: Example coverage of the (V_1, V_2) plane by a single vectorial large-signal measurement under 2-tone excitation.

The motivation for this approach to nonlinear system identification goes under the rubric of nonlinear time series analysis [5]. The suggestion to use this approach for nonlinear system identification is due to Casdagli [9]. The key idea is to embed the measured stimulus and response variables in a higher dimensional space built not only from the measured data, but also their transforms, for example, their time derivatives. Due to a theorem of Takens (with an extension to the driven case by Stark [10]), these embedded models can be faithful to the dynamics of the original system. In particular, deterministic prediction is possible from an embedded model that will mimic the actual dynamics.

We use an embedding technique in which the characteristics of the dependent variables (I_1,I_2) are unfolded by increasing the number of independent variables

$$(V_1(t), V_2(t), \dot{V}_1(t), \dot{V}_2(t), \ddot{V}_1(t), \ddot{V}_2(t) \cdots)$$

until a single-valued function for each current is obtained [11]. We found it necessary to include state variables up to $\ddot{V}_1$ for both I_1 and I_2 of the HEMT. No current derivatives were included in the embeddings. We are also investigating the construction of stable, free-running, dynamic models that include feedback terms such as $\dot{I}_1$ and $\dot{I}_2$ [12].

$$I_1(t) = f_1\left(V_1(t), V_2(t), \dot{V}_1(t), \dot{V}_2(t), \ddot{V}_1(t)\right) \qquad (2)$$

$$I_2(t) = f_2\left(V_1(t), V_2(t), \dot{V}_1(t), \dot{V}_2(t), \ddot{V}_1(t)\right) \qquad (3)$$

The functional relationships f_1 and f_2 in (2,3) are determined by fitting the predicted time-domain terminal currents, using the independent variables determined in the preceding step. In this work, we use multivariate polynomials to describe f_1 and f_2, but other types of fitting functions can also be used. A least-squares fitting procedure is used to obtain the multivariate polynomial coefficients.

Results

We implemented the HEMT behavioral model described above in *Agilent's Advanced Design System (ADS)* microwave circuit simulator by means of a symbolically defined device (SDD). The SDD determines the time-derivatives of the terminal voltages at each time-step in the simulation, hence enabling the functional forms for the currents to be evaluated.

Model validation begins by testing limiting cases, such as in DC or small-signal operation. We note that both DC and small-signal data were not explicitly used to construct the model. Further validation is achieved by comparing the simulated model performance with time-dependent large-signal measured data.

The DC I-V characteristics predicted by the model are shown in Figure 2. The DC behavior of the model arises from effectively setting all the derivative terms to zero in the functional equations for f_1 and f_2. The resulting I-V curves are then determined by the static nonlinearities in the functions of V_1 and V_2. The figure shows that the dynamical HEMT model predicts well the static behavior of the HEMT in the region of operation: V_1 spans the range of V_{gs} from –1.2V to 0V; V_2 covers V_{ds} from 0V to 5V.

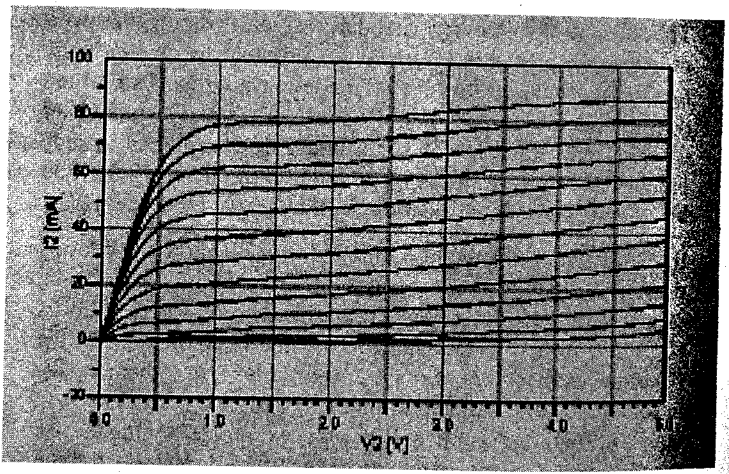

Figure 2: DC simulation of the dynamically modeled I_2 of a HEMT as a function of V_2,parameterized by V_1 in a range between -1.2 V and 0 V.

The HEMT behavioral model was used to generate the small-signal S-parameters, as functions of the applied DC bias and at several frequencies. The HEMT small-signal equivalent circuit parameters were then extracted using a typical equivalent circuit [13]. The parameters were extracted at 20 GHz, which is well above the frequencies at which the behavioral model time-domain data was measured.

In Figure 3 we show two examples of the small-signal equivalent circuit parameters: the transconductance, g_m, and total gate capacitance, C_g, are determined from the behavioral model-generated S-parameters, as functions of DC bias voltage V_{gs} (V_1) and V_{ds} (V_2), with V_{ds} ranging from 0.5 to 4.5 V. The extracted parameters display the general trends of the expected variations with the applied bias as described by the physics of the HEMT. Some capacitive elements, for example C_{ds}, are less well determined. One of the reasons could be the rather low frequencies that were used in the measurements: the fundamental frequency is less than 5GHz. This low frequency means that the capacitive component of I_2 is significantly smaller than the in-phase current contributions, and the extraction of this component is more difficult.

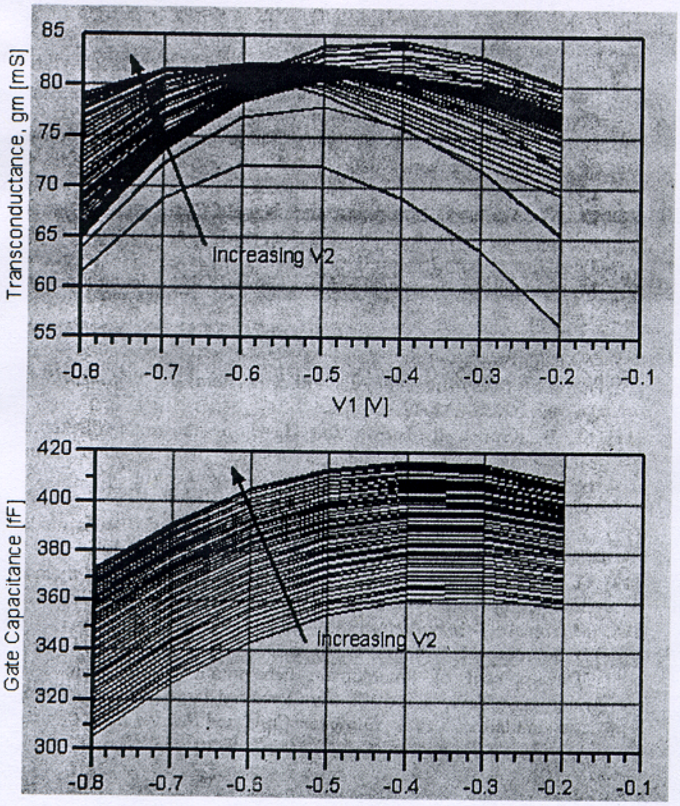

Figure 3: Small-signal equivalent circuit parameters of the HEMT derived from model-generated S-parameters at 20GHz.

Finally, the model was validated using large signal simulations. We used the behavioral model to predict the time-dependent output currents I_1 and I_2 as functions of the drive voltages V_1 and V_2, and compared the predictions with measured values. The measurements of the terminal currents and voltages were made with the NNMS. The simulations were carried out using the harmonic balance technique in *Agilent ADS*, using the same conditions as the measurements. The input signal was a two-tone excitation, with frequencies of 4.0 and 4.5 GHz. Figure 4 presents the excellent agreement between large-signal simulation and vector-corrected time-domain measurements that can be obtained with this new modeling technique.

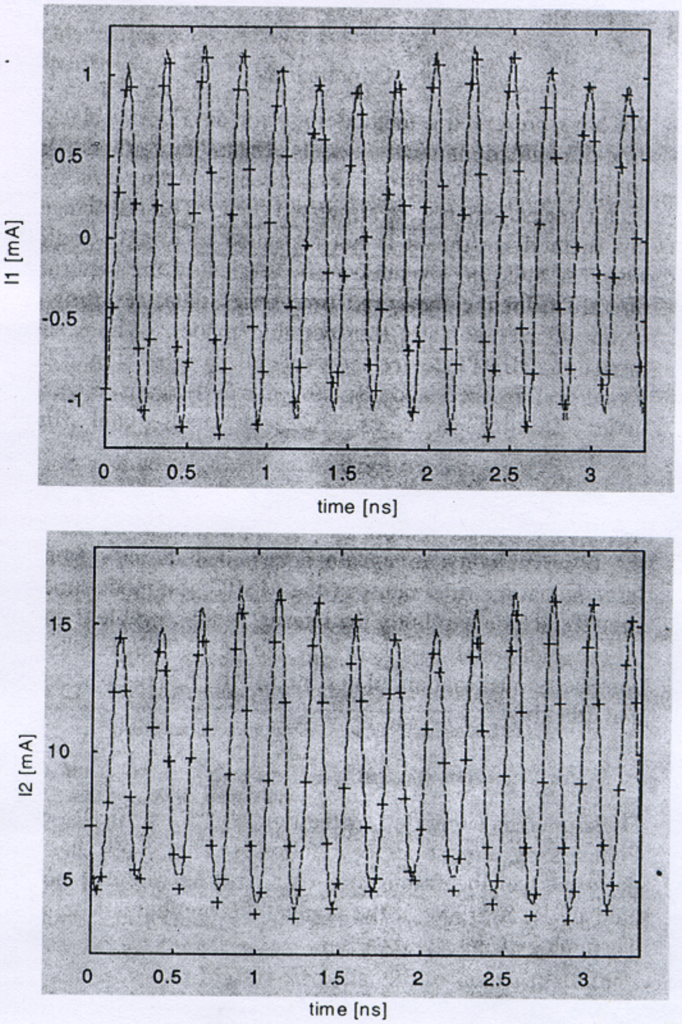

Figure 4: Comparison of measured (+) and modeled (solid line) $I_1(t)$ and $I_2(t)$ of the HEMT under two-tone excitation.

We have also generated behavioral models from simulated time-domain data: here the voltages and currents, and their time-derivatives, are determined directly in the simulator. The excitation design and model generation process follows the same principles as for the models produced from measured data.

This basic model generation procedure can also be applied at the circuit and system level. We have also determined behavioral models for GaAs monolithic microwave integrated circuits (MMICs) [14]. These models can be used in the *Agilent ADS* circuit simulator to predict the large signal circuit behavior of the MMIC, and preliminary results show over tenfold reduction in simulation time compared with the simulation of the full transistor-level representation of the IC.

This behavioral modeling technique thus offers a significant advantage for simulation of microwave systems and subsystems, enabling the design and simulation of large-scale circuits that would otherwise be too time-consuming, or even impossible.

Conclusions

We have presented a methodology for developing black-box time-domain dynamical models (behavioral models) for nonlinear microwave devices, directly from large-signal vector measurements, or simulated data. The advantages of this method are that it is not restricted to weakly nonlinear systems, and the dynamics of the device are determined directly from the measured time-series data, resulting in a compact, accurate and transportable model. The resulting model of a HEMT device shows excellent prediction of large-signal performance, and displays physically realistic behavior under limiting vases of DC and small-signal (linear) conditions.

Moreover, the methodology is not only applicable to microwave transistors, but can be applied to MMICs. Since the observable dynamics are determined directly from the large-signal measurements of the MMIC, the model does not need to include explicitly the internal, unobservable dynamics of the individual transistors in the IC. This results in a compact model that simulates the MMIC behavior accurately and quickly.

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