Direct Extraction of Nonlinear FET Q–V Functions from Time Domain Large Signal Measurements

M. C. Currás-Francos, P. J. Tasker, M. Fernández-Barciela, Y. Campos-Roca, and E. Sánchez

***Abstract*—This letter presents a simple and accurate procedure for the direct extraction of the quasi-static FET model nonlinear charge functions from large signal measurements. The method is based on the proper use of a vector nonlinear network analyzer (VNNA) with load-pull facilities. To our knowledge, these results show for the first time a direct procedure to extract the nonlinear charges of a FET using a very reduced number of large signal measurements.**

***Index Terms*—Microwave measurements, modeling, MODFETs, time domain measurements.**

I. Introduction

THERE is a increasing need of nonlinear transistor models operating at microwaves. Nonlinear models can be extracted using either small signal S parameters or large signal measurements. The second approach has been stimulated by the appearance of vector nonlinear network analyzers (VNNAs). The main advantages of this approach are that the extractions are performed under the real operating conditions of the device, and that the number of measurements required for the extractions are dramatically reduced.

Different techniques developed to date, using large signal measurements, have focused on the extraction of nonlinear models in terms of nonlinear conduction current generators and capacitances [1]–[3]. Another possibility is to extract the displacement current generators directly in terms of charges. To our knowledge, this was not done before. The method proposed here allows the direct extraction of both current and charge generators at all the dynamic voltage values present in a single time domain large signal measurement.

In Section II we present the theoretical approach. Section III shows the extraction results obtained from measurements using a VNNA with a HEMT device. Finally, the main conclusions of this work are summarized in Section IV.

II. Theoretical Analysis

The classical theory [4], [5] applied to obtain the nonlinear functions of a FET is based on an indirect integration process of the small signal y-parameters. A more realistic approach should extract these functions directly under nonlinear conditions. In this letter we show a mathematical procedure for the second approach.

For this analysis, the common assumption that the intrinsic quasi-static nonlinear HEMT model can be based on a parallel

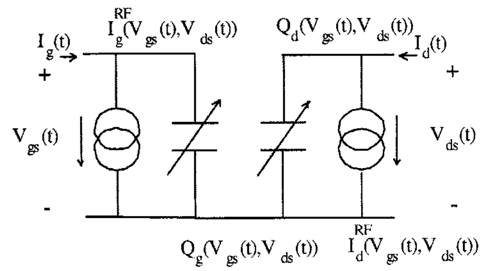

Fig. 1. Intrinsic quasi-static nonlinear HEMT model.

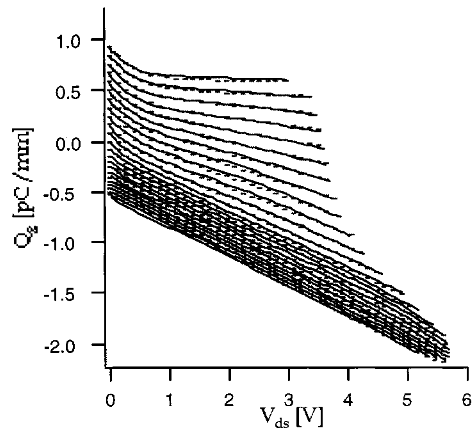

Fig. 2. Extracted Q_g from small (dots) and large signal (lines) data. Each trace is for a constant gate voltage.

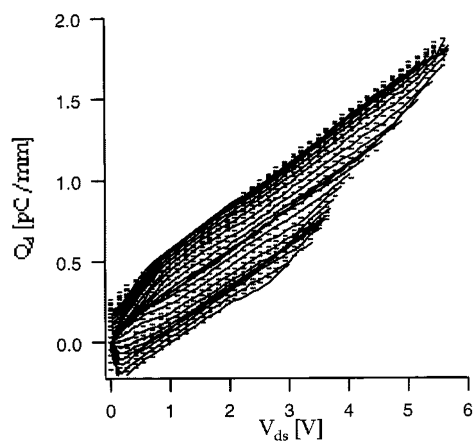

Fig. 3. Extracted Q_d from small (dots) and large signal (lines) data. Each trace is for a constant gate voltage.

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M. C. Currás-Francos, M. Fernández-Barciela, Y. Campos-Roca, and E. Sánchez are with the Universidad de Vigo, E.T.S.I. Telecomunicación, Campus Universitario, E-36207 Vigo, Spain (e-mail: curras@tsc.uvigo.es).

P. J. Tasker is with the Cardiff University, School of Engineering, Cardiff, CF2 3TF, U.K.

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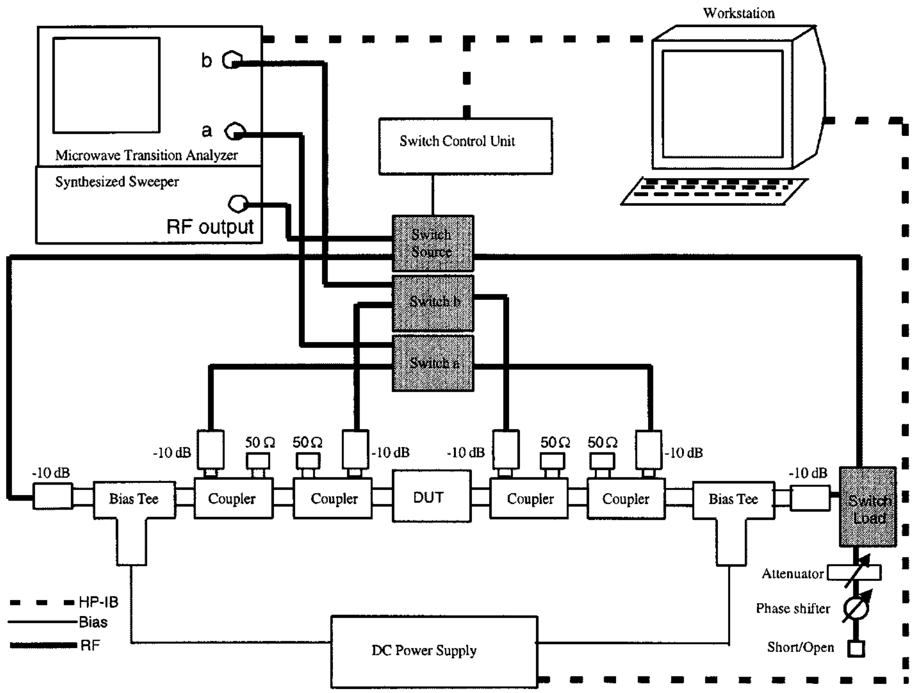

Fig. 4. VNNA measurement system set-up used based on the Microwave Transition Analyzer.

combination of a current source and a charge source at both the input (gate-source) and the output (drain-source) of a device in common source configuration is applied (see Fig. 1). Equation (1) defines mathematically the problem to solve at each port

$$I_i(t) = I_i^{RF}(V_{gs}(t), V_{ds}(t)) + \frac{dQ_i(V_{gs}(t), V_{ds}(t))}{dt} \quad \text{with } i = g, d. \tag{1}$$

In (1), I_i^{RF} symbolizes the conduction current term, and the derivative of the charge function Q_i represents the displacement term. In the same equation, $I_i(t)$ is the intrinsic current waveform in the gate (g) or drain (d) terminals, and $V_{gs}(t)$ and $V_{ds}(t)$ are the intrinsic gate-source and drain-source voltage waveforms, respectively. The displacement current in (1) can also be defined as a function of a new capacitance C_i term as in [6]–[8], $C_i = \delta Q_i/\delta V_{gs} + (\delta Q_i/\delta V_{ds})(\delta V_{ds}/\delta V_{gs})$, in the following form:

$$I_i^{disp}(V_{gs}(t), V_{ds}(t)) = C_i(V_{gs}(t), V_{ds}(t))\frac{dV_{gs}(t)}{dt}. \tag{2}$$

Combining (1) and (2), the terminal charge can be obtained from an integration process as (3) shows

$$Q_i(V_{gs}(t), V_{ds}(t)) = \int C_i(V_{gs}(t), V_{ds}(t))\frac{dV_{gs}(t)}{dt}\, dt + K. \tag{3}$$

The I_i^{RF} and C_i nonlinear functions can be directly calculated, as shown by the authors in [6], [7], if the intrinsic drain voltage $V_{ds}(t)$ versus gate voltage $V_{gs}(t)$ characteristic has no looping. This condition for the voltage waveforms can be achieved by varying the output load impedance presented to the device under test using a variable phase shifter and a variable attenuator in a VNNA measurement system. The C_i functions cannot be considered as state functions for the model since they do depend on the load impedance used in the extractions [7]. Once the I_i^{RF} and C_i nonlinear functions are calculated, it is possible also to calculate the Q_i nonlinear state functions just by using (3).

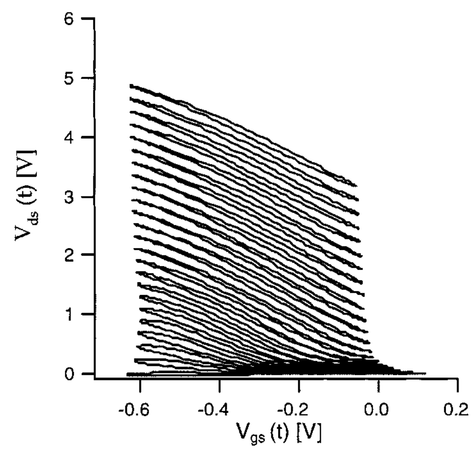

Fig. 5. Large signal measurements fulfilling the nonlooping condition.

Using this extraction approach only *one* large signal measurement is necessary to directly obtain all four state functions I_g^{RF}, I_d^{RF}, Q_g, and Q_d (defined at all the points on the gate/drain contour given by the measured voltage waveforms) of a quasi-static nonlinear model for a HEMT. This is not the case in all previous extraction techniques presented, where additional measurements are required for the extraction of all functions. Moreover, this procedure allows the extraction of all four state functions in real time and without any complex post-processing of the data.

A proper control of the bias points used, in a similar way as that utilized in [2], and of the amplitude of the waveforms through the input power applied to the device, enables the

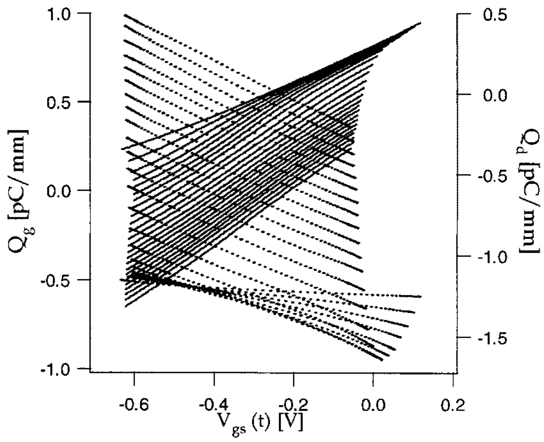

Fig. 6. Extracted Q_g (lines) and Q_d (dots) using the large signal measurements shown in Fig. 5. Each trace corresponds to a single measurement.

extraction of the nonlinear functions up to the breakdown, pinch-off, knee, and forward regions in the device. To demonstrate the potential of this technique in the absence of noise inherent to measurements, an analytical model has been utilized as data generator of an ideal device. Using this ideal device, the charges extracted based on the approach presented here, and the charges extracted based on the commonly used integration of small signal y-parameters [5] have been determined and compared. As can be seen in Figs. 2 and 3 a very good agreement is obtained, confirming the validity of the proposed technique.

One of the main advantages of this new approach is the big reduction in number of needed measurements to perform the extractions. In fact, for the extractions based on small signal y-parameters, a grid of 51×51 DC bias points have been selected in order to obtain the S parameters at each bias point. The extractions based on large signal data only needed 51 different bias points to cover the same range as in the former approach. Therefore, the reduction in number of measurements is n^2 to n.

The key point of this analysis is that it demonstrates a different and efficient way to extract the nonlinear functions of a HEMT using time domain large signal measurements.

III. Extraction From Measurements

Following the previous analysis, once the procedure has been validated using an ideal device, a VNNA measurement system with load-pull facilities (as Fig. 4 shows) has been used to extract the nonlinear functions from measurements on a real device. Fig. 5 shows the measured RF voltage transfer characteristic fulfilling the necessary nonlooping condition for a 0.25-μm, 4×60 μm GaAs Gec–Marconi HEMT after setting in the VNNA the proper load impedance that presented to the output of the device removes the looping in the $V_{ds}(t) - V_{gs}(t)$ plane. The fundamental frequency used in the extractions was $f_o = 8$ GHz. The complex load used to eliminate the looping was the same for the whole extracted range ($\Gamma_L(f_o) = 0.387\angle 174.4°$). Also a simple passive load-pull system was used to demonstrate the technique. That is why some residual looping can be appreciated in the measurements. Further accuracy could be realized using the exact complex load at each single measurement, and also a harmonic active load-pull system to completely remove any looping. In this case, as can be seen in the figure, only 24 large signal measurements have been used for the extractions. The bias points in these 24 measurements were selected in order to get symmetrical clipping in the output current waveforms; this corresponds to class A bias points. For the specific device used, the bias has been performed at a gate bias $V_{GS} = -0.25$ V as a constant value and sweeping the drain bias voltage V_{DS} for the 24 different measurements. The corresponding charge extractions are shown in Fig. 6. With the I_i^{RF} and Q_i state functions extracted from these large signal measurements, a table-based model has been successfully generated and validated in an identical manner to that formulated for S-parameters [5].

IV. Conclusion

A novel simple and accurate mathematical technique for the real time extraction of the intrinsic Q–V functions of a nonlinear HEMT model from time domain large signal measurements has been demonstrated and validated. Experimentally, this approach simply relies on a properly configured VNNA measurement system connected to a variable load termination.

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