Obtaining quasi-static models using a frequency domain extraction methodology

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***Abstract*— This contribution illustrates how a realistic nonlinear quasi-static model for FET-type devices can be extracted using an original frequency domain extraction technique. An ideal 'made-up' device is built from the measured bias dependence of a GaN medium power device. This ideal device is excited by two ideal voltage sources and its response (drain current) is used to illustrate how the extraction procedure can separate conduction and displacement current components provided the total current spectrum (or, alternatively, waveform) and control voltages are known.**

Keywords—quasi-static model, FET nonlinear model, frequency domain extraction technique, GaN HEMT, nonlinear CAD

I. INTRODUCTION

The use of quasi-static compact models for FET transistors is one of the approaches most cited in the literature. The general topology of this kind of model is detailed in Fig 1.a. for a generic common-source device. This two-port circuit has two control voltage variables and both port currents are considered as the circuit response. Each of these currents can be modelled by means of two shunt-connected, non-linear sources: a charged source and a current source. Under the quasi-static approach, both sources depend on the instantaneous values of the two control voltages.

In spite of the limitations of the quasi-static approach, which are mainly related to the maximum frequency taken into account, there are many reasons why this kind of model is adopted:

- Models based on current and charge nonlinear sources are a good compromise between empirical models (such as look-up table models) and physics-based modelling strategies.
- The equivalent circuit is compact, almost technology independent and easy to be included in CAD tools.
- The linearization of the circuit (see Fig. 1.b) can be used for small-signal simulations, having both a large-signal and small signal domains covered by the same model.
- There are a good number of strategies for extracting the model from measurements [1]-[4].

It is well-known that models are more accurate when they have been extracted with the device working under conditions as close as possible to those of the final designed circuit. The quality and availability of recent NVNA measurements has inspired the development of new extraction techniques [5].

How a new extraction method can be used to obtain quasi-static models for two-port devices using wide-band waveform measurements will be illustrated in this contribution. The basis of this method applied to nonlinear functions with only one control variable (one-port devices) has already been presented in [6]. In [7] the extension of the technique to two control variable problems (two-port devices) is shown by means of a simplified polynomial model for both current and charge sources. The limited complexity of this analytical model, with a band-limited frequency response, is upgraded in this contribution using a more realistic study case. In this case, the response will be obtained by means of an analytical model inspired in the measured behavior of a GaN medium power FET device [8].

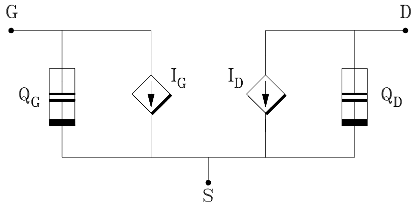
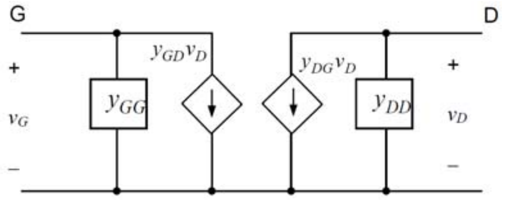


Fig. 1.a. Intrinsic quasi-static nonlinear generic FET/HEMT model in common source mode operation.



$$Y_{SS} = \begin{bmatrix} y_{GG} = G_{GG} + j\omega C_{GG} & y_{GD} = G_{GD} + j\omega C_{GD} \\ y_{DG} = G_{DG} + j\omega C_{DG} & y_{DD} = G_{DD} + j\omega C_{DD} \end{bmatrix}$$

$$G_{i,j} = \frac{\partial I_{\{G,D\}}}{\partial v_{\{G,D\}}} \qquad C_{i,j} = \frac{\partial Q_{\{G,D\}}}{\partial v_{\{G,D\}}}$$

Fig. 1.b. Intrinsic small-signal generic FET/HEMT model derived from the quasi-static nonlinear model

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After this Introduction, in Section II, the quasi-static nonlinear model is described and justified. In Section III the response of the device (illustrated by the total drain-current waveform) is obtained under the conditions required for the extraction of the model. The separated contributions to the drain current of both nonlinear sources (charge and current) are calculated from the drain current waveform, using the aforementioned extraction procedure. The conclusions of this work are summarized and future steps to be addressed are proposed in Section IV.

II. NONLINEAR MODEL FOR A GAN DEVICE

Once the extraction technique has demonstrated its potential with the simplified problem addressed in [7], its validation under conditions closer to experimental measurements is pursued. For this purpose, a 'made-up' device highly inspired by that presented in [8] for a medium power GaN transistor has been built.

Under usual working conditions (V_{GS} close to zero or negative), the conduction current (I_G) in an FET device can be ignored and only the displacement current due to Q_G is relevant for the response of the device. This is why it has been decided to pay attention to the total current at the drain terminal (I^T_D), assuming both conduction and displacement components will be significant enough. The total current at the drain terminal can be written as:

$$I_D^T = I_D(v_{GS}, v_{DS}) + \frac{dQ_D(v_{GS}, v_{DS})}{dt} \tag{1}$$

In [8] a nonlinear model for I_D was extracted using the analytical model proposed by Cabral et al. in [9]. The parameters of the model were obtained from the bias dependence of the elements in the small-signal equivalent circuit. Although capacitances connected to the drain terminal were then considered to be linear elements, they showed a clear dependence with the biasing voltages. Fig. 2. illustrates this behavior for both C_{DG} and C_{DD}. As these dependences are quite similar to those exhibited by G_{DG} and G_{DD}, respectively, the analytical model already used for I_D has been scaled and adapted for use by the Q_D too:

$$Q_D(v_G,v_D) = C_{GD0}v_G + C_{DD0}v_D + \frac{\beta_Q v_G^2}{1+\frac{v_{G3}^{plin_Q}}{VL_Q}}\left(1+\lambda_Q v_D\right)\tanh\left(\frac{\alpha_Q v_D}{v_{G3}^{psat_Q}}\right) \tag{2}$$

with

$$v_{G3}\left(v_{G2}\right) = VST_Q \ln\left(1+\exp\left(\frac{v_{G2}}{VST_Q}\right)\right) \qquad v_{G1}\left(v_G\right) = v_G - VT_Q$$

$$v_{G2}\left(v_{G1}\right) = v_{G1} - \frac{1}{2}\left(v_{G1} + \sqrt{\left(v_{G1}-VK_Q\right)^2 + \Delta_Q^{\,2}} - \sqrt{VK_Q^{\,2} + \Delta_Q^{\,2}}\right)$$

To illustrate the ability of the model to emulate the original device capacitances, both analytical derivatives $C_{DG} = \frac{\partial Q_D}{\partial v_G}$ and $C_{DD} = \frac{\partial Q_D}{\partial v_D}$ are represented in Fig. 3 as a function of the control voltages, in the same range of values as those used for extracting the small-signal equivalent circuit in the original device. Even though there is room for improving the fit, it is clear that the qualitative behavior is captured by this function. The selected parameter values for Q_D are $C_{GD0}=0.480\ pF$, $C_{DD0}=0.200\ pF$, $\beta_Q= -0.268\ pF/V^2$. The remaining parameters have the same values as those obtained for the current source I_D and presented in [8].

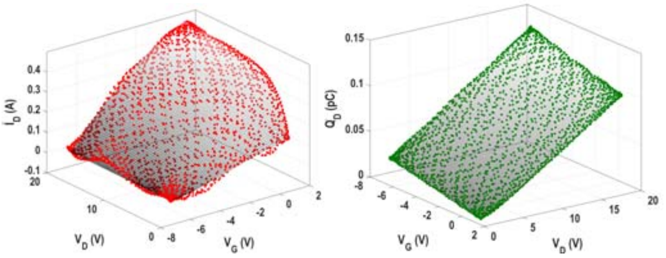

Fig. 5. Extracted (coloured dots) and analytical (grey grid) values for the nonlinear functions I_D and Q_D as a function of the instantaneous control voltages.

As a result, an analytical model for the total drain current I^T_D as a function of the control voltages v_G and v_D is available and can be used to test the extraction procedure.

III. EXTRACTION PROCEDURE

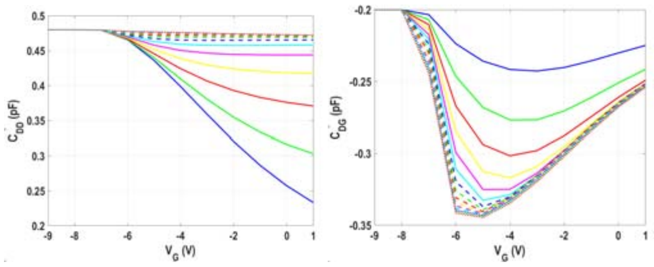

Fig. 3. Voltage dependence of small-signal drain capacitances calculated with (2) as a function of v_G (v_D as a parameter from 0 to 15 V)

The proposed extraction method requires that the control variables (control voltages in this case) of the nonlinear function sweep the whole range of interesting values in the v_G-v_D plane. In doing so, one of the most efficient solutions is to choose $v_G(t)$ and $v_D(t)$ to be pure sinusoidal signals with the non-commensurate frequencies f_G and f_D and considering a long enough time interval. The selected values are $f_G= 1\ GHz$ and $f_D=1.37\ GHz$. In this numerical test, control variables can be applied by means of ideal voltage sources connected directly to the intrinsic terminals of the device. Under experimental conditions, the method would require the effect of parasitic elements and source and load impedances to be considered in order to access to the intrinsic values of the control voltages. Moreover the resulting intrinsic control variables will be quasi-periodic functions. These details have to be considered when designing the experiment in order to guarantee a proper coverage of the desired control voltage values.

The decision on the bias conditions is also important. Here, a bias point adequate to cover the linear region and its transition to the saturation zone, is proposed. Although this is not the bias point originally suggested by the manufacturer of the device for optimal operation, it was chosen because it allowed the capabilities of the extraction method to be demonstrated better. The resulting applied voltages were:

$$v_G(t) = -3 + 4\cos(2\pi f_G t) \qquad v_D(t) = 10 + 9\sin(2\pi f_D t) \quad (3)$$

The current waveform ($I^T_D(t)$) throughout the whole time interval can be calculated by substituting (3) in Q_D (in (2)) and in the corresponding equations for I_D (see [8]). As the extraction method requires the spectrum of the response, the Fourier Transform provides these coefficients. Fig. 4 illustrates the total current as a function of the time and its spectrum (up to the highest frequency taken into account in the test).

The result of the extraction procedure is detailed in Fig. 5, for both sources: I_D and Q_D. For the sake of comparison, the original values of these sources have also been included. The figure shows how the total current is properly split into the conduction current and the charge contributions. From a practical point of view the extracted 'samples' of I_D and Q_D can be used to calculate the appropriate nonlinear functions by means of any interpolation/fitting tool, provided the v_G-v_D plane coverage is sufficient. It is worth mentioning that the extraction method directly provides the charge source without having to calculate the nonlinear capacitances and integrating their values.

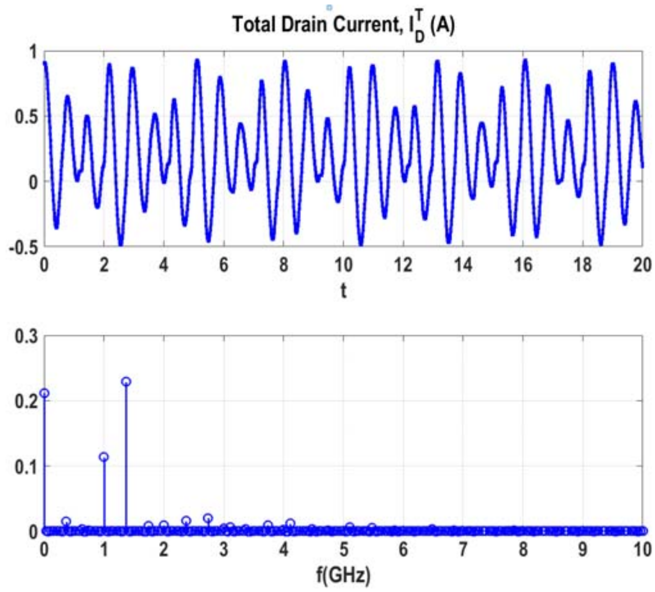

Fig. 4. Total drain current waveform and its spectrum

IV. CONCLUSIONS

An extraction procedure that obtains quasi-static models for FET devices using the measured waveforms of the terminal voltages and currents has been illustrated. The presented test has been carried out using an analytical model valid for the current at the drain terminal of a 'made-up' device greatly inspired by the actual performance of a GaN medium power HEMT [8]. The results confirm the ability of the extraction procedure to separate the contributions of the two nonlinear sources (conduction current and charge respectively) included in the quasi-static model. This means that, assuming the quasi-static model is applicable, this extraction method can obtain the nonlinear model almost directly from the measured waveforms (terminal voltages and currents) under nonlinear operating conditions and after a proper de-embedding of parasitic (linear) elements. This also means that the characterization of the device is carried out under conditions very close to the actual operating environment of the device. The obtained results are considered very promising in order to begin testing the extraction method for a measured device; this work is in progress.

V. ACKNOWLEDGMENT

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