AUTOMATICALLY CONTROLLED COVERAGE OF THE VOLTAGE PLANE OF QUASI-UNILATERAL DEVICES

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Abstract

We developed a systematic procedure to efficiently cover the (V_1, V_2) voltage plane of two-port microwave devices. The method is restricted to (quasi-)unilateral devices, because we assume that the $V_1(t)$ does not change when applying an additional a_2 travelling voltage wave. By choosing the adequate magnitude and phase of this a_2 signal, the V_2 of interest can be constructed. We illustrate this method on a HEMT and show that, for the used experimental conditions, only 27 vectorial large-signal measurements are sufficient to cover the (V_1, V_2) operating region of the device. This is a significant reduction in the number of required measurements for non-linear model generation, in comparison to the classical approach based on multi-bias broadband S-parameter measurements.

I. Introduction

Large-signal models for microwave devices are classically derived via a small-signal detour, because only *vectorial small-signal* (= S-parameter) measurements have been widely available during the past decades. Due to the recent advances in the metrology area of *vectorial large-signal* measurements [1-4], the development of novel modelling methodologies circumventing this small-signal detour could be initiated. Several approaches in both time- and frequency domain, and based on either an equivalent circuit or black-box representation have already been reported [5-9]. An important aspect that these methods have in common is the minimisation of the required number of vectorial large-signal measurements for model generation, such that they can become a valuable alternative for the conventional procedures based on multi-bias broadband S-parameter measurements. As in the case of the S-parameter measurements, the goal of the large-signal measurements is to adequately cover the predefined operating region of the device-under-test. Previously, we indicated the importance of well using the available degrees of freedom of the large-signal measurement system in order to render this process efficient [5]. In this work, we present a method that enables to automatically calculate the excitation signal to be applied in order to cover a predefined point in the voltage space of a (quasi-)unilateral device. The methodology is explained in Section II and illustrated on a HEMT in Section III. Finally, the results are summarised in Section IV.

II. Methodology

In order to explain the principle, we focus to the non-linear behavioural modelling approach as explained in Ref. [9], but the presented method can also be linked to other time-domain techniques, such as [5,7]. The considered black-box technique involves that any microwave two-port device can be described by equations of the form:

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

$$I_2(t) = f_2\left(V_1(t), V_2(t), \dot{V}_1(t), \dot{V}_2(t), \ddot{V}_1(t), \ddot{V}_2(t), \ldots, \dot{I}_1(t), \dot{I}_2(t), \ldots\right) \quad (2)$$

with $I_1(t)$ and $I_2(t)$ the terminal currents, and $V_1(t)$ and $V_2(t)$ the terminal voltages. The purpose of the technique is to find the functional relationships $f_1(.)$ and $f_2(.)$ by fitting the measured terminal currents to the measured independent variables or state variables. At the start of the modelling process, the operating bounds for the model are established by defining the minimum and maximum values of the state variables. These bounds define the operation region within the state space 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 operation region efficiently. However, since the orders of the voltage and current derivatives that have to be taken into account in Equations (1) and (2) are unknowns at the start of this particular method, we begin by defining the minimum and maximum V_1 and V_2 voltages. The method to determine the required number of state variables can be found in Ref. [9]. Considerations about the coverage of their part of the state space will be discussed in Section III. For reasons of simplicity, we assume that the defined (V_1, V_2) operating region is rectangular. Next, we divide this (V_1, V_2) voltage plane in sections, which in theory can have any shape. For the example of a HEMT, we take rectangular sections with (V_1, V_2) dimensions of 50 mV x 100 mV. The purpose of the data gathering process is to have a minimum number of time domain data, e.g., 10, in each of the sections. Hence, the aim of the vectorial large-signal measurements is to cover in an efficient way this (V_1, V_2) voltage plane.

Until now, only results have been reported by which this coverage is obtained by varying the variables of the excitations, such as input frequencies, input powers, DC bias, ... [5]. The setting of these ranges was done by the user, and furthermore the necessary excitations are strongly device-dependent. The contribution of this work is to have a systematic way to calculate the excitation signal to be applied in order to cover a particular point in the (V_1, V_2) plane. To illustrate the principle, we consider the following case: Figure 1 shows the (V_1, V_2) plane of a HEMT. We apply a single-tone signal at the gate and plot the time-domain waveform of $V_2(t)$ as function of the time-domain waveform of $V_1(t)$. Due to the inherent inverter characteristic of a HEMT, we are not able to cover points of simultaneously low instantaneous $V_1(t)$ and low instantaneous $V_2(t)$ values with a single-tone excitation. The goal of this example is to calculate the required a_2, such that we get a $V_1(t)$-$V_2(t)$ characteristic that crosses the (V_1, V_2) point (0 V, 0.5 V) (denoted by Y on Figure 1). We notice that the original $V_1(t)$-$V_2(t)$ characteristic has an instantaneous V_1 equal to 0 V at two distinct time points. We pick out the point (0 V, 1.04 V), denoted by X on Figure 1, and determine at which time point t_1 of the period this point is reached. The general phasor representation of the terminal voltages $V_1(t)$ and $V_2(t)$ is given by

$$V_i = \sum_{h=0}^{H} C_{ih}\, e^{j\left(h\omega_0 t + 2\pi \frac{\phi_{ih}}{360^\circ}\right)} \tag{3}$$

with subscript i=1,2 and H the number of considered harmonics. The corresponding time domain equation is

$$V_i(t) = \sum_{h=0}^{H} C_{ih} \cos\left[h\omega_0 t + 2\pi \frac{\phi_{ih}}{360^\circ}\right] \tag{4}$$

Hence, t_1 can be calculated from the equation

$$V_1(t_1) = C_{10} + C_{11} \cos\left[\omega_0 t_1 + 2\pi \frac{\phi_{11}}{360^\circ}\right] \tag{5}$$

because ω_0, the amplitudes C_{10} and C_{11}, the phase ϕ_{11} and $V_1(t_1)$ (= 0 V) are known from measurements. Next, we fix $V_1(t_1)$ to 0 V and move $V_2(t_1)$ from 1 V to 0.5 V, by applying a second signal at port 2, a_2, at the same fundamental frequency f_0. Since V_2 is equal to the sum of b_2 and a_2, $V_{2_{new}}(t_1) = V_{2_{old}}(t_1) + a_2(t_1)$ and the required a_2 can be calculated from:

$$\text{Mag}(a_2) = \text{Mag}\left[V_{2_{new}}(t_1) - V_{2_{old}}(t_1)\right] \quad (6)$$

$$\text{Phase}(a_2) = (2\pi - \omega_0 t_1)\frac{360^\circ}{2\pi} \quad (\text{if } V_{2_{new}}(t_1) > V_{2_{old}}(t_1)) \quad (7)$$

$$\text{Phase}(a_2) = (\pi - \omega_0 t_1)\frac{360^\circ}{2\pi} \quad (\text{if } V_{2_{new}}(t_1) < V_{2_{old}}(t_1)) \quad (8)$$

In terms of phasors, the geometrical interpretation is to add to the phasor of $V_{2_{old}}$ a phasor a_2 of which the instantaneous phase at time point t_1 reaches 0° in case of addition, or $V_{2_{new}}(t_1) > V_{2_{old}}(t_1)$, or 180° in case of subtraction. As a result, the new $V_1(t) - V_2(t)$ characteristic will cross the point (0 V, 0.5 V) at time point t_1 (see Figure 1).

This method supposes that $V_1(t)$ remains unchanged if a_2 is applied, which is valid for (quasi-)unilateral devices, where feedback between port 2 and port 1 can be neglected. Also, the original $V_1(t) - V_2(t)$ characteristic already has to cover the V_1 range of interest, which can be accomplished by well choosing the DC bias point and the input power at port 1. The reason is that we pick out a particular V_1 and consequently try to realise a corresponding V_2 of interest. In the above equations, we also implicitly assume that the b_2 of the device does not change, if an a_2 is applied. In practice, b_2 is slightly dependent on a_2, as a result of which the Mag(a_2) might have to be re-iterated. Note that a varying b_2 does not influence the required Phase(a_2).

III. Experimental results

We implemented the above outlined procedure in the Mathematica software that controls the Non-linear Network Measurement System [4]. The required a_2 can be realised by either an (automatically controlled) tuner or by an additional microwave synthesiser. In the latter case, it is not possible to set the phase of a_2 to the wanted value, and therefore the phase of the source needs to be randomised until the required Phase(a_2) is obtained. We tested the method on a HEMT device, of which we intended to cover the rectangle defined by the (V_1, V_2) points (-0.8 V, 0 V) and (0 V, 1 V). The DC bias condition is fixed to (-0.4 V, 1 V), as well as the excitation frequency and power at port 1. We applied a two-tone excitation at port 1 in order to increase the variation in $\dot{V}_1$. The variation in $\dot{V}_2$ is automatically larger, due to the fact that we apply various a_2's at the drain during the measurement sequence. This effect is however not noticeable at the gate side, because there is little feedback between drain and gate at the considered fundamental frequencies (< 5 GHz), which also means that the HEMT can be considered as a quasi-unilateral device at these conditions. The magnitude of the second tone has however to be relatively small compared to the magnitude of the first tone at port 1. Otherwise, it is not guaranteed that the value of $V_1(t)$ remains the same at time point t_1, because the phasor of the second tone turns at a different speed than the phasor of the first tone. During the automatic measurement sequence, the next (V_1, V_2) point to be crossed is taken from a section with the minimum number of data points at that moment. The algorithm stops by the criterion of having obtained at least the minimal required number of data points in each of the grid sections. In this case, 27 vectorial large-signal measurements were sufficient to cover the predefined operating region. Figure 2 presents the coverage of the (V_1, V_2) plane, as well as the corresponding $\left(\dot{V}_1, \dot{V}_2\right)$ coverage. Although the uniformity of the data points is not controlled, we notice that the measurements are more or less equally spread over the operation region. Although we only controlled the measurements up to a V_2 value of 1 V, we notice that the region up to V_2 value of 2 V is nearly completely covered. This positive consequence depends of course on the device and the initial excitation design. Finally, we used these measurement data to create a behavioural model following the procedure outlined in [9]. Figure 3 shows the well modelled $I_1(t)$ and $I_2(t)$ waveforms. Note that this experimental validation has been conducted at another DC bias condition than the one used during the controlled data gathering.

IV. Conclusions

We developed a systematic procedure to efficiently cover the (V_1, V_2) voltage plane of two-port microwave devices. The method is restricted to (quasi-)unilateral devices, because we assume that the $V_1(t)$ does not change when applying an additional a_2 travelling voltage wave. By choosing the adequate magnitude and phase of this a_2 signal, the V_2 of interest can be constructed. We illustrated this method on a HEMT and showed that, for the used experimental conditions, only 27 vectorial large-signal measurements are sufficient to cover the (V_1, V_2) operating region of the device. This is a significant reduction in the number of required measurements for non-linear model generation, in comparison to the classical approach based on multi-bias broadband S-parameter measurements.

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References

[1] F. van Raay and G. Kompa, "A new on-wafer large-signal waveform measurement system with 40 GHz harmonic bandwidth", *IEEE MTT-S Int. Microwave Symp. Digest*, 1992, pp. 1435–1438.

[2] M. Demmler *et al.*, "A vector corrected high power on-wafer measurement system with a frequency range for the higher harmonics up to 40 GHz", *Proc. 24th European Microwave Conference*, 1994, pp. 1367–1372.

[3] C. Wei *et al.*, "Waveform characterization of microwave power heterojunction bipolar transistors", *IEEE MTT-S Int. Microwave Symp. Digest*, 1995, pp. 1239–1242.

[4] J. Verspecht *et al.*, "Accurate on wafer measurement of phase and amplitude of the spectral components of incident and scattered voltage waves at the signal ports of a nonlinear microwave device", *IEEE MTT-S Int. Microwave Symp. Digest*, 1995, pp. 1029–1032.

[5] D. Schreurs, "Overview of non-linear device modelling methods based on vectorial large-signal measurements", *Proc. European Gallium Arsenide and related III-V compounds Application Symp. (GAAS '99)*, 1999, pp. 381–386.

[6] M. Curras-Francos *et al.*, "Direct extraction of nonlinear FET I-V functions from time domain large signal measurements", Electronics Letters, vol. 34, 1998, pp. 1993–1994.

[7] D. Schreurs and J. Verspecht, "Large-signal modelling and measuring go hand-in-hand: accurate alternatives to indirect S-parameter methods", *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 10, 2000, pp. 6–18.

[8] J. Verspecht *et al.*, "System level simulation benefits from frequency domain behavioral models of mixers and amplifiers", *Proc. European Microwave Conference*, 1999, pp. 29–32.

[9] D. Schreurs *et al.*, "The construction and evaluation of behavioral models for microwave devices based on time-domain large-signal measurements", *Proc. IEEE International Electron Devices Meeting (IEDM)*, 2000, pp. 819–822.

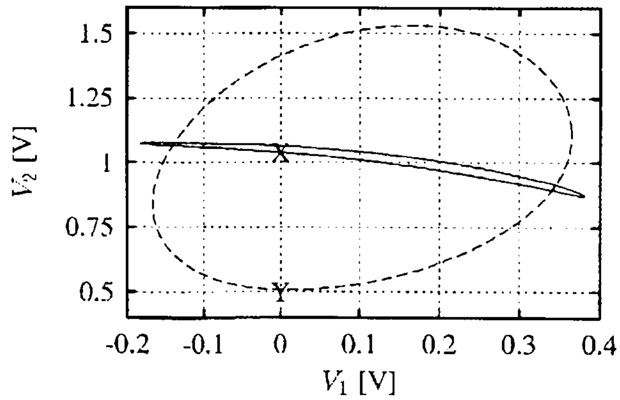

Figure 1: *(V_1, V_2) voltage plane of a HEMT with the $V_1(t) - V_2(t)$ characteristic if no a_2 applied (solid line) and with the adequate a_2 applied to cross the (0 V, 0.5 V) point (dashed line).*

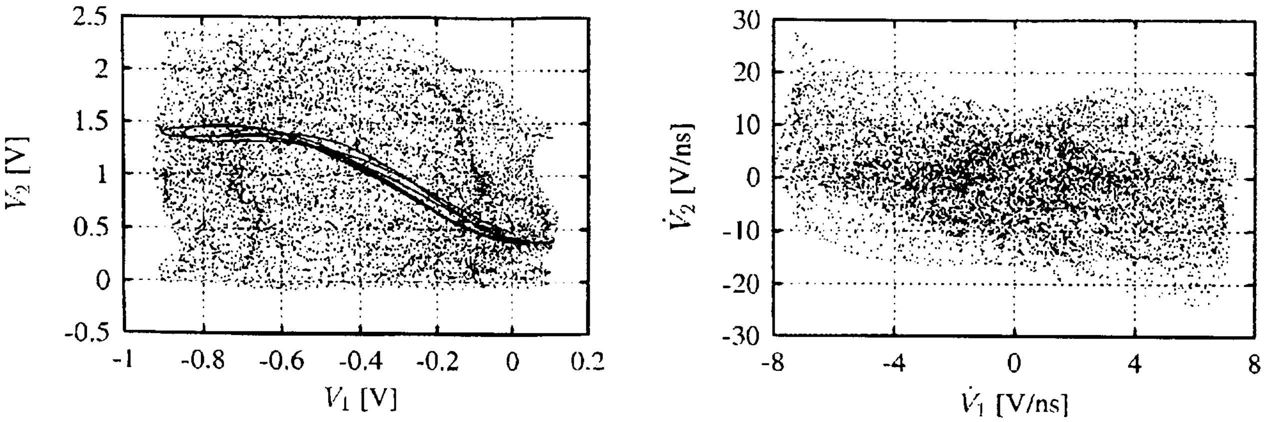

Figure 2: *(left) Automatically controlled coverage of the (V_1, V_2) plane of a HEMT by 27 vectorial large-signal measurements. The solid line represents the case with no a_2 present. (right) Corresponding coverage of the $\left(\dot{V}_1, \dot{V}_2\right)$ plane.*

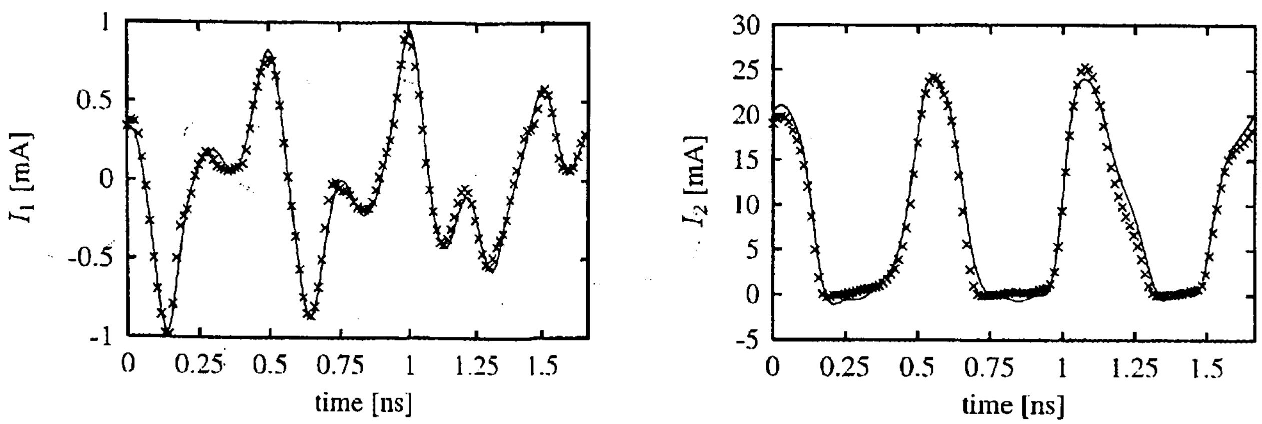

Figure 3: *Comparison of the measured (x) and modelled (_) $I_1(t)$ (left) and $I_2(t)$ (right) of a HEMT under two-tone excitation.*