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Nonlinear Characterization of GaN Transistors under Dynamic Bias Operation

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Abstract

This paper describes a measurement technique suitable for the characterization of GaN-based FET devices, based on exciting the device simultaneously with low-frequency large-signal and high-frequency small-signal tones. This technique allows one to accurately characterize low-frequency dispersion affecting this technology and at the same time the high-frequency behavior. We also discuss how to effectively use these measurements for modeling purpose.

1 Introduction

Nowadays the most important challenge that communication systems have to deal with is reaching the demanding performance imposed by the upcoming 5G networks, that need solutions with more and more power, efficiency and bandwidth up to very high frequencies. In this scenario, the Gallium Nitride (GaN) is assessing as one of the technologies that best fits the requirements imposed by the market, for example for base stations, radars or space applications. GaN transistors, in fact, have excellent properties in terms of high-power handling capabilities thanks to the high-breakdown field and the excellent thermal properties of the Silicon Carbide (SiC) substrate. These considerations make the systems realized with GaN devices superior to other competitor technologies (e.g., Gallium Arsenide (GaAs)) and sometimes GaN represents the only solution to address the requested circuit performance.

Unfortunately, the GaN technology has some foibles, mainly due to intrinsic proprieties of this material that make the accurate characterization and modeling of GaN devices a very complex task for the research community. The main issue is the presence of low-frequency dispersion due to trap state and thermal phenomena which degrade the performance of the devices under actual operating conditions [1, 2]. The impact of these phenomena is quite hard to be accounted for in a global model with good level of accuracy, since they strongly depend on the device static and dynamic operations. For such a reason, the characterization of low-frequency dispersion in GaN devices is very important both for quantifying the performance degradation under actual operating conditions and the extraction of accurate models.

Having an accurate nonlinear model is extremely important especially when the operating frequencies require monolithic implementation that does not allow the tuning of the circuit after its realization. In addition, common architectures adopted for PA design, as Doherty PA, require models that show the same accuracy for different operating conditions, like class AB and class C. Moreover, a good model must guarantee accurate predictions from back-off to output-power saturation operation; this represents a necessary requirement as an example in multi-stage PAs, where the driver stages operate in quasi-linear conditions whereas the final stage is under hard nonlinearity regime. In this scenario, the nonlinear characterization of GaN devices under all these conditions becomes crucial to obtain reliable and accurate predictions of the circuit performance before sending to foundry for massive production.

In this paper a smart characterization technique, i.e., the dynamic-bias (DB) technique, will be discussed. It is based on both low- and high-frequency measurements, that enables a complete characterization of low-frequency dispersion effects and provides a very effective technique for model extraction. In this characterization technique the device-under-test (DUT) is excited simultaneously with a large signal at low frequency, which defines the large-signal operating point (LSOP), and a small signal at high frequency [3, 4]. This operating regime enables the accurate characterization of low-frequency dispersion effects, linked to the device current-generator behavior, and, simultaneously, the characterization of high-frequency dynamic behavior due to linear and nonlinear parasitic elements (i.e., linear parasitic network, nonlinear capacitances, and non-quasi-static effects [5]).

2 Measurement Setup

The setup is shown in Fig. 1, whereas Fig. 2 reports the excitation provided to the DUT. As it can be noticed, the response of the DUT to such a kind of excitation is composed by: 1) low-frequency fundamental and harmonic tones, arising from the low-frequency excitation; 2) high-frequency fundamental component, due to the high-frequency small signal; 3) intermodulation tones due to the interaction between large-signal low-frequency and small-signal high-frequency spectral components [3].

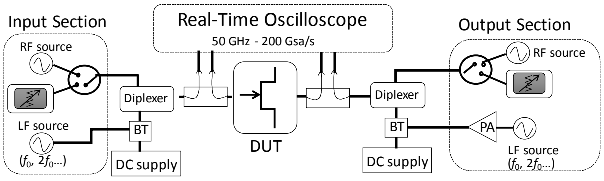

Figure 1. Low-frequency/high-frequency measurement setup implemented to perform the dynamic-bias characterization technique.

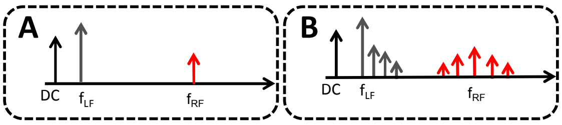

Figure 2. Spectra of incident and scattered waves under dynamic-bias operation.

The low-frequency part of the spectrum imposes the large-signal operating point, and therefore the trap and thermal state of the DUT; the high-frequency part is linked to the nonlinear capacitances which are characterized for the LSOP defined at low frequency.

In addition, if the frequency of the small-signal HF excitation is swept, keeping the LSOP fixed, it can be obtained a frequency dependent characterization of the device behavior under dynamic nonlinear operation.

3 Experimental results

Figure 3 shows an example of measurement carried out on a 0.25-µm GaN HEMT device under class AB operation for a drain bias of 20 V. The low-frequency signal is applied at 10 MHz and the high-frequency small signal is swept from 2 GHz to 13 GHz. For each high-frequency fundamental tone the same condition is set at low frequency, so that the device has the same LSOP (i.e., trap and thermal state) during the measurement. Figure 4(a) shows the LSOP in terms of load-line, corresponding to the condition of figure 3. By selecting an instantaneous value along the load-line, that corresponds to of gate and drain voltage pair (v_g, v_d), as highlighted in figure 4(b) by the dots, it is possible to elaborate the high-frequency spectra in terms of scattering parameters. The result is a situation that is similar to S-parameter measurements, but under dynamic-bias operation instead of static bias. Figures 4 (c) and (d) show the S-parameters obtained for one pair of (v_g, v_d).

The same can be done for each instantaneous value along the load line obtaining a multi-bias like characterization of the DUT under dynamic-bias operation, as shown in Figure 5.

The characterization obtained in this regime can be effectively used to extract the nonlinear model of the DUT, by adopting the LSOP to identify the current-generator model and the high-frequency response to identify the nonlinear capacitances.

4 Acknowledgements

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5 References

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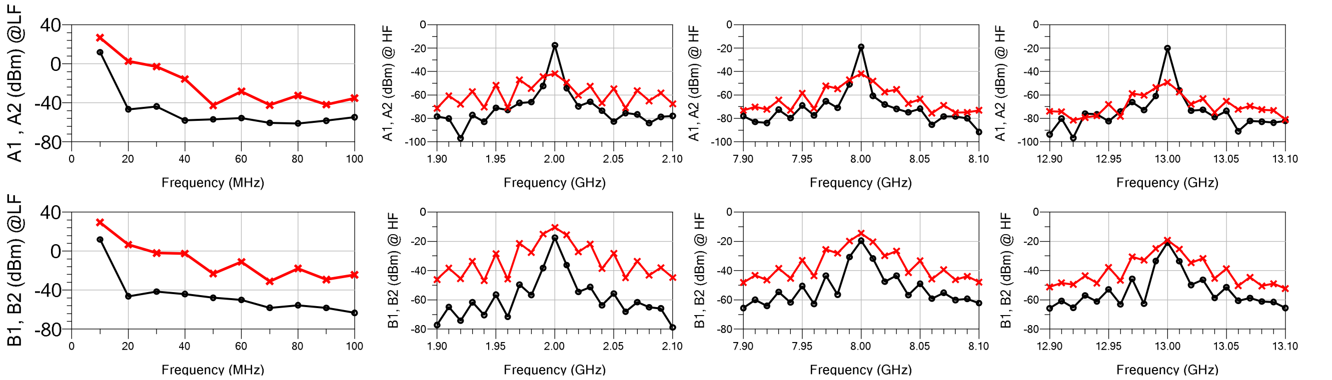

Figure 3. Spectra of incident (red crossed lines) and reflected (black circled lines) waves during dynamic-bias measurements performed on a 200-µm GaN HEMT. f_{LF} = 10 MHz. f_{HF} swept. High frequency spectra are reported for 2 GHz, 8 GHz and 13 GHz.

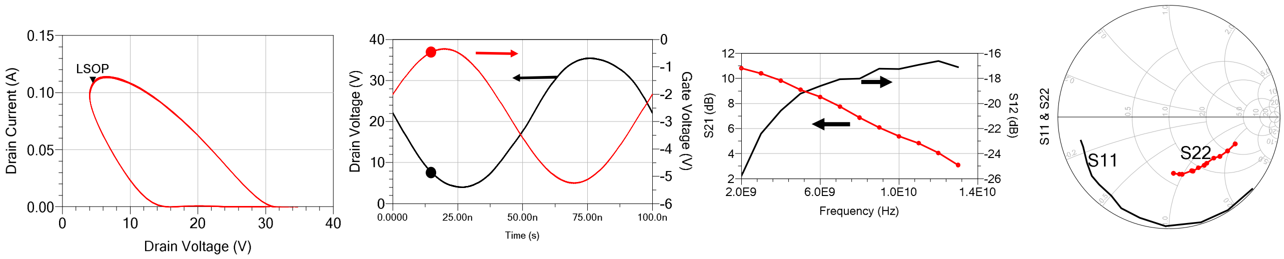

Figure 4. Dynamic-bias measurements performed on a 200 µm GaN HEMT. f_{LF} = 10 MHz. f_{HF} swept from 2 GHz to 13 GHz. (a) LSOP, (b) drain and gate voltages, (c) S_{21}, S_{12} (d) $S_{11}$and S_{22} parameters corresponding to the dots in (b).

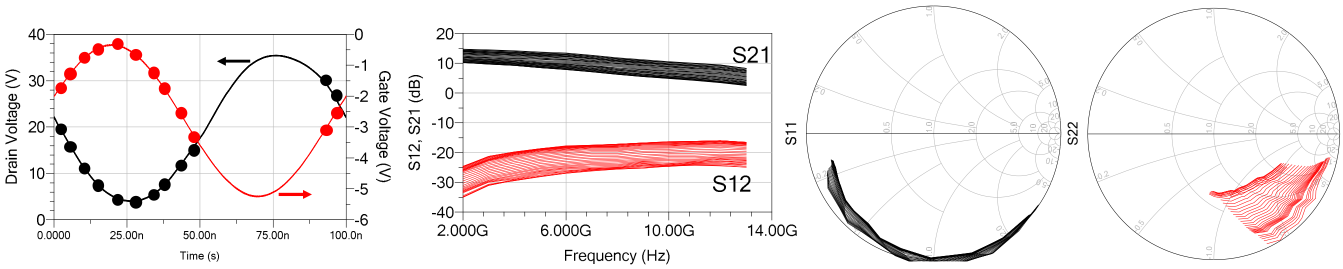

Figure 5. Multi-bias dynamic-bias S-parameters measurements performed on a 200-µm GaN HEMT. f_{LF} = 10 MHz. f_{HF} swept. (a) drain and gate voltages, (b) S_{21}, S_{12} (c) $S_{11}$and (d) S_{22} parameters corresponding to the dots in (a).