Multi-harmonic characterization of electron devices for micro- and mm-wave applications

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***Abstract*—The advancements in microwave technology and design techniques require accurate measurement setups to fully characterize electron devices. In this report, a low-frequency measurement setup with multi-harmonic capabilities is adopted for the characterization of microwave active devices oriented to the design of high-efficiency power amplifiers.**

***Index Terms*—FETs, harmonic tuning, microwave amplifier, semiconductor device measurements.**

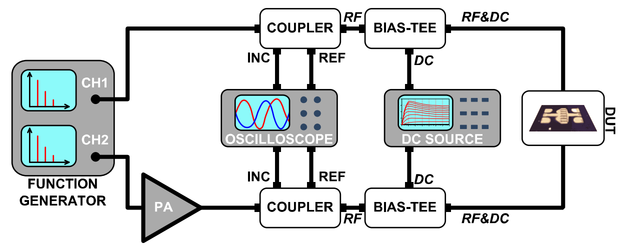

Fig. 1. Low-frequency measurement setup for active device characterization.

I. Introduction

IN microwave electronics, new generations of electron devices allow to fulfill the more and more challenging requirements for power amplifiers (PA). In the last years, the interest in new operating classes and design techniques has grown in order to maximize device performance in terms of output power and efficiency. The latter has become one of the keywords in PA design since it is the component that draws the largest part of supply power in a telecommunication system.

Active device characterization plays an important role in a PA design, since it provides fundamental information to identify the transistor optimum operating condition. High-frequency (HF) measurement setups, such as conventional load-pull (LP) systems or time-domain large-signal network analyzers (LSNAs) are typically exploited to this end. However, with such measurement setups it is not possible to directly control the behavior of the device at the intrinsic current-generator plane (CGP), which is the section where design techniques are referred to. Indeed, at HF, this reference plane is completely hidden by the contributions of the parasitic elements and, above all, of the transistor intrinsic capacitances.

This is an important limitation, especially when high-efficiency operation must be obtained. As an example, a class-F PA needs a short circuit and an open circuit to be synthesized at the CGP for the 2nd and 3rd harmonic respectively. This is not a straightforward operation to be done at HF since the information at the CGP is not directly available. Moreover, harmonic control could be even unfeasible. State of art LSNA setups have a total bandwidth of 67-GHz, which cannot be enough for PA classes exploiting harmonic tuning at microwave frequencies.

In this report, a time-domain low-frequency (LF) measurement setup is used to fully characterize an active device when multi-harmonic conditions must be fulfilled. From such a characterization, important information on the optimum operating condition at design frequency can be achieved by exploiting a design methodology based on the nonlinear embedding approach [1].

II. Multi-harmonic Low-Frequency Characterization

The setup described in [2] and shown in Fig. 1 implements a time-domain active load-pull (LP) setup operating at LF. It can be exploited to directly perform measurements at the device CGP, since at the operating frequency of the system (i.e., 2 MHz), the parasitic and intrinsic nonlinear dynamic effects can be neglected for microwave devices. Moreover, such a frequency is high enough to gather the effects of LF dispersion phenomena, providing a characterization of the device in the same operating condition (i.e., identical load-line) achievable at microwave frequency [3].

Basically, once selected the bias condition, the device under test (DUT) is excited by two incident waves provided by a function generator. Reflected and incident waves are measured through a 4-channel oscilloscope and shifted at the DUT plane by a dedicated calibration procedure. The impedances are actively synthesized by properly tuning incident waves in terms of their amplitude and relative phase.

Such a setup has been improved [4] with multi-harmonic capabilities, allowing to synthesize at the CGP the desired load condition at both the fundamental frequency and harmonics. This allows analyzing the device behavior under high-efficiency operating conditions, such as the ones expected for a class-F PA.

In Fig. 2, an example of LF LP contours obtained for a 0.25-µm 1.25-mm periphery GaN HEMT biased in class AB are depicted. Class-F terminations up to the third harmonic have been synthesized: 2nd and 3rd harmonics were terminated on a short circuit and a high impedance, respectively, while different values for the fundamental impedance have been considered. Contours are shown for a constant level of the

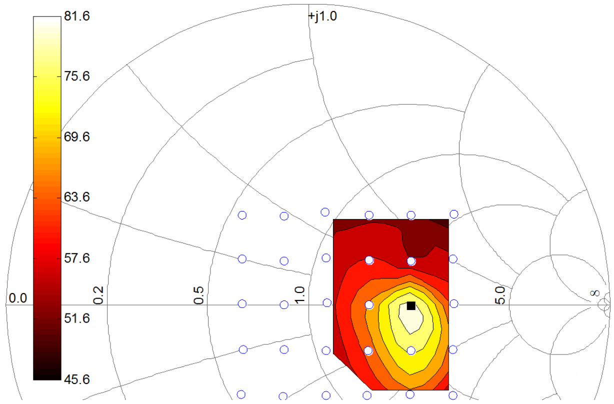

Fig. 2. Constant efficiency contours for a constant value of the minimum gate-drain dynamic voltage V_{GD} = -69 V. Measurements carried out at 2 MHz on the GaN HEMT biased at V_{DS} = 32 V, I_D = 10 mA (class AB).

minimum gate-drain voltage V_{GD} at the intrinsic plane. This information is very important since it is related to the reliability of the device (i.e., the breakdown) and is not straightforwardly available when HF setups are used. A dynamic minimum value of V_{GD} = -69 V has been chosen since it is close to the minimum allowed for this technology (i.e., 70 V). Under such a condition a maximum efficiency of 81.6% has been achieved, which is consistent with the theoretical class of operation, considering device non idealities (e.g., the knee voltage).

III. Assessing High-Frequency Performance

A nonlinear embedding technique [1] can be exploited to assess the device performance at the design frequency starting from the LF measurements. By assuming as frequency independent the behavior of the current generator (i.e., the same measured LF load line can be imposed also at HF) and with the availability of a model for the parasitic effects and the intrinsic capacitances of the device, it is possible to calculate their current contributions at the design frequency and add them to the LF measured currents re-mapped at HF. This procedure allows determining the source and load-impedances to be synthesized at the selected design frequency in order to obtain the same load line (and then the same performance) measured at LF.

This procedure has been carried out for the considered GaN HEMT after its low-frequency characterization. Results are shown in Fig. 3, where efficiency LP contours are depicted for a constant value of the minimum gate-drain dynamic voltage V_{GD} = -69 V. The impedances reported in the Smith chart at the new fundamental frequency (i.e., 2.4 GHz) correspond to the ones at the CGP reported in Fig. 2, and for each one of them the proper terminations (i.e., short circuit and high impedance) are synthesized at harmonics at the CGP. The maximum efficiency is slightly lower with respect to the one measured at LF. This is ascribed to the power losses of the parasitic network.

Results have been validated by realizing a PA with the terminations predicted by this design methodology. The maximum efficiency achieved at 2.4 GHz is about 80% with

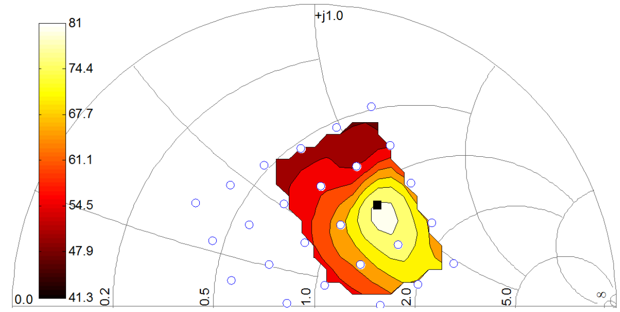

Fig. 3. Constant efficiency LP contours for a constant value of the minimum gate-drain dynamic voltage V_{GD} = -69 V at the fundamental frequency of 2.4 GHz obtained from the measured grid in Fig. 2.

an output power of 5.4 W. This confirms the validity of the design methodology based on multi-harmonic LF device characterization.

IV. Conclusion

The capabilities of LF measurements for the characterization of microwave active devices have been discussed in this work. An existing setup has been improved to implement multiharmonic capabilities in order to characterize high-efficiency operating classes oriented to PA design.

The LF characterization has been carried out on a GaN HEMT under class-F operation synthesized at the CGP as theory suggests. From LF data, HF information has been assessed by using a design methodology based on nonlinear embedding, identifying the optimum loads to be synthesized at the extrinsic plane in order to obtain the measured LF performance. Predictions have been confirmed by a power amplifier prototype.

Acknowledgement and Future Work

The recognition of my research activity by receiving the MTT-S Graduate Fellowship Award was certainly very pleasing and stimulating. Thanks to the economic contribution, I attended some international conferences as the IMS in 2013 in Seattle. Those events played an important role in my personal and scientific growth.

In the next future, I plan to continue my activities as a research assistant, possibly through international experiences that could introduce me to other research environments and increase my scientific and cultural baggage.

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