Pre-Pulsing Characterization of GaN PAs with Dynamic Supply

Corrado Florian*, Daniel Niessen*, Tommaso Cappello*, Alberto Santarelli*, Fabio Filicori*, Zoya Popovic°

*Department of Electrical, Electronic and Information Engineering, University of Bologna, 40136, Italy

° University of Colorado – Boulder, Room ECEEIB55, 425 UCB, Boulder, CO S0309-0425, USA

corrado.florian@unibo.it, daniel.niessen@unibo.it, tommaso.cappello@unibo.it,
alberto.santarelli@unibo.it, fabio.filicori@unibo.it, zoya.popovic@colorado.edu

Abstract — Nonlinear charge-trapping observed in the electrical characteristics of GaN FETs can introduce distortion in GaN-based power amplifiers (PA), especially in supply-modulated (envelope tracking) transmitters. A measurement approach is developed for large signal characterization of GaN-based PAs operated with dynamic bias supplies for efficiency enhancement. A new pre-pulsing technique is introduced which forces the active device to operate in trapping and thermal states close to those found in the actual application. The characteristics obtained with this technique are shown to give an accurate description of the PA performance. The measured data are used for the direct computation of pre-distortion functions for the linearization of a 10-GHz Envelope Tracking (ET) 12-W GaN MMIC PA for amplitude-modulated pulsed radar transmitters. The demonstrated measurement method can be also exploited for the identification of PA behavioral models, which take into account trapping effects.

Index Terms – GaN, amplifier measurement, trapping effects pulsed measurement.

I. Introduction

The electrical performance of GaN based HEMTs is affected by charge trapping mechanisms documented in the literature [1]-[4], such as current collapse and knee walkout in the device pulsed I/V characteristics. These in turn have an impact on PA design, and are responsible for reduced output power density and PAE at increasing drain voltages [5]. As shown in [1]-[4], time constants associated with charge trapping effects in GaN FETs show an asymmetry between charge capture (very fast, in the order of ps) and release (up to several seconds). Moreover, it has been observed that the trap state is set by the instantaneous peak values of the voltages applied to the device terminals with nonlinear dependence. While device models specific to GaN HEMTs have been proposed to describe such behavior [1],[6]-[7], measurements for pulsed I/V characterization also need to be suitably modified to account for trapping mechanisms. Pulsed I/V systems should produce conditions that maintain the device in isothermal and constant trapped charge state. In the pulsed I/V setup described in [2], this is accomplished by applying a very fast pre-pulse that sets the trap state, shortly before each point of the pulsed I/V measurement. This very fast pre-pulse sets the trap-state corresponding to an arbitrary combination of gate and drain voltages, typically the ones reached by the device load line when used for HPA operation. In this paper, a similar concept is applied at the amplifier level: pre-pulsing enables large signal characterization of a microwave PA at a controlled charge-trapping state and thermal condition of the active devices. The setup can be used in particular with PAs operated with dynamically-variable bias regimes (*e.g.* ET), which are more affected by trapping phenomena, since the trapping state is a nonlinear function of the instantaneous voltages applied to the active device [1],[2],[7]. Here we present the characterization of an X-band GaN MMIC PA operating in pulsed-mode ET regime for high efficiency radar applications with radar pulse shaping (*i.e.* pulse modulation).

II. Description of the Measurement Setup

The measurement setup block diagram is shown in Fig.1, where a FPGA-based National Instruments PXIe-5644R VST is used for the generation (VSG) and analysis (VSA) of arbitrary digital modulated RF signals.

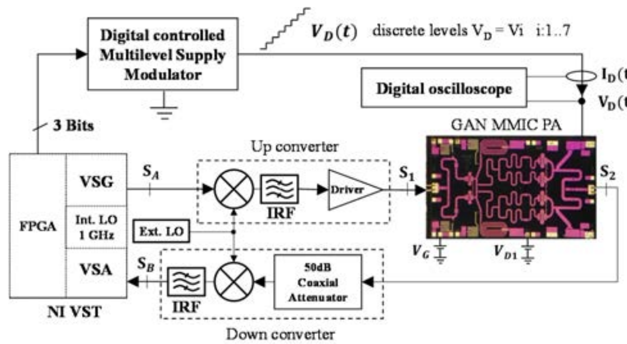

Fig. 1. Schematic description of the set-up with the MMIC DUT.

The signal is generated in digital baseband and up-/down-converted directly within the VST with a maximum output frequency of 6 GHz. For the test of X-band PAs, the signal is generated at 1 GHz at section S_A at the VST output, and additional up- and down- conversion stages for X-band are implemented externally with COTS components and a driver

978-1-5090-0698-4/16/$31.00 ©2016 IEEE

amplifier. Vector modulation can be applied to the baseband signal prior to up-conversion with 80 MHz instantaneous bandwidth. The dynamically variable voltage supply $V_D(t)$ is provided to the DUT by a multilevel supply modulator developed in house with the architecture described in [8]. This circuit is controlled by digital signals from the VST instrument FPGA and can commutate between seven different discrete drain bias voltage levels $V_D = Vi$ $(i=1,..,7)$ distributed over a 0-42 V dynamic range with 3-ns speed. The FPGA control of the supply and RF paths enables the synchronization of the DUT dynamic bias and RF driving signals. The DUT supply voltage $V_D(t)$ and current $I_D(t)$ are acquired by a digital oscilloscope equipped with wideband voltage and current sensors. The I/Q data of the RF signals at S_1 and S_2 are stored in the VST and used for the computation of AM-AM/AM-PM DUT characteristics, whereas $V_D(t)$ and $I_D(t)$ enable the computation of power consumption and efficiency.

III. PA Characterization

In this work, the PA is operated in pulsed mode with 50 µs pulse width (PW) and 10% duty cycle (T_P=500 µs) at 10 GHz. Envelope tracking can be used to maintain efficiency for amplitude-modulated radar pulses that improve spectral confinement [9].

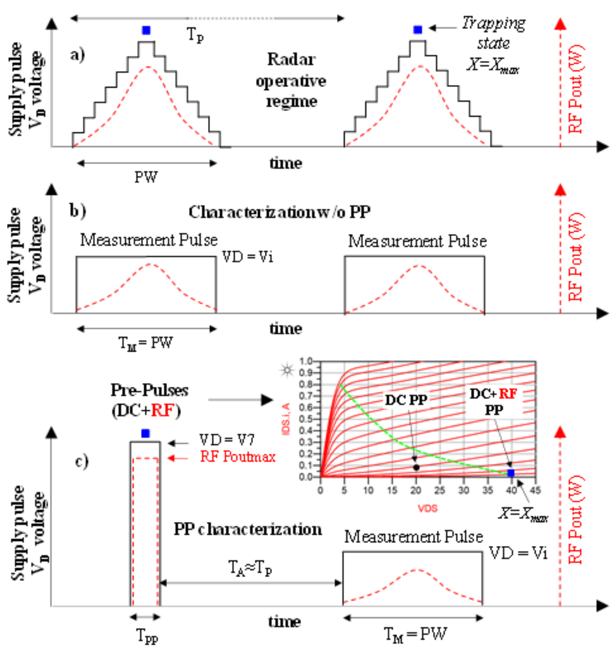

Fig. 2. Operative pulse shaping radar regime with ET and characterization regime with and without pre-pulse (PP).

Fig.2a shows a discretized multi-level approximation of a Gaussian-like dynamically variable supply profile $V_D(t)$, synchronized with the envelope of the RF pulse. The efficiency is enhanced by forcing the PA to operate at a certain level of gain compression during the entire pulse, which results in nonlinearities that need to be compensated by digital pre-distortion (DPD).

The PA under test is a 12-W two-stage X-band MMIC designed in the 0.15-µm GaN-on-SiC Qorvo process. A preliminary AM-AM/AM-PM characterization of the PA at each V_D level is needed to find the DPD coefficients. The supply modulator included in the setup enables the characterization of the PA in a pulsed regime, under thermal conditions very similar to the actual operating ones. The AM-AM/AM-PM measurements of the PA are performed by pulsing the supply with the same PW and duty cycle as that of the radar pulse and simultaneously driving the PA input with an amplitude-modulated RF pulse, which sweeps its entire dynamic range within the supply voltage pulse duration. This is repeated at the different supply voltage levels V_i (see Fig. 2b). However, since the period T_P (in the range 10 µs - 1000 µs, typical of pulsed radars) is shorter than the slow trap release transient [1]-[4], the GaN PA performance during each level of a given pulse is still affected by the large amount of charge trapping from the previous pulse level, where the peak level $V_D = V7$ corresponds to the trap state $X=X_{max}$ (Fig. 2).

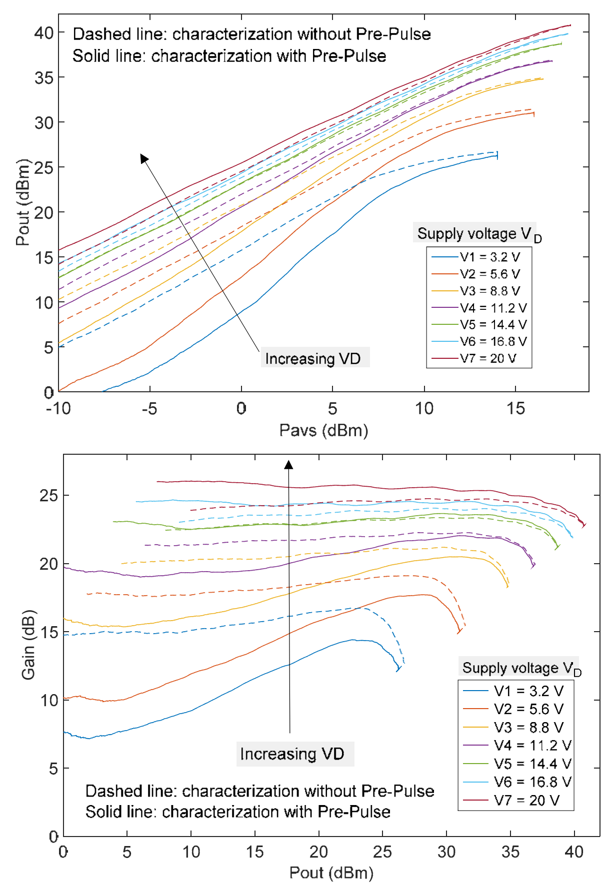

Fig. 3. Output power and available gain of the PA at different V_D: comparison between measurement with and without pre-pulse.

Thus, in order to obtain a more representative characterization of the PA at the different levels V_i under pulsed radar operation, a pre-pulse (PP) is applied to the PA before the actual "Measurement Pulse", as described in Fig. 2c. The PP is composed of a bias pulse (DC PP) at the maximum level $V_D = V7$ provided by the supply modulator, and an RF pulse (RF PP) synthesized by the VST that drives the PA to operate at its peak output power. In this way, the trapping state is set to $X=X_{max}$ at the end of the pre-pulse (blue squares in Fig. 2). The characterization of the PA at each V_D is performed with a peak trap state (set by DC+RF PP) that is equal to the one in the radar operating regime. In the inset of Fig. 2c, it is interesting to observe how the combination of the DC and RF Pre-Pulses drives the devices in the PA to the peak V_{DS} voltage of their operative dynamic load line (green line superimposed over the dynamic IV characteristic), thus setting the trapping state to $X=X_{max}$, due to the very fast charge trapping mechanism of GaN devices.

Characterization is performed with and without the pre-pulse, and Fig. 3 shows the *Pout/Pavs* and *Gain/Pout* characteristics comparison. There are remarkable differences between the two sets of data, especially at low power levels and low V_D, indicating a strong influence of the peak trapping state on PA performance under ET conditions. Further examination of the measured data shows that the gains at V_D = V1,V2 and low *Pavs* characterized with the PP are about 7 dB lower than the ones measured without PP: this is due to a strong PA current collapse observed in the PP characterization, measured at 91% and 88%, respectively, for the two V_D levels.

Next, both measured sets are used (by inverting AM-AM and AM-PM characteristics) for the identification of complex DPD coefficients used for the linearization of the PA operating in ET regimes with discrete levels of V_D provided by the supply modulator according to a selected trajectory (shaping function $\mathcal{F}_D$) for efficiency enhancement. The adopted memoryless polynomial model is defined by

$$z(n) = \sum_{k=1}^{K_i} a_{k,i} x(n) |x(n)|^{k-1} \qquad (1)$$

$$a_{k,i} = |a_{k,i}| e^{j\angle a_{k,i}} = a_{k,i}(V_i) \qquad i = 1 \ldots N \qquad (2)$$

$$V_i = \mathcal{F}_D(|x(n)|) \qquad i = 1 \ldots N \qquad (3)$$

where $x(n)$ and $z(n)$ are the baseband original and predistorted signals respectively, and $a_{k,i}$ are the complex polynomial coefficients dependent on the instantaneous bias voltage V_i. The instantaneous voltages V_i's are selected by the input signal amplitude $|x(n)|$, according to the discretized shaping function $\mathcal{F}_D$.

Fig. 4 shows clearly that the DPD identified from the data acquired w/o PP fails to linearize the ET PA, especially at low *Pavs* and V_D levels, where the differences due to trapping effects are more prominent (see Fig. 3).

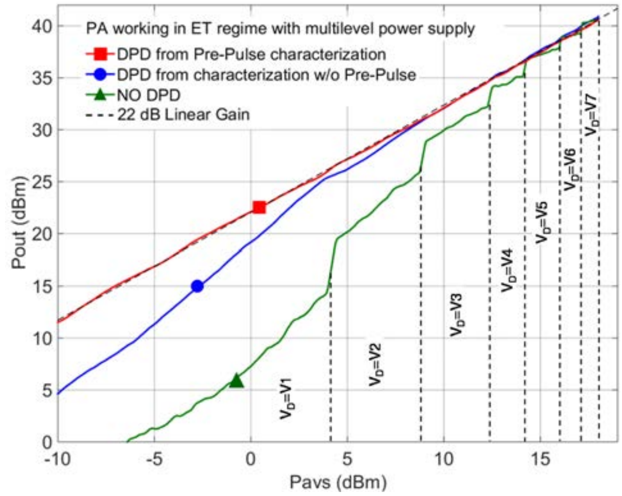

Fig. 4. ET PA linearization with data acquired with and w/o PP.

Additional experiments were performed for a better understanding of the influence of traps on the PA performance. In Fig. 5, the sensitivity of the PA peak RF output power and peak supply current to different PP amplitudes is investigated by measuring the PA performance at a given V_D level, by applying PPs of increasing DC voltage amplitudes (V_D=Vi) and RF powers with constant PP time advance (T_A= 2 μs and V_D = 5.6 V in the case of Fig. 5).

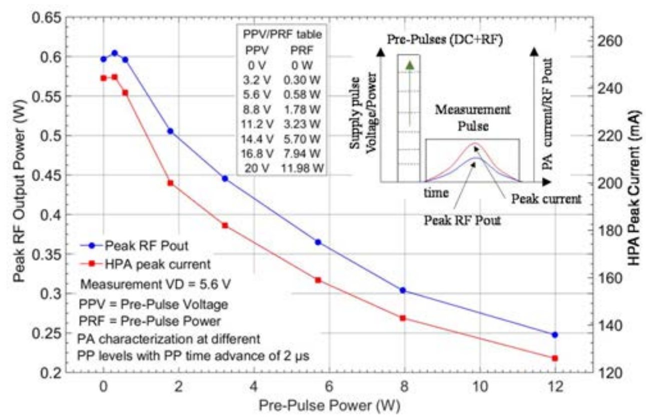

Fig. 5. PA performance sensitivity to Pre-Pulse amplitude.

It is interesting that for amplitudes below the actual measurement pulse with V_D = 5.6 V, there is no sensitivity to PP, whereas higher amounts of trapped charges induce large current and *Pout* drops for DC and RF PP levels exceeding the measurement pulse. In Fig. 6, the length of the trap release mechanism is investigated, by measuring the PA with PPs of fixed DC amplitude and RF power (PP with V_D=20 V, PRF = 12 W in Fig. 6) while the PP time advance (T_A) is varied. From the data in Fig. 6, it is evident that the trap release mechanism is very slow and has not ended after 10 ms. The same characterization of the trap release mechanism duration can be performed with different PP amplitudes (DC and RF), thus extracting additional information about the time constants' nonlinearity with respect to signal amplitudes.

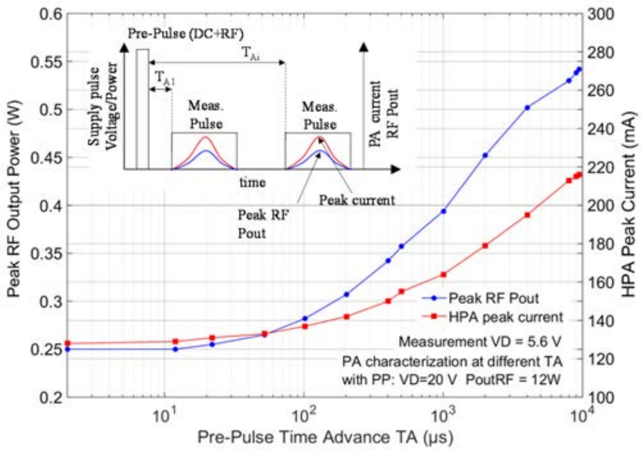

Fig. 6. PA performance sensitivity to Pre-Pulse time advance (T_A).

As shown in the data of Fig. 3, the proposed pre-pulsing technique, by controlling both trapping and thermal states, is effective for a PA characterization that enables a direct identification of the complex DPD coefficients used for ET transmitter linearization, in applications where the PA regime is a priori known, as in radar transmitters with pulse shaping [9]-[11].

Moreover, measured data as the ones in Fig. 5-6 can be very useful for the identification and validation of PA behavioral models that take into account nonlinear trapping effects. These models are useful for the linearization of PAs operating in ET regimes with high-PAPR and wide-bandwidth telecommunication signals. In those operating conditions, only the statistical properties of the PA working regime are known, and an efficient real-time adaptive DPD strategy should exploit accurate HPA behavioral models, since a direct closed-loop approach is unpractical and inefficient with wideband signals. The information of Fig. 5-6 regarding the trap state sensitivity to signal amplitudes and the nonlinear duration of the trap release mechanisms can be exploited for the formulation and identification of behavioral models that would improve the accuracy of DPD for GaN-based power amplifiers (e.g. [12]).

REFERENCES

[1] O. Jardel, F. De Groote, T. Reveyrand, J.-C. Jacquet, C. Charbonniaud, J.-P. Teyssier, D. Floriot, R. Quere, "An electrothermal model for AlGaN/GaN power HEMTs including trapping effects to improve large-signal simulation results on high VSWR," *IEEE Transactions on Microwave Theory Techniques, vol. 55*, no. 12, pp. 2660–2669, Dec. 2007.

[2] A. Santarelli, R. Cignani, G. P. Gibiino, D. Niessen, P. A. Traverso, C. Florian, D. M. M. -P. Schreurs, F. Filicori, "A double-pulse technique for the dynamic characterization of GaN FETs," *IEEE Microwave and Wireless Components Letters, vol. 24,* no. 2, pp. 132–134, February 2014.

[3] J. Jungwoo and J.A. d. Alamo, "A current-transient methodology for trap analysis for GaN high electron mobility transistors," *IEEE Transactions on Electron Devices, vol. 58*, no. 1, pp. 132–140, 2011.

[4] A. Santarelli, R. Cignani, D. Niessen, P. A. Traverso, F. Filicori, "New pulsed measurement setup for GaN and GaAs FETs characterization," Cambridge Int. Journal Microw. Wireless Tech., vol.4, no. 3, pp. 387–397, Apr. 2012.

[5] S. C. Binari, K. Ikossi, J. A. Roussos, W. Kruppa, D. Park, H. B. Dietrich, D. D. Koleske, A. E. Wickenden, R. L. Henry, "Trapping effects and microwave power performance in AlGaN/GaN HEMTs," *IEEE Transactions on Electron. Devices, vol. 48*, no. 3, pp. 465–471, Mar. 2001.

[6] J. Xu, R. Jones, S. A. Harris, T. Nielsen, D. E. Root, "Dynamic FET model–DynaFET–for GaN transistors from NVNA active source injection measurements," *IEEE MTT-S International Microwave Symposium Dig*est, June 2014.

[7] A. Santarelli, D. Niessen, R. Cignani, G. P. Gibiino, P. A. Traverso, C. Florian, D. M. M. P. Schreurs, F. Filicori "GaN FET Nonlinear Modeling Based on Double Pulse I/V Characteristics," *IEEE Transactions on Microwave Theory Tech*nique, vol. 62, Iss.12, pp. 3262 – 3273, 2014.

[8] C. Florian, T. Cappello, R.P. Paganelli, D. Niessen, F. Filicori, "Envelope Tracking of an RF High Power Amplifier With an 8-Level Digitally Controlled GaN-on-Si Supply Modulator," *IEEE Transactions on Microwave Theory Techniques,* vol. 63, Iss. 8, pp. 2589 - 2602, Aug. 2015.

[9] M. Roberg, M. Rodriguez, D. Maksimovic, Z. Popovic, "Efficient and Linear Amplification of Spectrally Confined Pulsed AM Radar Signals," *IEEE Microwave and Wireless Components Letters*, Vol. 22, Iss. 6, 2012, pp. 279 – 281.

[10] M. Rodriguez, M. Roberg, A. Zai, E. Alarcon, Z. Popovic, D. Maksimovic, "Resonant Pulse-Shaping Power Supply for Radar Transmitters", *IEEE Trans. on Power Electronics,* vol. 29, no. 2, pp. 707-718, Feb. 2014.

[11] Zai, A.; Pinto, M.; Coffey, M.; Popovic, Z., "Supply-Modulated Radar Transmitters With Amplitude-Modulated Pulses," in *IEEE Trans. on Microwave Theory and Tech.,* vol.63, no. 9, pp. 2953-2964, Sept. 2015.

[12] G. P. Gibiino, G. Avolio, D. M. M. P. Schreurs, A. Santarelli and F. Filicori, "A Three-Port Nonlinear Dynamic Behavioral Model for Supply-Modulated RF PAs," in *IEEE Trans. on Microwave Theory and Tech.*, vol. 64, no. 1, pp. 133-147, Jan. 2016.