



Accurately Characterizing the Vdd-to-AM and Vdd-to-PM Nonlinearities in a GaN HEMT Class E Power Amplifier

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Abstract- In this paper, an experimental procedure is proposed for accurately characterizing the Vdd-to-AM and Vdd-to-PM nonlinearities in a class E power amplifier (PA). Based on GaN HEMT technology, this transmission line switching PA is aimed to be used as modulating stage of a 900 MHz polar transmitter. Measured results under a two-tone excitation support the need for predistorting functions.

Index Terms- Efficiency, nonlinear distortion, polar transmitters, power amplifiers.

I. INTRODUCTION

Polar transmitter nonidealities may limit the great potentialities of this emerging technique for simultaneously providing high linearity and efficiency figures in future wireless services. A pioneer work on the subject is due to Raab [1], who considered two principal sources of nonlinear distortion associated to the architecture: finite AM modulator bandwidth and differential delay between the amplitude modulating component and the phase modulated RF carrier.

Finite AM modulator bandwidth was there treated in an approximate way, assuming an ideal brick-wall reconstruction filter, while the differential delay between the AM and PM paths was considered a constant and independent

quantity respect to the base-band envelope frequency. However, Raab also recognized the existence of other sources of distortion associated to the switching mode modulating stage: the Vdd-to-AM and Vdd-to-PM characteristics (a notation proposed later in [2]).

Milosevic et al. in [3] extended the finite AM bandwidth analysis, considering a general reconstruction filter. The distortion caused by the PA nonlinearities, together with the differential delay, were then experimentally investigated in [4]. Recently, a comprehensive analysis of all these nonlinear distortion generation mechanisms has been proposed in [5], including analytical models for the AM-AM and AM-PM nonidealities.

Following this line, an experimental procedure is proposed in this paper for accurately characterizing the Vdd-to-AM and Vdd-to-PM nonlinearities in a GaN HEMT class E PA to be employed in a polar transmitting architecture.

II. TRANSMISSION LINE CLASS E PA

A class E PA was designed at the 900 MHz frequency band, following the transmission line topology proposed in [6]. A 15W GaN HEMT from Cree was selected, the CGH35015F a device conceived for WiMAX class AB amplifier applications.

The optimum load impedance value at the fundamental was in a first approach computed as in Eq. 1, while open circuit conditions were assured at the second and third harmonics.

$$Z_{opt} = \frac{0.28}{\omega \cdot C_{out}} e^{j49^\circ} \quad (1)$$

In the search for the highest power added efficiency (PAE), further Z_{opt} refinements were made through load pull simulations.

In Fig.1, a photograph of the implemented PA is shown. The drain biasing path was prepared for inserting a low frequency envelope signal, aimed to modulate in amplitude the PM carrier.

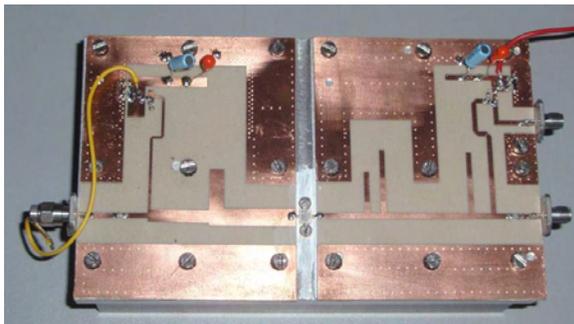


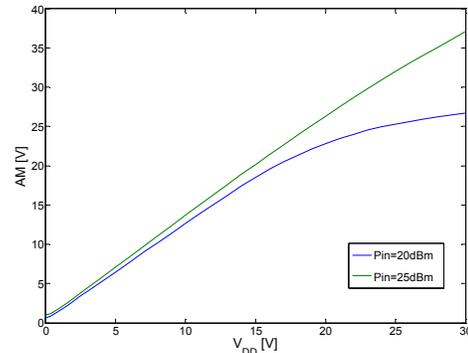
Fig.1. Photograph of the implemented class E PA, based on Cree CGH35015 GaN HEMT.

III. CHARACTERIZING THE V_{dd}-to-AM and V_{dd}-to-PM NONLINEARITIES

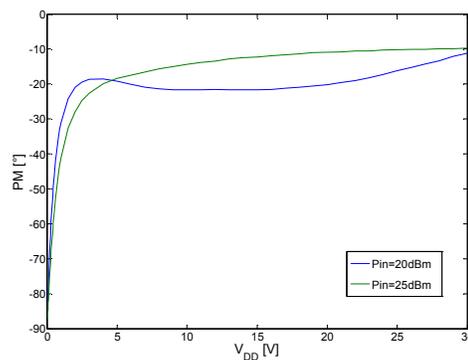
Using the traditional experimental procedure, with the PA excited by a CW signal, the drain biasing voltage was varied from 0 to 30V. The evolution of the output signal amplitude and phase components was measured. In Fig. 2, those characteristics may be observed for two different input power levels.

At a moderate excitation, $Pin = 20\text{dBm}$, saturation of the amplitude characteristic is observed for high V_{dd} values. This behavior, associated to the device abandoning the switching mode of operation, seems however corrected for a larger drive level.

When the drain bias voltage is lowered close to 0V, a residual RF carrier leakage exists together with a significant parasitic phase modulation.



(a)



(b)

Fig.2. (a) V_{dd}-to-AM and (b) V_{dd}-to-PM static characteristics.

IV. EXTRACTING THE MODULATING STAGE NONLINEARITY DERIVATIVES

In order to improve the accuracy in the characterization of the modulating stage nonideal behavior, both in amplitude and phase, a procedure for extracting their Taylor-series coefficients in Eqs. 2 and 3 was designed.

It follows the principle of previous procedures for nonlinearity derivative characterization [7], based on measurements of the harmonic content produced by the device under a small-signal excitation.

$$AM(V_{dd}) = AM_0 + m_1 \cdot v_{dd} + m_2 \cdot v_{dd}^2 + m_3 \cdot v_{dd}^3 + \dots \quad (2)$$

$$PM(V_{dd}) = PM_0 + p_1 \cdot v_{dd} + p_2 \cdot v_{dd}^2 + p_3 \cdot v_{dd}^3 + \dots \quad (3)$$

A low level and low frequency AM modulating tone was added to the DC voltage value and inserted by the drain biasing path. The PA output was captured, employing Agilent 89600 Vector Signal Analyzer. The harmonic content in the amplitude and phase components of the complex envelope (obtained through FFTs) was then used for extracting the m 's and p 's.

In Fig.3, the evolution of the expansion coefficients of first, second and third degree for the Vdd-to-AM characteristics is presented.

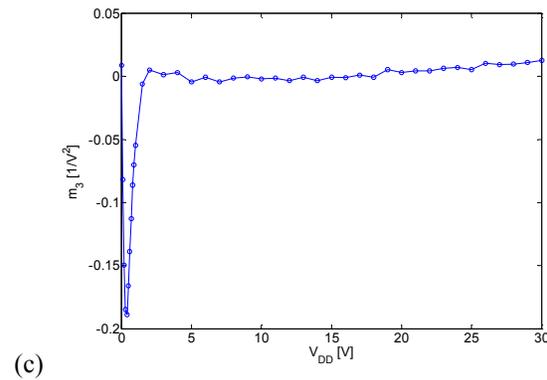
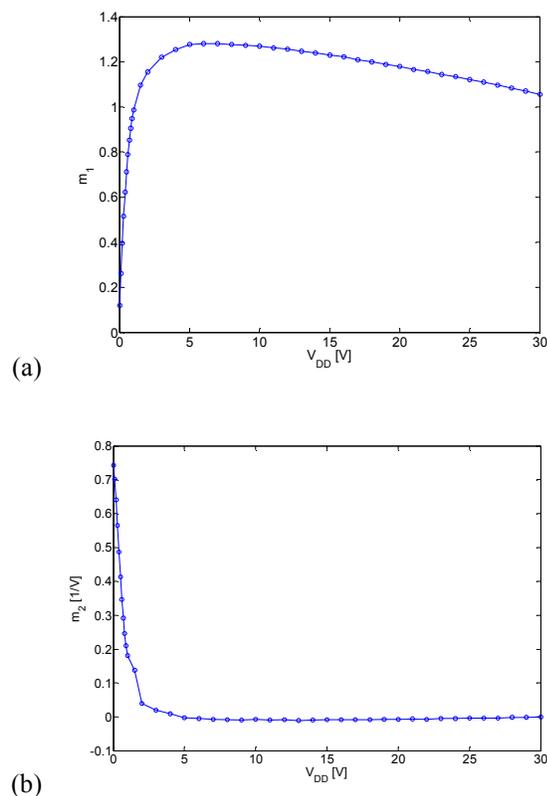


Fig.3. Vdd-to-AM extracted derivatives: (a) m_1 , (b) m_2 and (c) m_3 .

The gate biasing condition, $V_{GS} = -2.8$ V, and input power level, $P_{in} = 25$ dBm, were selected as optimum for a class E zero voltage switching operation at $V_{DS} = 28$ V.

Carrier feedthrough is mainly responsible for the derivatives' evolution. Carrier leakage had been also observed in the past for class C high level AM modulators [8] and bipolar-based class E amplifiers [9].

A careful insight into m_1 shows that the saturation of the amplitude characteristic for high V_{dd} values has not been totally corrected, and that a further increase in the RF input power level would be certainly welcome in order to avoid residual IMD distortion at high envelope excursions.

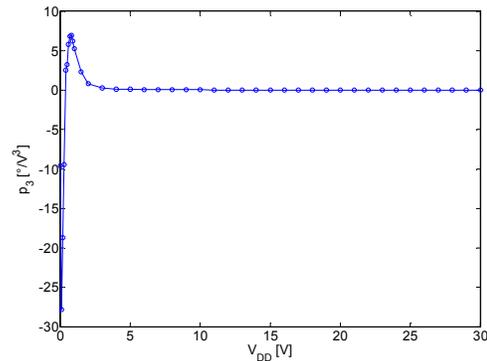
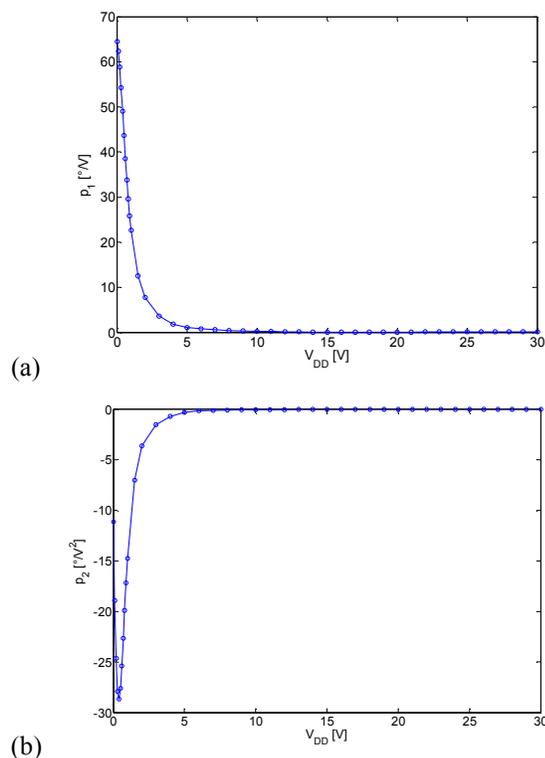
In Fig.4, the expansion coefficients for the Vdd-to-PM characteristic are also shown. A main nonlinear region is observed at low V_{dd} values, coinciding with the already appreciated behavior in the amplitude nonlinearity.

V. DEVICE FACTORS LIMITING THE MODULATION LINEARITY

Different works have dealt with the origins of the Vdd-to-AM and Vdd-to-PM nonlinearities, but a detailed analysis had been missing.

A. Feedthrough

In [8], Raab gave some insight into the amplitude-modulation characteristics of a BJT amplifier. The feedthrough was there associated to the capacitive coupling between the base and collector, which produces a minimum output signal that is present even when $V_{CC} = 0V$. The amount of carrier leakage could be estimated by considering it to be the result of applying the fundamental frequency component of the base-emitter voltage to a series arrangement of the base-collector capacitance and the collector load impedance.



(c)

Fig.4. Vdd-to-PM extracted derivatives: (a) p_1 , (b) p_2 and (c) p_3 .

Recently, a comprehensive study was employed to accurately describe the Vdd-to-AM and Vdd-to-PM profiles of a PHEMT based class E PA [5]. The nonlinear gate-to-drain capacitance in the device equivalent circuit was shown to be responsible for the observed behavior.

In this GaN HEMT switching mode PA, the measured amplitude and phase characteristics may also be reproduced with the aid of C_{gd} . Since the feedthrough is coupled through a reactance that is generally larger than output load resistance, the feedthrough signal is generally in phase-quadrature with the amplified component at the output. This causes a phase variation in the carrier (Vdd-to-PM conversion) close to 90° at low modulating levels.

B. Vdd-to-AM saturation

In [5], the saturation of the AM/AM curve for high biasing voltages has been associated to the device I/V characteristic. For a linear amplitude modulation, the maximum drain biasing voltage and the input power level should be selected to guarantee that the drain current gets saturated in the transition to the linear region. As the saturation value is almost linearly proportional to V_{DD} for a fixed load, the sought linear modulation would be assured.

If the RF excitation is not enough or the drain biasing voltage too high, the case of $P_{in} = 20\text{dBm}$

in Fig. 2, the device operation may get into the saturated region where it works in current source mode. In such operating condition, the drain current does not linearly follow the drain voltage, but it tends to a constant. With the aid of the measured higher order derivatives, an optimum RF drive level may be searched for to assure maximum linearity.

VI. IMD BEHAVIOR UNDER TWO-TONE EXCITATION

In order to describe the impact of the above characterized Vdd-to-AM and Vdd-to-PM nonlinearities, on the IMD performance of a polar transmitter, the measurement system of Fig. 5 was implemented.

Two vector signal generators, controlled from Matlab, allowed exciting the class E GaN HEMT PA with a phase modulated carrier and the modulating amplitude component. A linear stage was used in order to accommodate the envelope signal to the required levels at drain terminal for an optimum modulation performance of the switching stage.

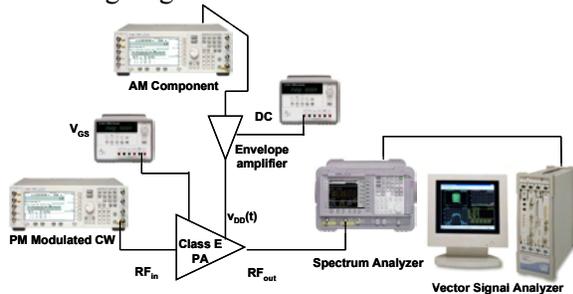


Fig.5. Implemented characterization system.

Using the classical linearity test, with two tones at a frequency spacing of 100 kHz, the output spectrum was captured with the aid of a vector signal analyzer.

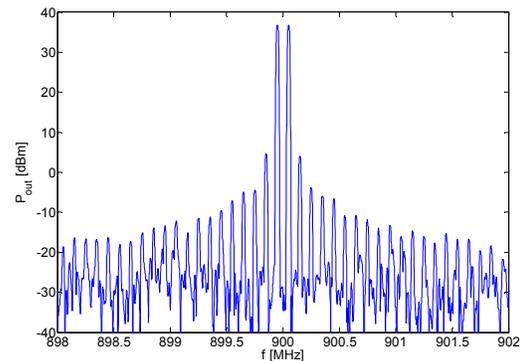


Fig.6. Measured output spectrum, as captured from a vector signal analyzer under two-tone excitation.

As observed from Fig. 6, a carrier to intermodulation distortion (CIMD) rejection of more than 30 dB was obtained, mainly due to the linear AM characteristic. Using a slightly higher input power level and incorporating predistorting functions, both for the phase and amplitude components, this result could be enhanced.

VII. CONCLUSION

An experimental procedure has been proposed for accurately characterizing the Vdd-to-AM and Vdd-to-PM nonlinearities in a class E PA, designed over a 15W GaN HEMT from Cree. The observed nonlinearities may be also described using the device mechanisms discussed in [5], and the extracted derivatives may help optimizing the operating conditions for linear modulation. Measurement IMD results of a polar transmitter architecture support the need for correcting the modulating stage nonlinearities.

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