LARGE Characterization of Power GaN FETs and PAs Linearity at Different Load Impedances Under CW Conditions and Multitone Signals Based on the USRP LFTX Daughterboard

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***Abstract*— This paper introduces a test bench to characterize the linearity of a packaged power GaN-HEMT or power amplifiers (PAs) to assess the linearity using continuous waves and multitone signals. The proposed test setup uses an RF daughter board and a Universal Software Radio Peripheral (USRP) instead of an Arbitrary Wave Generator (AWG) to generate the tones in the baseband. A VNA is used along with the Spectrum Analyzer Option (SA) to acquire the incident and reflected multitone signals at the input and output of the Device Under Test (DUT). The load-pull system is completely calibrated and can characterize the transistor or the PA linearity, such as the static AM-AM, AM-PM, C/I, and IMD at any load impedance.**

***Keywords*— Power amplifier; AM-AM; AM-PM C/I; IMD**

I. INTRODUCTION

The most important metrics used to evaluate the performance of RF power amplifiers (PAs) are output power, efficiency, and linearity. These metrics depend on the load impedance of the FET that are typically determined using high-frequency harmonic load-pull systems, either passive or active. Wireless communication systems require high linearity power amplifiers to mitigate in-band distortion, loss of information, and spectral regrowth, which can interfere with other channels that share the same communication medium [1]. It has been demonstrated that the PA is more efficient when it works near to or beyond the 1 dB compression point (P1dB) where it exhibits a nonlinear behavior producing a distorted output signal and increasing the spectral regrowth. Moreover, digital modulation techniques like Quadrature Amplitude Modulation (QAM) are very susceptible to any change in phase or amplitude produced by the nonlinearity effects of the PA causing loss of information.

Different figures of merit characterize the PA linearity, e.g., AM-AM (Amplitude-to-Amplitude distortion), AM-PM (Amplitude-to-Phase distortion), IMD (3^{rd}, 5^{th}, etc., intermodulation order),or C/I (carrier to intermodulation). These nonlinear effects can be compensated through linearization schemes such as digital pre-distortion (DPD). In [2] a PA linearity characterization of a millimeter Wave-GaN HEMTs is carried out using Vector Signal Generator (VSG), Vector Signal Analyzer (VSA) and SA. In [3], [4] linearity characterization is studied using multitone signals generated by an Arbitrary Wave Generator (AWG) with IQ modulation capabilities and Sample Based Receivers (LSNA). In [5], [6], [7] amplifier linearity characterization is investigated using Unequal Space Multitone Signal (USMT) along with a load-Pull system. For this purpose, a Nonlinear Vector Network Analyzer (NVNA) fully calibrated along with the SA option was used, whereas in [8], a LSNA fully calibrated was used instead of the NVNA.

In this work, we present a test bench to characterize the linearity of a packaged GaN-HEMT power transistor or PA under CW and multitone signals excitation with different load conditions using a FOCUS Multi-Purpose Tuner (MPT). One novelty of the presented test bench is that the baseband tones are generated through USRP and an RF daughter board instead of utilizing an Arbitrary Wave Generator (AWG). The generated signal is fed into PSG E8267D in order to up-convert the signal. The static AM-AM and AM-PM characteristics at the fundamental frequency, carrier to intermodulation and load-pull measurements are obtained by measuring the incident and reflected waves from the DUT using the PNA-X 5245A along with Spectrum Analyzer (SA) option, which is one of the originalities of this work, and it is different from the most recent work [7], [8]. The test bench is a more simple system and not uses phase calibration which is an advantage when contrasted with [5] which uses an NVNA.

II. THE PROPOSED TEST-BENCH

Fig. 1 shows a complete description of the proposed test bench to characterize the linearity of packaged transistor or PA under CW and multitone signals excitation. It is important to highlight that this configuration can handle high power. It consists of an RF daughter board and a USRP board used to generate the baseband tones. The tones are fed into the PSG E8267D to upconvert the signal. The PSG is configured as an external source in the PNA-X and the synchronization between both is done using trigger signals and the 10 MHz clock signal. In addition, to protect the driver (AR 40SG10), a 20 dB attenuator is added to its input and an isolator to its output, this guarantees that the input level is less than 0 dBm, and no reflected signal is feedback into the output of the driver. External directional couplers with a coupling factor of 40 dB are used to sense the incident and reflected waves

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from the DUT. For security, external attenuators are used at the receivers of the PNA-X to avoid their saturation. The attenuation value must guarantee a signal level below -20 dBm (the value recommended by Keysight to guarantee that the receivers work in their linear region). A computer-controlled microwave tuner (FOCUS iCCMT 5020) and a multi-purpose tuner (FOCUS MPT 1808) are used to generate the input and output impedances, respectively, at the fundamental frequency at the DUT planes. The whole system is controlled from a PC using the ethernet connection, whereas the USRP board is controlled by another PC that runs the GNU Radio Companion (GRC) development tool.

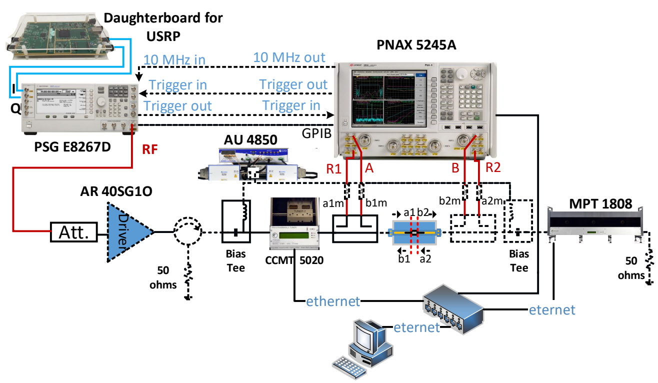

Fig. 1. Test Bench for linearity characterization.

A. Signal generation

The characterization of the transistors or PAs under multi-tone conditions is performed using an LFTX (Low-Frequency Transmitter) daughterboard from Ettus Research. The LFTX runs on Linux and, using software-defined radio, can be programmed to generate one or more tones in a frequency range of 1 to 30 MHz or I/Q signal simultaneously.

The multi-tones are generated using a procedure similar to these employed to generate an OFDM symbol, this means using the IFFT technique (which is available as a function block in GRC). Since each tone represents a sub-carrier, it is necessary to define a frequency spacing and a vector with a value of one in the positions where we want to generate multiples of the first sub-carrier that will be generated when the IFFT is applied to this vector.

$$x(n) = \frac{1}{N}\sum_{k=0}^{N-1} \mathbf{X}(k) \exp(\frac{j2\pi nk}{N}) \quad (1)$$

$$x(n) = \mathbf{W}^H \mathbf{X}(k), k, n = 0, 1, 2, ..., N-1 \quad (2)$$

Equation (1) shows the IFFT formula, while equation (2) shows the equivalent in matrix notation. The IFFT can be represented as the product of the vector $\mathbf{X}(k)$ and a complex matrix $\mathbf{W}$ defined in equation (3), where N is the number of bins on the IFFT.

In OFDM $\mathbf{X}(k)$ is a vector of complex symbols which are the result of a digital modulation as BPSK, QPSK, and M-QAM.

$$\mathbf{W} = \begin{pmatrix} 1 & 1 & 1 & ... & 1 \\ 1 & e^{(\frac{-j2\pi}{N})} & e^{(\frac{-j4\pi}{N})} & ... & e^{(\frac{-j2\pi(N-1)}{N})} \\ ... & ... & ... & ... & ... \\ 1 & e^{(\frac{-j2\pi(N-2)}{N})} & e^{(\frac{-j4\pi(N-2)}{N})} & . & e^{(\frac{-j2\pi(N-1)(N-2)}{N})} \\ 1 & e^{(\frac{-j2\pi(N-1)}{N})} & e^{(\frac{-j4\pi(N-1)}{N})} & . & e^{(\frac{-j2\pi(N-1)(N-1)}{N})} \end{pmatrix} \quad (3)$$

Fig. 2 shows the GNU radio blocks that describe the process needed to generate the baseband tones.

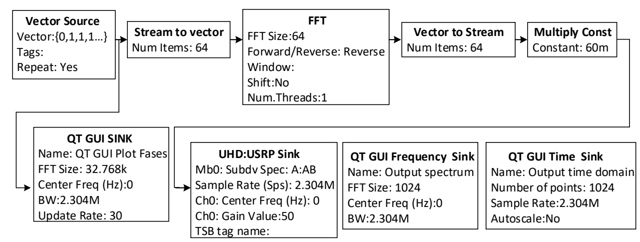

Fig. 2. GNU radio blocks to generate the baseband tones.

B. Calibration

Due to nonidealities of the measurement system, shown in Fig. 1, (Errors of VNA, couplers, and test fixture), a relative and power calibration is required at the DUT reference plane at the center of the test fixture. The calibration of a load-pull system consists of two parts: 1) relative calibration, used to determine ratios of parameters, and 2) power calibration, used to determine the power levels at the DUT ports. The relative calibration may be carried out by using two-port calibration techniques. The load-Pull calibration is done according to the procedure reported in [9], [10]. Once the calibration is done, the static AM-AM, AM-PM, C/I, power contours, input and output spectrum measurements, and the optimum load impedance at the DUT reference planes can be measured.

III. Measurement Results

A. One tone measurement

The GaN FET CGH40010F was utilized as the DUT and characterized at 2.0 GHz. Fig. 3 shows the output power at the fundamental frequency and at the second harmonic, carrier to second harmonic, and gain. These measurements are useful in the development of memoryless nonlinear models [11]. It is important to highlight that these measurements are done with the SA option of the PNA-X in the transistor reference plane and loaded at optimal impedance. Moreover, these measurements do not require phase calibration as reported in [5], [7]. Fig. 4 and Fig. 5 show the static AM-AM, and AM-PM, respectively, at different bias points.

Fig. 6 shows the output power contours of CGH40010F at 2 GHz, loaded with the optimum load impedance (17.18+9.18i Ω), with a quiescent bias point $V_{GS} = -2.6\ V$, $V_{DS} = 26\ V$.

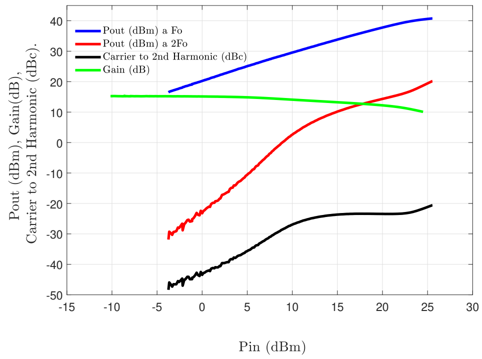

Fig. 3. AM-AM, Gain and 2nd harmonic distortion of CGH40010F transistor.

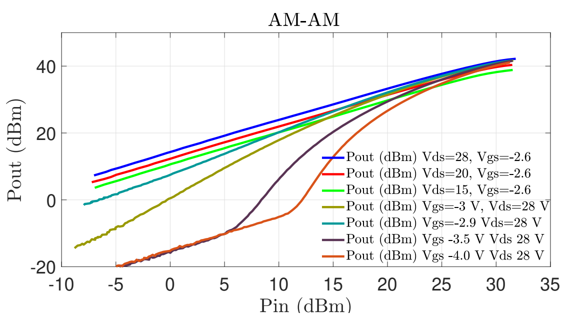

Fig. 4. AM-AM for different quiescent points of CGH40010F transistor.

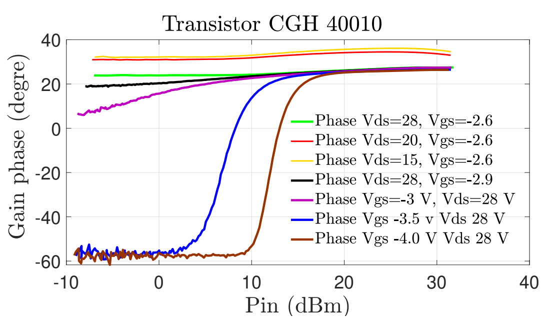

Fig. 5. AM-PM for different quiescent points of CGH40010F transistor.

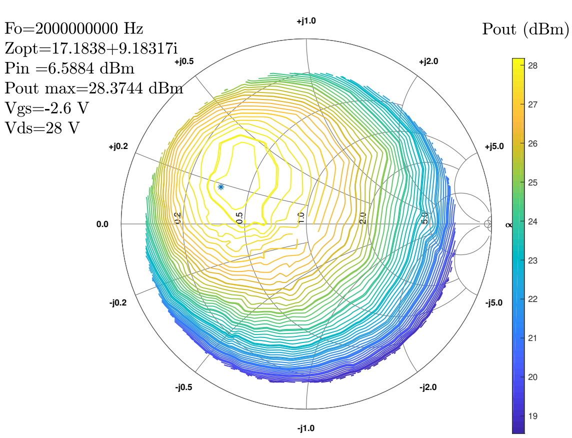

Fig. 6. Power contour CGH40010F transistor.

B. *Carrier to intermodulation with 2 tones*

One of the measurements used for characterizing the linearity of the transistor is the carrier to third intermodulation order (C/IM_3 (dBc)), measured according to [5]. In equation (4) P_{tones} is the total power of the fundamental tones, and P_{IM_3} is the power of the third-order intermodulation.

$$\frac{C}{IM_3} = 10log_{10}(\frac{P_{tones}}{P_{IM_3}}) \tag{4}$$

Fig. 7 shows the C/IM_3 contours using two tones located at 2.0 GHz and 2.000015 GHz. The maximum value of C/IM_3 (26.06 dBc) is obtained when an impedance of 18.33+21.03i Ω is presented at the frequency of the first tone (2 GHz).

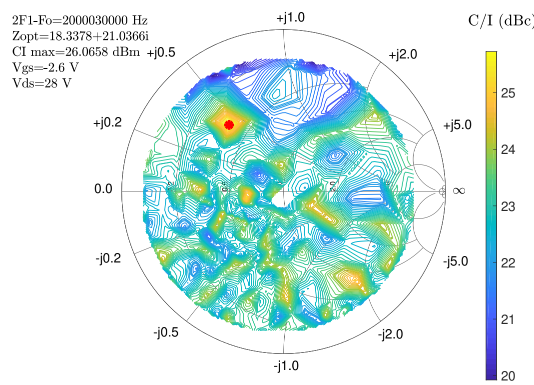

Fig. 7. Carrier to Intermodulation (dBm).

C. *Multitone Load-Pull Results*

For load-pull measurements with multitone, we use 10 tones separated at 35.875 KHz and centered at 1.999839 GHz. Fig. 8 and Fig. 9 show the input and output spectrum of the transistor CGH40010F, respectively, when the optimum impedance at 1.999999125 GHz is presented at the output of the transistor.

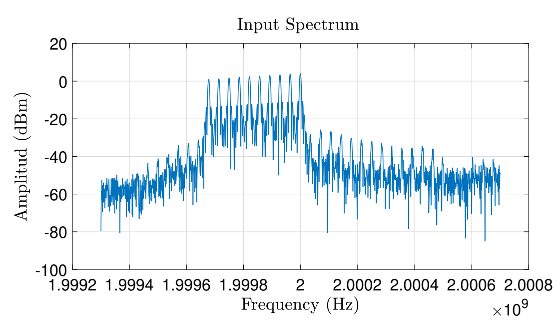

Fig. 8. Input spectrum of the DUT.

Fig. 10 shows the total output power contours and the optimum loads in each tone when the optimum load at 1.999999125 GHz is applied. The total input and output powers are 15.74 dBm and 30.83 dBm, respectively. To observe the different optimum impedances at each tone, a large zoom has been done in the area where they are located.

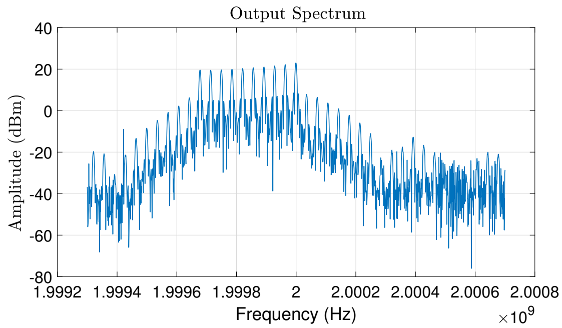

Fig. 9. Output spectrum of the DUT.

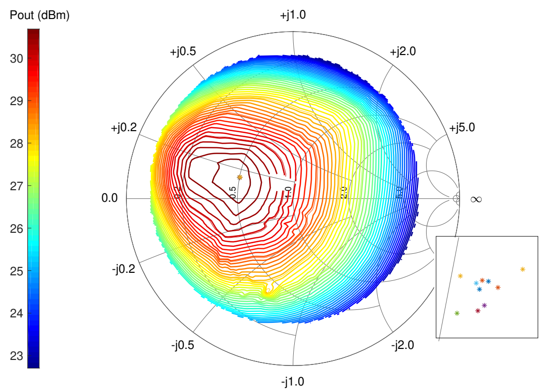

Fig. 10. Power contours and optimum impedances with multitone signals.

IV. Conclusion

A test bench to characterize the linearity of power GaN FETs or power amplifiers under CW and multitone signals excitation with different load conditions has been developed. The novelty of the proposed test bench consists of the use of an RF daughter board and a Universal Software Radio Peripheral (USRP) to generate the tones in the baseband instead of an arbitrary wave generator (AWG) and a VNA (PNA-X) with the spectrum analyzer option. The proposed test bench can measure the static AM-AM, AM-PM, C/I, and IMD for any load impedance without a phase calibration

Acknowledgement

We thank M. Sc. Diana Soto-Castañeda for her assistance in formatting the manuscript.
This work has been partially supported by the National Council of Science and Technology (CONACYT-México). Projects numbers: INFR-2014-01 No.228580, CB 2013-222949-Y, and INFR-2016-01 No. 269927.

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