High Resolution Wideband Calibration Procedure for RF Time-Domain Measurement of Non-linear Devices

K. El-Akhdar, S. Ahmed, T. Reveyrand, G. Neveux, D. Barataud, and J.M. Nebus

University of Limoges, XLIM, UMR n°7252, 123 Av. A. Thomas, 87060 Limoges Cedex, France

Kassem.el-akhdar@xlim.fr

Abstract — **This paper proposes a high resolution wideband calibration procedure for RF time-domain measurement of non-linear devices. This calibration is based on the use of wideband multi-sine signal and is applied to a 4 channel Track and Hold Amplifier (THA) based measurement setup. The absolute magnitude and phase calibration is performed with a calibrated coherent interleaving sampling oscilloscope as reference. The new calibration procedure without any IF calibration assumption allows a 10 kHz resolution over 3 GHz bandwidth. A 40 W GaN high power amplifier, driven by a pulsed RF signal at the input, is characterized with this time-domain measurement setup. The fully calibrated measurement setup has the capability to give an accurate visualization of time-domain distortions on input/output voltage and current waveforms within the pulse. Calibrated rising and falling transitions of the pulse are also exhibited.**

Index Terms — **Wideband calibration, multi-sine, RF time-domain characterization, GaN, power amplifiers.**

I. INTRODUCTION

Wireless telecommunication and radar systems require working with broadband RF excitation signals. To achieve wideband performances, it is of prime importance that the nonlinear devices (High Power Amplifiers - HPA) are characterized in time-domain under RF modulated signals. For accurate time-domain acquisition of voltage and current waveforms at both ports of non-linear devices, the measurement systems should be calibrated for wide bandwidth, with high resolution and high dynamic range constraints.

In the last decades, many time-domain measurement systems have been developed with specific calibration procedures. They were developed in the frequency domain due to the lack of voltage and current calibrated probes at RF frequencies. The characterization of non-linear devices excited with CW RF large signals can be performed with calibrated setups using Large Signal Network Analyzers (LSNA) [1], [2] Non Linear Vectors Network Analyzers (NVNA) [3] and Digital Sampling Oscilloscopes (DSO) [4].

Modulated signals and especially pulsed RF signals are required for the extraction and validation of electro-thermal models of non-linear devices involving memory effects. Similarly, RF pulsed excitations are needed for the determination of power performances of GaN HPA.

Customized measurements test benches like LSNA [5], [6] NVNA [7] have been developed to measure pulsed RF CW time-domain voltage and current waveforms at both ports of non-linear devices. These instruments measure only the CW signal and its associated harmonics within the pulse. They are all based on the use of the same absolute magnitude and phase calibration reference as the ones used for CW measurements (composed of the carrier frequency and its multiple harmonics) and assume a constant group delay.

For the characterization of non-linear devices under pulsed and wideband modulated signals, a very accurate reference signal that includes all the spectral components in the frequency grid present in the modulated signal is required.

This paper proposes a calibration procedure based on the use of wideband high resolution multi-sine signal described in section II. This calibration procedure is applied here on a THA-based measurement setup [8]. The validation of this calibration procedure is discussed in section III. Section IV presents the measurement results of a 40 W GaN HPA demonstrator under RF pulsed conditions.

II. DESCRIPTION OF THE CALIBRATION PROCEDURE

A. 4-channel time-domain measurement setup

Fig. 1 describes the proposed 4 channel time-domain interleaved high sampling rate measurement setup based on the use of THAs [8] to measure calibrated complete transient voltage and current responses of non-linear devices excited with pulsed RF CW and wideband modulated signals.
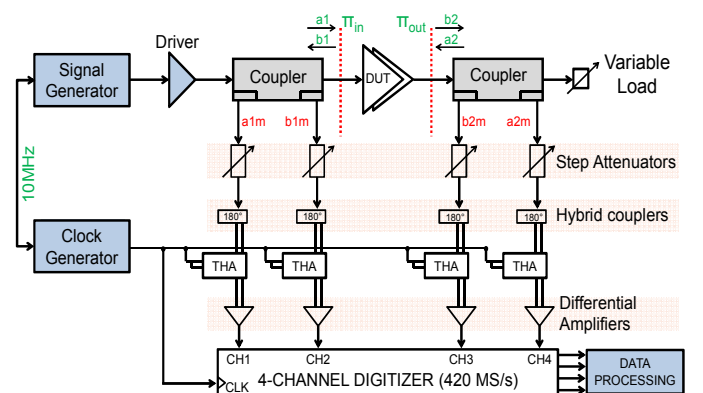

Fig. 1.   Block diagram of measurement system.

20 dB wideband bi-directional couplers enable to simultaneously capture the incident and reflected voltage waves at the input and output of the Device Under Test (DUT). Variable calibrated attenuators are required to avoid saturation of THA based receivers.

The excitation signal is linearly amplified using a broadband high gain amplifier (driver in Fig. 1) before feeding the DUT.

B. Multi-sine calibration procedure

The goal of this procedure is to calibrate the test setup for a wide spectrum bandwidth with a very high resolution. For modulated signal excitation, as pulsed signals for instance, the resolution increases with Pulsed Repetition Interval (PRI) and the spectrum is spread over infinite bandwidth. The calibration that is performed in the frequency domain requires a signal with a frequency grid that contains all the spectral lines present in the spectrum of the signal for a large bandwidth. This signal can be used to perform the relative error correction with a single measurement for all the desired spectral components. The same signal when measured with a calibrated oscilloscope could be used as a phase and amplitude reference for absolute calibration.

To achieve this objective, a multi-sine signal consisting of summation of sinusoids with constant amplitude and different phases is generated. The frequency spacing (Δf) among these sinusoids is constant and depends upon the desired frequency spectrum resolution. The generation of band limited multi-sine signal between f_{min} and f_{max} with a period time ($T=1/\Delta f$) is defined by following Eq. 1.

$$x(t) = \sum_{k=1}^{N} A \cos(2\pi f_k t + \phi_k) . \qquad (1)$$

where $N = [(f_{max}-f_{min})/\Delta f]+1$.

To obtain an optimum Signal to Noise Ratio (SNR), the Crest Factor (CF) of a multi-sine signal should be kept as small as possible. The CF is defined in Eq. 2.

$$CF = \frac{X_{peak}}{X_{RMS}} = \frac{\max(|x(t)|)}{\sqrt{\frac{1}{T}\int_0^T |x(t)|^2 .dt}} . \qquad (2)$$

To reduce this CF value, the phase of each sinusoid signal with given spectral amplitude is adjusted using Schroeder phase approach [9] as defined in Eq. 3.

$$\phi_k = -\frac{k(k-1)}{N}\pi . \qquad (3)$$

This Schroeder-phased multi-sine signal is computed using DSP techniques in Matlab. The synthesis parameters that include the calibration band (f_{min}, f_{max}) and spectral resolution (Δf) are predefined for the signal to be generated. This signal is then converted from digital to analog domain using an Arbitrary Waveform Generator (AWG7122C-TEK) [10] with a high interleaved sampling frequency of 24 GS/s and analog bandwidth of 10.6 GHz.

The THA based measurement setup has a maximum dynamic range of 70 dB (-45dBm to 25dBm). The maximum number of spectral indexes that can be calibrated is calculated considering the required dynamic range of the measurement set-up, the maximum and minimum power levels at the input of the receiver to avoid saturation and to obtain the minimum power required for each spectral line. Considering all these parameters, a calibration of the test-bench with 300,000 tones and a 10 kHz frequency resolution (Δf) is reachable over a 3 GHz bandwidth.

In the following and as a matter of example, a numerical Schroeder-phased multi-sine (36000 tones) signal of 100 kHz resolution and a 3.6 GHz bandwidth is defined and depicted in Fig. 2. The calibration is then performed with this signal.
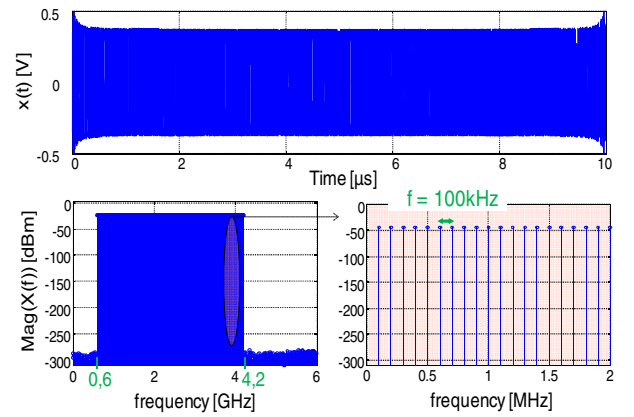

Fig. 2.   Time domain multisine signal (CF=1.8) and its spectrum.

The first step of the calibration procedure, for connectorized Devices Under Test (DUT) consists in a relative error correction to compute the error coefficients described in Eq. 4. This relative calibration is performed by using SOLT standards [11]. To extract the error coefficients for all the spectral lines to be calibrated, a single measurement is made for each standard reducing calibration time.

$$\begin{bmatrix} a_1^i \\ b_1^i \\ a_2^i \\ b_2^i \end{bmatrix}_{DUT} = K^i \begin{bmatrix} 1 & \beta_1^i & 0 & 0 \\ \gamma_1^i & \delta_1^i & 0 & 0 \\ 0 & 0 & \alpha_2^i & \beta_2^i \\ 0 & 0 & \gamma_2^i & \delta_2^i \end{bmatrix} \begin{bmatrix} a_{1M}^i \\ b_{1M}^i \\ a_{2M}^i \\ b_{2M}^i \end{bmatrix} . \qquad (4)$$

where i=1, … N and denotes the frequency index.

For absolute calibration the same signal measured by a calibrated Digital Sampling Oscilloscope (DSO) is used as a reference. The measurement setup is then described in Fig. 3.
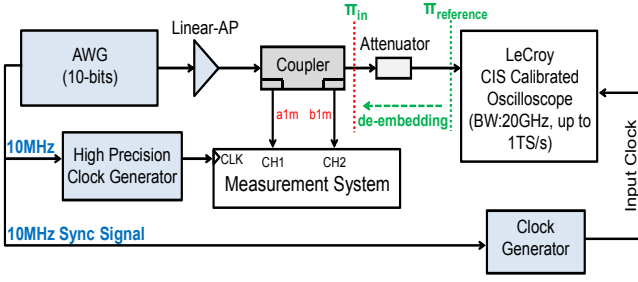
Fig. 3.   Measurement setup for Absolute Calibration.

The DSO that works on the Coherent Interleaved Sampling (CIS) [12] principle is configured to acquire the signal at an equivalent high sampling rate. The acquired waveform is processed to de-embed the effect of the attenuator using their respective S-parameters.

III.   CALIBRATION VERIFICATION AND VALIDATION

For the calibration of the 4-channel test-bench presented in Fig. 1, a pulsed signal with PRI of 10μs and a duty cycle of 10% at a carrier frequency of 1GHz is used as a test signal. To validate the multi-sine calibration procedure, two different calibrations are performed as followed:
a) Calibration only for carrier and harmonic frequencies.
b) Calibration using a large bandwidth multi-sine signal with high resolution.

Fig. 4 depicts the magnitude of the absolute error coefficient (K^i) of Eq. 4 for the two calibration procedures.
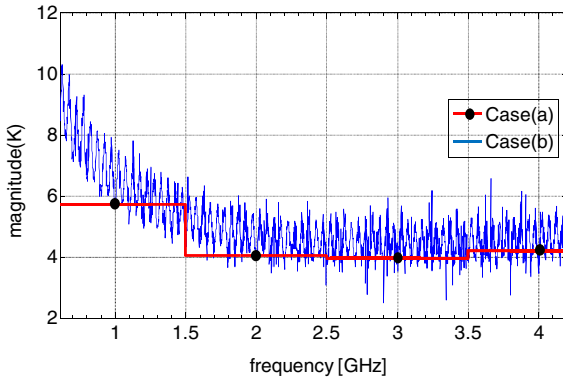

Fig. 4.   Absolute error coefficient for the two different calibration procedures.

In the first case, the complete spectrum is divided into windows of a same specific bandwidth (1GHz) around the carrier and its subsequent harmonic frequencies. Each spectral line within these bands is corrected for its corresponding error factor (f_c, $2f_c$….). To verify the calibration procedure a measurement is made in a through connection to observe its influence on the time-domain measured waveforms as shown in Fig. 5.
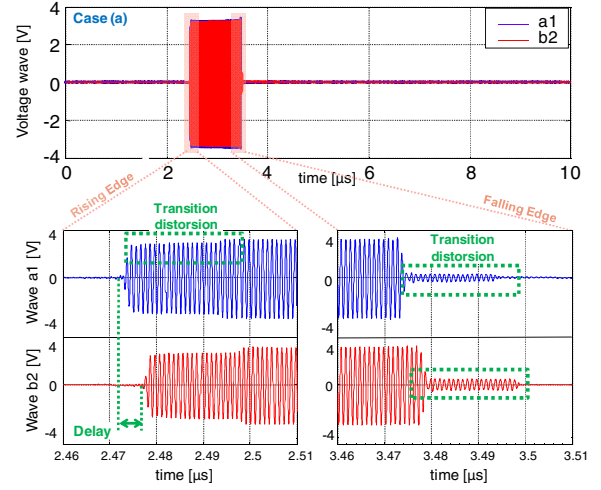

Fig. 5.   Incident $a_1(t)$ and transmitted $b_2(t)$ voltage waves at both reference planes for carrier and harmonic frequencies calibration.

In Fig. 5 it is noted that a group delay between the incident $a_1(t)$ and transmitted $b_2(t)$ voltage signals occurred due to phase distortion (constant group delay assumption) for each spectral line. Similarly amplitude distortion is noticed at the rising and falling edge of the pulse.

In the second case, multi-sine signal is used for calibration and the test-bench is calibrated for a very high resolution of 100 kHz. In this measurement, the calibration bandwidth (0.6GHz - 4.2GHz) is limited by the linear amplifier. Fig.6 describes the measurement results for the incident $a_1(t)$ and transmitted $b_2(t)$ voltage signals in through mode.
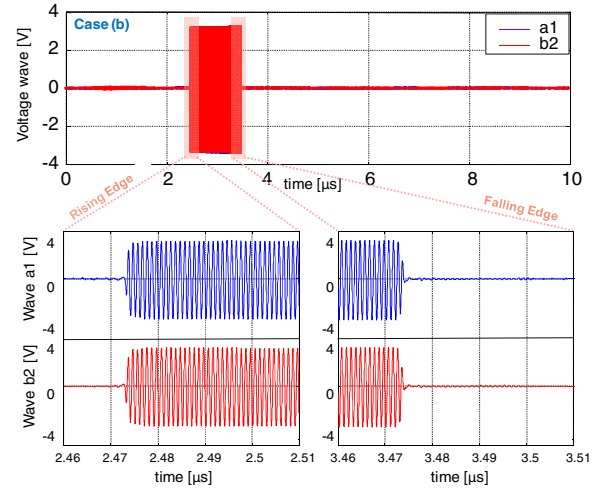

Fig. 6.   Incident $a_1(t)$ and transmitted $b_2(t)$ voltage waves at both reference planes for multi-sine calibration.

It's observed that a very good coherence between the two signals is obtained. The amplitude of the RF pulse signal for the two waveforms is exactly the same validating the calibration procedure with the wideband multi-sine signal.

IV. CALIBRATED TIME-DOMAIN MEASUREMENT RESULTS

In this section, a complete pulse characterization of a 40 W GaN HPA is performed. The HPA is excited at a carrier frequency of 1 GHz with 10μs pulse period and a duty cycle of 10%. Complete calibrated time-domain characteristics for voltage and current waveforms of the HPA at saturation point are measured at a high equivalent sampling rate of 60 GS/s. The input voltage and current waveforms are displayed in Fig. 7.
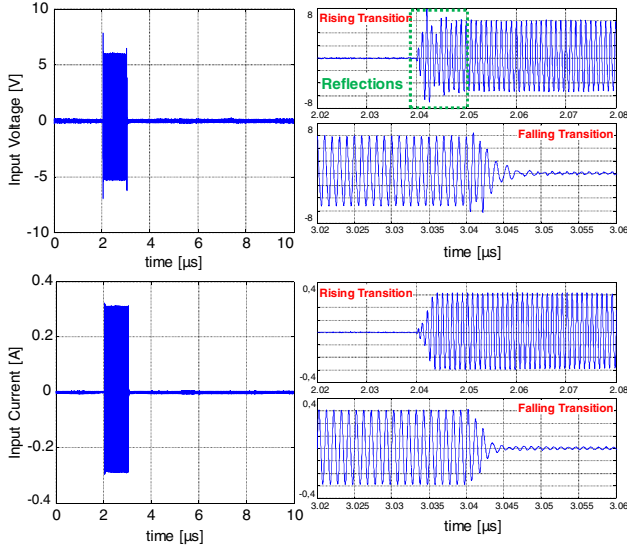

Fig. 7.   Calibrated measured input transient voltage and current responses.

Observing the pulsed transient characteristics, it's noticed that the frequency dependent reflections at the rising edge of the input pulse waveform are due to high reflection presented by the input matching network (measured $\Gamma_{in}(f_c)=0.8e^{j140°}$). Fig. 8 describes the output voltage and current waveforms.
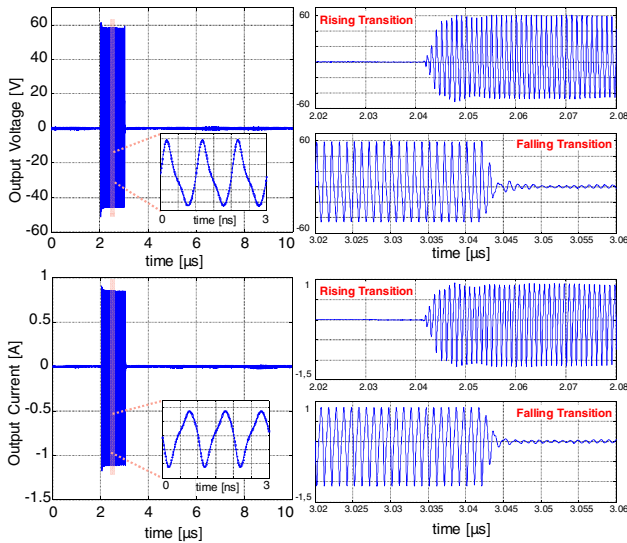

Fig. 8.   Calibrated measured output transient voltage and current responses.

The measured output RF pulsed waveforms depict the presence of multiple harmonics inside the pulse. The

calibrated test-bench also allows the visualization of all rising and falling transitions of voltage and current waveforms. These measurements are strongly useful to model memory effects characteristics.

V. CONCLUSION

This paper presents a wideband high resolution calibration procedure for RF time-domain characterization of high power devices under pulsed and wideband modulated signals. This procedure applied to a 4 channel time-domain THA based measurement system allows a spectral resolution as high as 10 kHz over a 3 GHz bandwidth. The validation of the multi-sine calibration procedure is done by comparing the calibration results with the case where a constant group delay is assumed. The transient and transition responses for pulsed waveforms for a HPA are presented. This calibration procedure is adaptable to different modulation schemes. Application of this setup and calibration procedure can now be used to investigate pulse to pulse stability of PAs for radar application. It can also be useful for wideband (higher than 1GHz bandwidth) NPR measurements.

REFERENCES

[1] J. Verspecht, "Large-signal network analysis," *IEEE Microwave Magazine,* vol. 6, no. 4, pp. 82-92, 2005.

[2] W. Van Moer and L. Gommé, "NVNA versus LSNA : Enemies or Friends?," *IEEE Microwave Magazine,* vol. 11, no. 1, pp. 97-103, 2010.

[3] R. Ouhachi, D. Ducatteau, C. Gaquiere, T. Lacave, P. Chevalier, and D. Gloria, "Calibration of the Non Linear Vector Network Analyser (PNA-X) for probe measurements," *European Microwave Integrated Circuits Conference*, pp. 81-84, Manchester, October 2011.

[4] P. J. Tasker, "Practical waveform engineering," *IEEE Microwave Magazine,* vol. 10, pp. 65-76, December 2009.

[5] Y. S. Ko, P. Roblin, S. Myoung, J. Strahler, F. De Groote, and J. P. Tessier, "Multi-harmonic broadband measurements using an large signal network analyser," *75th ARFTG Microwave Measurement Conference*, pp. 1-6, Anaheim CA, June 2010.

[6] T. Reveyrand, and Z. Popovic "A new method to measure pulsed RF time domain waveforms with a sub-sampling system," *IEEE MTT-S INT. Microwave Symp. Dig.,* pp. 1-3, June 2012.

[7] P. Roblin, Y. S. Ko, C. K. Yang, I. Suh, and S. J. Doo "NVNA Techniques for pulsed RF Measurements," *IEEE Microwave Magazine,* vol. 12, pp. 65-76, April 2011.

[8] S. Ahmed, G. Neveux, T. Reveyrand, D. Barataud, and J. M. Nebus "Time-domain interleaved high sampling rate system for large signal characterization of non-linear devices," *79th ARFTG Microwave Measurement Conference*, Montreal QC, June 2012.

[9] M. Schroeder, "Synthesis of low-peak factor signals and binary sequences with low autocorrelation," *IEEE Trans. Information Theory,* vol. 16, pp. 85-89, January 1970.

[10] Tektronix corp., "Arbitrary Waveform Generator (AWG7122C)," [Online]. Available: http://www.tek.com/sites/tek.com/files/media/media/resources/76W_22259_16.pdf.

[11] J. Verspecht, "Calibration of a measurement system for high frequency non-linear devices," *Doctoral Dissertation,* Vrije universiteit Brussel, November 1995.

[12] Lecroy corp. "Coherent Interleaving Sampling," patent: WO/2006/086257, August 2006.