A Calibrated Time Domain Envelope Measurement System for the Behavioral Modeling of Power Amplifiers

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This paper presents a set-up which enables the generation and the calibrated time domain measurements of complex envelopes of modulated signals at both ports of non linear microwave power amplifiers. The architecture of the characterization tool is given. Examples of error corrected time domain envelopes at the input / output RF ports of a 36 dBm output power – 30dB power gain L-band SSPA are shown.

Futhermore, the use of this characterization tool and a suitable processing of measurement data are applied to a novel measurement based behavioral modeling approach of non linear devices accounting for memory effects.

INTRODUCTION

Great efforts and enhancements of the non linear characterization of microwave power devices under CW stimuli (fundamental and harmonics) have been made during the past two decades. Looking at the transistor level (circuit level) they provide valuable and very useful information for the validation of transistor nonlinear models for CAD. They provide also experimental confirmations of the optimum operating conditions of active cells in terms of power, gain and efficiency [1] [2] [3]. Additive characterization and test signal configurations (like two tone – multitone) using vector network analyzers, or spectrum analyzers provide additive information concerning linearity / efficiency trade-offs. Looking at the subsystem or system levels (50 Ω or closed to 50 Ω matched modules) calibrated measurement systems are required for the accurate characterization of modulated signal distorsions due to non linear devices [4].

As a matter of fact, CW tests only provide information on non linear static aspects (through the well known AM/AM and AM/PM conversion characteristics). CW measurements performed on a frequency grid within the device operating bandwidth provide additive information on AM/AM and AM/PM dispersions. If the characterization and the modeling of such non linear dispersive effects are commonly assumed to be sufficient for TWTAs [5], they are not for SSPAs.

Hence, when SSPAs are used for the amplification of non envelope constant modulated signals, they exibit low frequency (rather long time constants) non linear dispersion associated to slow variations of the envelope compared to RF carrier variations. Thermal as well as dynamic envelope spurious in transistors biasing circuits are obviously responsible of this [6]. The purpose of this paper is to present an accurate characterization of non quasi static envelope distorsions caused by power amplifiers as well as a novel behavioral modeling approach.

MEASUREMENT SET-UP DESCRIPTION

A block diagram of the measurement set-up that we have developed is given in figure 1 (L-S bands).

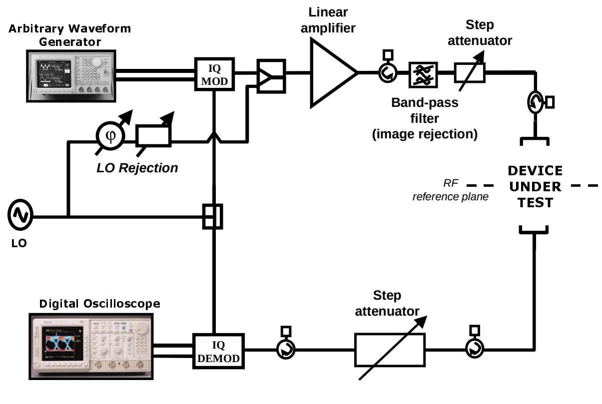


Fig. 1. **The measurement setup block diagram**

Baseband modulation schemes are achieved by using a computer controlled arbitrary waveform generator (12 bits – 250 Ms/s). The corresponding baseband envelope is then up-converted to the microwave domain using an I/Q modulator and linearly amplified using an amplifier to drive the input of the amplifier under test (AUT). A programmable step attenuator is used to enable average power sweeps.

The RF output signal of the AUT is then down converted to baseband using and I/Q demodulator and the corresponding complex envelope including distorsions is measured using a sampling scope. (1 Gs/s, 500 MHz bandwidth, 8 bits). A calibrated step attenuator connected at the RF port of the I/Q demodulator is used to keep it working in its linear operation regime. In the emitter part of the set-up a specific circuit arrangement is used to improve LO leakage rejection at the RF output of the I/Q modulator.

A bandpass filter is also used to improve image rejection. The receiver part of the set-up consists of a RF block (couplers and attenuators) and a frequency translating and measurement block (I/Q demodulator and sampling scope).

This receiver part must be calibrated in order to get error corrected time domain envelopes (analytic signals) associated to the real RF modulated signals at AUT reference planes.
The calibration procedure of the receiver part is divided in two steps. The first step consists in measurements of the [S] parameters of the linear RF bloc : the step attenuator.
The second step consists in the characterization of the frequency translating block witch is composed with the I/Q demodulator and the digital scope as sketched in figure 2. Loss conversions, group delay and phase imbalance of the I/Q demodulator are determined as the function of the frequency each side away from the LO frequency. Theses parameters are the calibration parameters.

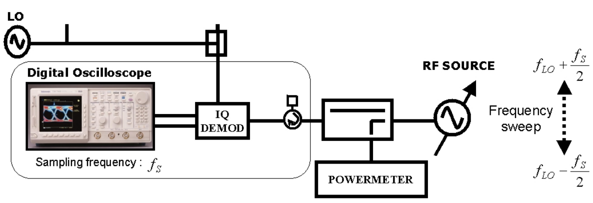


Fig. 2. **Dynamic AM/AM measurements for different kind of modulation**

To characterize a device under test, the non corrected complex envelope is recorded with the digital oscilloscope. The correction to get the complex envelope at the AUT reference plane consist on weighting calibration parameters on the recording waveform in the frequency domain.

A 36 dBm output power, 30 dB gain SSPA has been measured at 1.5 GHz for several baseband modulation schemes. A sinusoïdal baseband generation provide two tone (C/I) measurements. Multitone CW format as well as QPSK modulation were also performed.

Figure 3 sketches a intantaneous output power of the AUT when the input signal is a 2 tones with a 250 kHz beat frequency. Notice the hyteresis for high envelope instantaneous output power value : this memory effect event can be linked to trapping effects [7] or the bias circuits [8] in the AUT.

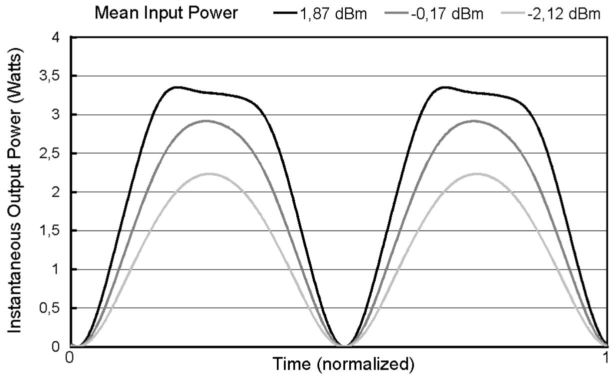


Fig. 3. **Instantaneous enveloppe at the output of the SSPA driven by a 2 tones modulation**

Figure 4 shows dynamic AM/AM and conversion characteristics. The three cases corresponds to a same +2 dBm average input power driving the AUT. For each cases the peak to average ratios, the modulation bandwidth and the statistic distribution of the envelope are different thus leading to different, non linear dynamic behavior of the AUT.

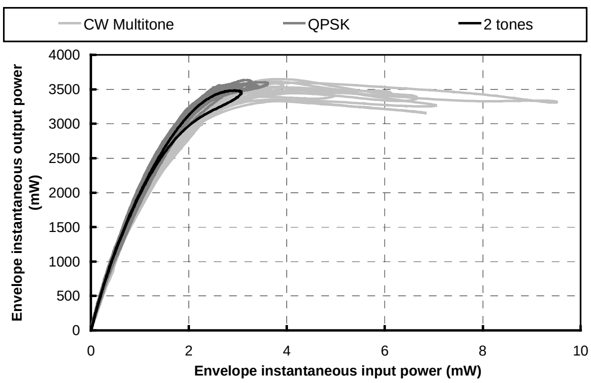


Fig. 4. **Dynamic AM/AM measurements for different kind of modulation**

A NOVEL APPROACH OF DYNAMIC BEHAVIORAL MODELING OF POWER DEVICES

Using the versatility offered by our measurement system concerning modulation schemes, vector corrected envelopes were recorded and processed for the identification of the dynamic non linear behavior of the AUT. The input complex envelope is named

$\tilde{x}(t) = A(t)e^{j\varphi(t)}$. The distorted output complex envelope is named $\tilde{y}(t)$.

Assuming an explicit first order behavioral function linking $\tilde{x}(t)$ and $\tilde{y}(t)$, one can write :

$$\tilde{y}(t) = f_{NL}\left(\tilde{x}(t), \frac{\partial \tilde{x}}{\partial t}\right) \qquad (1)$$

however,

$$\frac{\partial \tilde{x}(t)}{\partial t} = \tilde{x}(t)\left(\frac{\frac{\partial A(t)}{\partial t}}{A(t)} + j.\frac{\partial \varphi(t)}{\partial t}\right) \qquad (2)$$

thus, equation (1) can also be written as :

$$\tilde{y}(t) = f_{NL}\left(A(t), \varphi(t), \frac{\partial A(t)}{\partial t}, \frac{\partial \varphi(t)}{\partial t}\right) \qquad (3)$$

By applying this type of formulation to a complex gain expression, one define a new function independent of the input envelope phase such as:

$$\tilde{y}(t) = g_{NL}\left(A(t), \frac{\partial A(t)}{\partial t}, \frac{\partial \varphi(t)}{\partial t}\right)\tilde{x}(t) \qquad (4)$$

This “dynamic” complex gain constitutes a enhancement of the complex gain used in system simulation and obtained with CW measurements.

A(t) is the instantaneous magnitude of the input envelope. If we use only this parameter in the previous relationship, we have only a static non linear behavioral description of the AUT.

The first derivatives $\frac{\partial A(t)}{\partial t}, \frac{\partial \varphi(t)}{\partial t}$ provide first order dependence of $\tilde{y}(t)$ to the low frequency dynamic variations of $\tilde{x}(t)$ including both high frequency and low frequency non linear memories (group delay, thermal dependence, envelope spurious within the DC biasing circuits).

The functional g_{NL} was chosen to be represented by using a neural network [9].

The behavioral model topology is sketched in figure 5.

A multitone test envelope (64 carriers) was used for the training procedure of the neural network. This envelope was synthesized by performing an appropriate loading of the baseband signals into the AWG (similar than the one that can be used for NPR tests) [10]. Input and output envelopes of the corresponding pseudo-noise modulated signal at both RF ports of the AUT were recorded using the sampling scope.

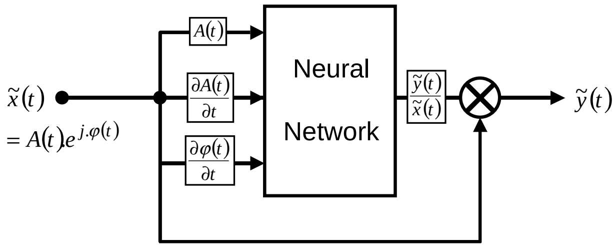


Fig. 5. **Behavioral model topology**

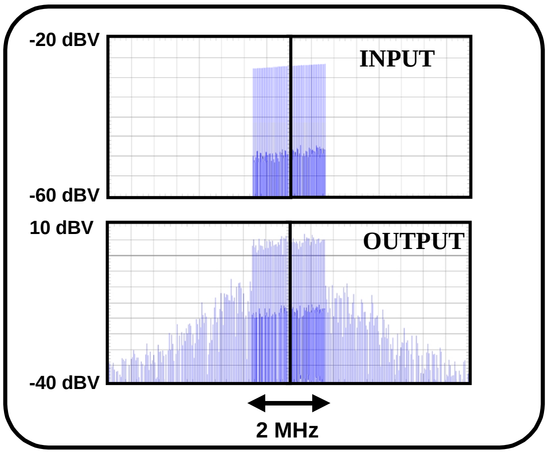
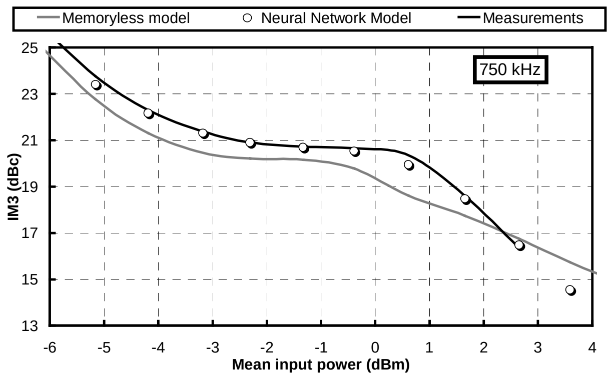
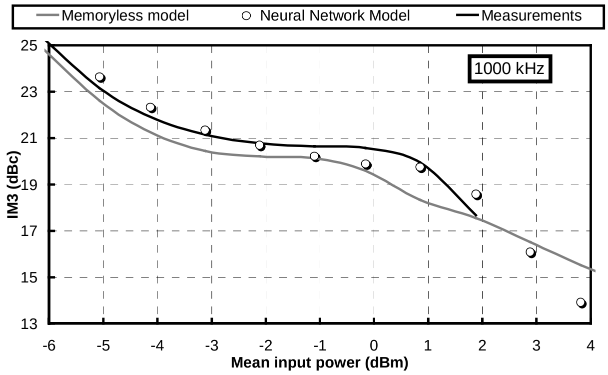


Fig. 6. **Spectral shape of the test signals used for the neural network training**

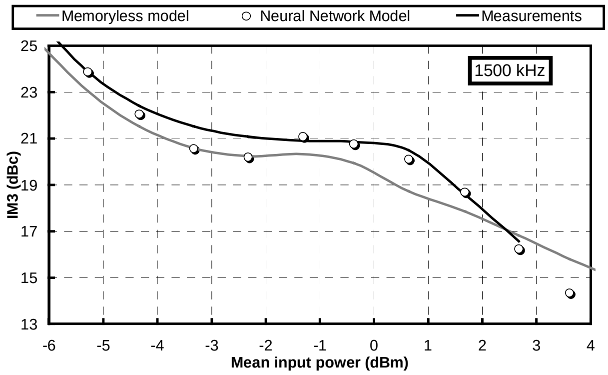
Once the behavioral model is built, it is used for the prediction of the envelope response of the AUT to other modulations. For example, we have performed predictions of third order intermodulation (two tone tests) at different carrier spacing. Two tone envelope measurements were performed and compared to simulation results obtained with our behavioral model. They have been also compared to the purely static response obtained with the well-known memoryless complex gain method derivated from center frequency AM/AM, AM/PM characteristics. Figures 7a, 7b and 7c show the set of curves superimposed on the same plot for different frequency distance between the two tones of the excitation RF signal.



(a)



(b)



(c)

Fig. 7a, 7b and 7c. **IM3 of New Model / Measurement /AM/AM AM/PM Model**

These curves demonstrate the significant enhancement of our dynamic behavioral modeling approach for the predictions of non linear envelope distorsions caused by microwave solid state power devices.

CONCLUSION

This paper has proposed a calibrated time domain envelope measurement system for the characterization of non linear equipment driven by microwave modulated signals. The application to the dynamic behavioral modeling of power amplifiers has been demonstrated. One of the main point to be mentioned is that we report in this paper on a measurement based behavioral modeling of a rather large size SSPA (2 stages - HFET cells). The architecture of the set-up (digital baseband modulation synthesis by using an AWG) offers the versatility required for in depth investigations. The extension of the approach (software and hardware aspects) to the Ka band is being implemented at CNES Toulouse (France Space Agency) [11].

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