A fully calibrated four channels time domain RF envelope measurement system for the envelope characterization of non-linear devices in a load-pull environment

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Abstract **— This paper presents a fully calibrated four channels time domain radio-frequency (RF) envelope characterization system. This measurement system enables the acquisition and the vector-correction of the 4 input and output envelope voltage/current waves, including both amplitude and phase, of RF non-linear microwave devices. The capabilities of the system, when it is associated with passive load pull techniques, are presented to investigate the effects of RF impedance termination on the envelope linearity of mismatched RF non-linear devices.**

The proposed measurement set-up is described. Calibration and measurement procedures are detailed. Examples of the 4 fully error corrected time domain envelopes at the input/output RF ports of an optimised gain power MESFET are reported and discussed.

I. INTRODUCTION

The trade-off between linearity, output power and efficiency is a key point for the design of mobile communications amplifiers. To know the nonlinear behaviours of devices excited by modulated signals in the presence of losses of adaptability is thus fundamental and necessary. In the last few years, a lot of measurement systems have been developed to investigate the non-linear behaviour of microwave amplifiers under modulated excitation.

These systems based on the use of Microwave Transition Analyser (MTA) [1], and/or Digital Storage Oscilloscopes DSO) [2], [3], or on the use of Large Signal Analyser (LSNA) [4] allow the envelope characterization of non-linear devices under CW or two-tone excitation. Specific calibration procedures have been developed with these systems to extract CW and two-tone time domain signals at both port of the device under test (DUT).

Associated with different load-pull setup at RF or/and IF frequencies, these systems are very useful, in the one hand, to increase the knowledge of the effects of the impedance terminations, at IF and RF frequencies, on the linearity of power transistors [5], [6], and on the other hand, they provide valuable, accurate and additive information for the power amplifier modelling [7], [8]. Moreover, the influence of mismatched impedances on high and low frequency memory effects in non-linear RF devices requires the major knowledge of the Four time domain envelope signals at both ports of these devices.

In this paper, more in depth description of the envelope measurement is presented. This system is proposed based on the use of a fully calibrated four channel digital scope to extract time domain RF envelope of complex modulated signals. A specific envelope calibration procedure is presented. And finally, envelope measurements results obtained for an L Band optimised gain-power MESFET are reported.

II. DESCRIPTION OF THE MEASUREMENT SYSTEM

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

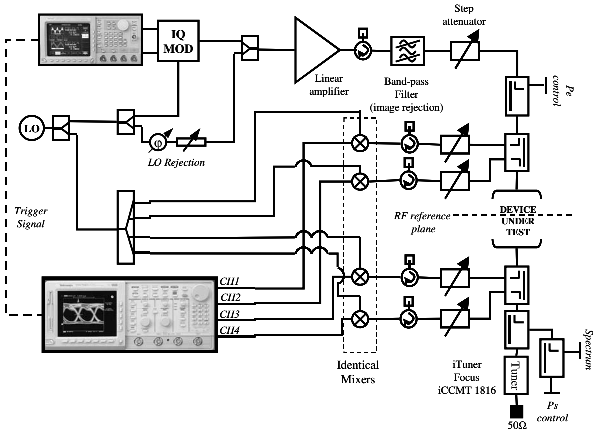

Figure 1: Schematic of the 4 channels time domain RF envelope measurement system.

The first part of the measurement system consists in the generation of the complex RF modulations. The IF modulation schemes are achieved by using a computer controlled arbitrary waveform generator (12 bits – 250Ms/s).

The corresponding IF envelope is then up-converted to the microwave domain using an I/Q modulator and linearly amplified using a linear amplifier to drive the input of the device under test. The offset levels of the I and Q AWG are then adjusted to decrease the local oscillator leakage in the I/Q modulator. This leakage is also improved with a specific circuit arrangement. The image rejection of the modulated signals is obtained with a band-pass filter. A programmable step attenuator is used to enable average power sweeps. The second part of the measurement system is the receiver block based on the use of four synchronized channels. Each receiver channel consists in a directional coupler, step attenuators, a frequency-translating block (mixer) and ADC (running at 2 GS/s). These four receivers' channels allow extracting simultaneously the four voltage/current waves at the input and output of the DUT. The same local oscillator drives the four mixers to ensure that the four channels are synchronized and phase coherent with the signal generation.

Calibrated step attenuators are used in the four receiver channels to ensure the mixers to work into their linear region. A computer achieves the signal processing tasks and controls a wideband fundamental tuner (Computer Controlled Microwave iTuner iCCMT) [9]. This receiver part including the four synchronised channels must be fully calibrated in order to get error-connected time domain envelopes (analytic signals) associated to the real RF modulated signals at the DUT reference planes.

III. DESCRIPTION OF THE CALIBRATION PROCEDURE

The main goal of the calibration procedure remains in determining the frequency response of the four channels of the RF receiver block at the different envelope frequencies of the generated signals described on the following Figure 2 [10].

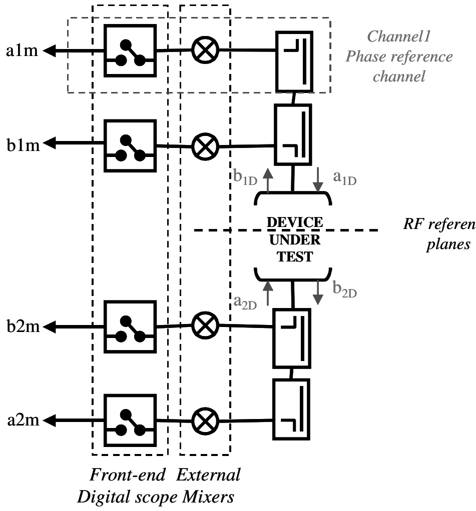

Figure 2: RF receivers' blocks

This calibration procedure is divided in two steps. A classical SOLT calibration is first performed in order to determine all relative calibration coefficients depicted in the flow graph of the figure 3.

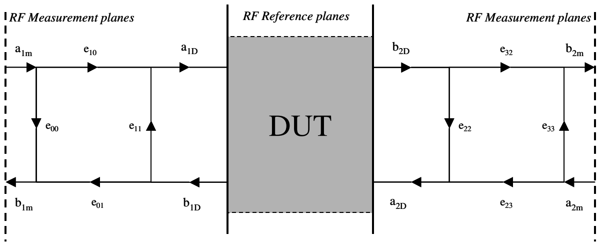

Figure 3: Flow graph representation

The relationships between the measured and the RF reference plane power waves can be written as followed. The determination of all these coefficients is based on the Least Mean Square (LMS) root resolution.

$$\begin{pmatrix} a_{1D(\Omega)} \\ b_{1D(\Omega)} \\ a_{2D(\Omega)} \\ b_{2D(\Omega)} \end{pmatrix} = \frac{1}{e_{01}} \begin{bmatrix} e_{10}.e_{01} - e_{00}.e_{11} & e_{11} & 0 & 0 \\ -e_{00} & 1 & 0 & 0 \\ 0 & 0 & \dfrac{\left(e_{32}.e_{23} - e_{22}.e_{33}\right).e_{10}.e_{01}}{e_{32}.e_{10}} & \left(\dfrac{e_{22}.e_{10}.e_{01}}{e_{32}.e_{10}}\right) \\ 0 & 0 & -\left(\dfrac{e_{33}.e_{10}.e_{01}}{e_{32}.e_{10}}\right) & \left(\dfrac{e_{10}.e_{01}}{e_{32}.e_{10}}\right) \end{bmatrix} . \begin{pmatrix} a_{1m(\Omega)} \\ b_{1m(\Omega)} \\ a_{2m(\Omega)} \\ b_{2m(\Omega)} \end{pmatrix}$$

Figure 4: errors coefficients matrix

Then a second step of the calibration procedure consists in an absolute magnitude and phase calibration to determine magnitude $|e_{01}|$ of the e_{01} coefficient at the different envelope frequencies of the excitation signals. The magnitude of this e_{01} coefficient is obtained by a classical power calibration using a power meter as power reference.

During the measurement step, the DUT is excited with periodic modulated signals. The 4 modulated signal synchronized acquisitions are realized simultaneously with the digital scope. The scope is triggered by a specific TTL pulse signal generated from the AWG. This specific signal is fully phase coherent with the envelope of the modulated signal and has exactly the same periodicity as the envelope of the modulated signal.

The envelope of the modulated signals and the local oscillator are not phase coherent signals. To limit time jitter errors on the envelope signal, a specific post processing averaging procedure is applied in the frequency domain with an error phase correction. This phase correction is based on the assumption that the group delay of the phase reference channel remains constant. The envelope of the modulated signal is then deduced by calculating the RELATIVE phase shift between each envelope frequencies. Only one absolute phase references is required and it corresponds to the phase of a significant magnitude frequency of the envelope spectrum. The relative phase shift is independent from the absolute phase of the carrier frequency (local oscillator). The deduced DUT envelope (RF DUT planes) has exactly the same delayed waveform as the measured envelope (RF measurement planes).

IV. CAPABILITIES OF THE FULLY CALIBRATED SYSTEM: APPLICATION TO THE MEASUREMENT OF A FET TRANSISTOR

The capabilities of the system are demonstrated by extracting the 4 fully error corrected time domain input and output envelope of a Fujitsu FLK012 power transistor. Operating in a class A (Vgs_0=1V, Ids0=1mA, Vds0=6V, Ids0=30mA) operation mode, the load impedance of the transistor has been optimised (using the passive iTuner iCCMT) to obtain a maximum power gain at the carrier frequency of 1.6 GHz ($\Gamma_{load}(f_0)=0.548e^{-j80}$) for the 1 dB compression.

Then this optimised transistor is driven by a two-tone excitation signal (Δf=10 MHz). The Figure 7 shows the 4 fully corrected voltages waves at the input/output of this highly mismatched transistor and then proves the great capabilities of the previously described measurement system. It permits the visualization of the different input and load impedances, time domain voltage/current envelope waveforms. The evolution of the magnitude and phase of intermodulation product (IMD) of the 4 voltage/current envelope signals presented at the input and output DUT can also be obtained as depicted in Figure 8. The HF memory effects of transistor, placed in an environment different from 50Ω, is observed on the dynamic AM/AM curve for different power levels (Figure 9). This information is of prime importance for the linearization and the design of power amplifier. It could be used to validate or extract new bilateral behavioural model of non-linear RF actives devices.

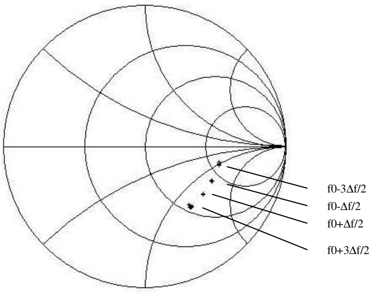

Figure 5 : Mismatch at output signal's frequencies (two tones and third order intermodulation).

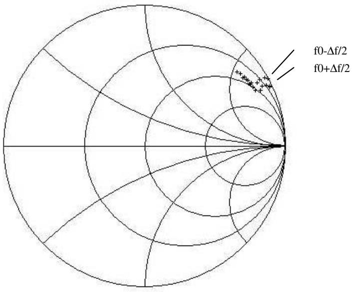

Figure 6: Mismatch at input signal's frequencies (two tones).

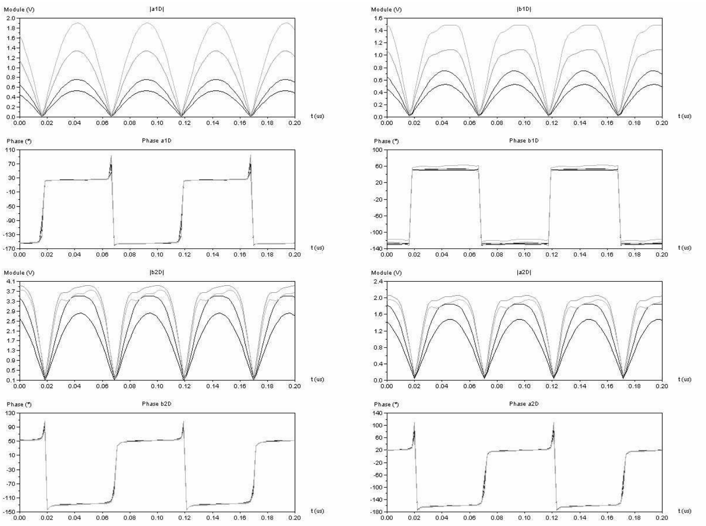

Figure 7: Time domain input/output of 4 corrected voltage wave of the FLK012 transistor

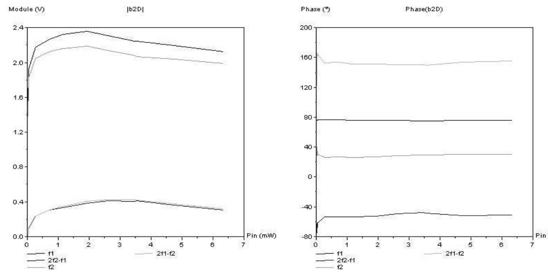

Figure 8: Example of the magnitude and phase evolution of IMD products versus input power

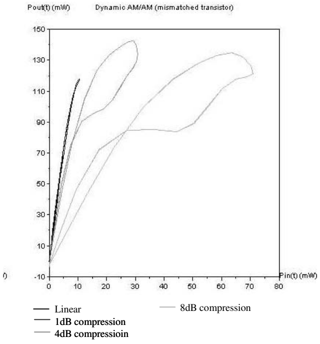

Figure 9: Dynamic AM/AM of the mismatched transistor

CONCLUSION

This paper has proposed a four fully-calibrated synchronous channels time domain RF envelope characterization system. This measurement system combined with load-pull techniques enables the extraction of the input/output envelope voltage waves of RF non-linear microwave devices driven by complex modulated signals and placed in an environment different from 50Ω.

The calibration procedure of this measurement system has been detailed and completely verified.

The capabilities of the system have been demonstrated by realising the complete envelope characterization of a power MESFET transistor pre-adapted in IMD product driven by a two tone modulation input signal.

These input/output envelope voltage waves characterization would be very useful for the main goal of bilateral behavioural model generation and verification [11].

REFERENCES

[1] C.J. Clark, G. Chrisikos, M.S. Muha , A.A. Moulthrop and C.P. Silva, "Time-Domain Envelope Measurement Technique with Application to Wideband Power Amplifier Modeling," *IEEE Trans. Microwave Theory and Tech.*, Vol. 46, No. 12, pp. 2531-2540, December 1998.

[2] David J; Williams, Jonathan Leckey, Paul J. Tasker, “Envelope Domain Analysis of Measured Time Domain Voltage and Current Waveforms Provide for Improved Understanding of factors Effecting Linearity”, *2003 IEEE MTT-S Int. Microwave Symp.*, pp. 1411-1414, June 2003.

[3] A. Mallet, F. Gizard, T. Reveyrand, L. Lapierre, J. Sombrin, “A new satellite repeater amplifier characterization system for large bandwidth NPR and modulated signals measurements”, *IEEE MTT-S Digest*, Seattle, Vol. 3, pp 2245-2248, June 2002.

[4] F. Verbeyst, E. Vandamme “Large-Signal Network Analysis. Overview of Measurement capabilities of Large-Signal Network Analyzer” *IEEE 58th ARFTG Conference Digest*, November 2001, pp.136-149

[5] David J; Williams, Jonathan Leckey, Paul J. Tasker, “A Study of the effect of envelope impedance on Intermodulation asymmetry using a two-tone Time Domain Measurement system”, *IEEE MTT-S Int. Microwave Symp. Dig.*, Vol. 3, 2002, pp. 1841-1844.

[6] J.F. Sevic et al., “A Novel Envelope Termination Load-pull method for ACPR Optimization of RF/Microwave Power amplifiers”, *IEEE MTT-S Int. Microwave Symp. Dig.*, Vol. 2, 1998, pp. 723-726.

[7] T. Reveyrand, C. Mazière, J.M. Nébus, R. Quéré, A. Mallet*, L. Lapierre, J. Sombrin, “A Calibrated Time Domain Envelope Measurement System for the Behavioral Modeling of Power Amplifiers”, *GAAS*, Milan, pp. 237-240, 2002.

[8] C. Maziere, T. Reveyrand, S. Mons, D. Barataud, J.M. Nebus, R. Quere, A. Mallet, L. Lapierre, and J. Sombrin, “A novel behavioral model of power amplifier based on a dynamic envelope gain approach for the system level simulation and design.” *Microwave Symposium Digest, 2003 IEEE MTT-S International*, vol. 2, pp. 769-772, 2003.

[9] Focus Microwaves “Measurement system Operation Manual” *Version 7.7 March 2003.*

[10] J. Qiu, D. Abe, T. M. Antonsen, B.G. Danly, and B. Levush, “Calibration of a Gigahertz-Bandwidth Vector Signal generation and Analysis system.” *Microwave Symposium Digest, 2003 IEEE MTT-S International*, pp. 1659-1662, 2003.

[11] A. Soury, E. Ngoya, J. Rousset, “Behavioural Modeling of RF and Microwave Circuit Blocs for Hierarchical Simulation of Modern Transceivers” *Microwave Symposium Digest, 2005 IEEE MTT-S International*, 2005.