Calibrated Measurements of Waveforms at Internal Nodes of MMICs with a LSNA and High Impedance Probes

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***Abstract* — Waveforms measurements at internal nodes of MMICs are essentials for the analysis of both operating conditions and reliability aspects. Currently, the Large Signal Network Analyser (LSNA) is the most suitable time domain measurement setup. We propose, in this paper to associate the LSNA with high impedance probes (HIPs) and to do a new calibration procedure, in order to perform measurements at internals ports of multi-cells power amplifiers. Our novel measurement setup enables an easy and fast way to get corrected time domain waveforms measurements. The HIP calibration and measurement procedures can be easily added to the original LSNA driver software. Indead, the HIPs are considered like a classical test-set through the software and do not modify the traditionnal use of LSNA.**

This work is applicated here to the caracterisation of a class F amplifier at S band.

I. INTRODUCTION

This paper deals with internal waveform probing of power amplifiers by using high impedance probes along with the LSNA instrument.

Our aim is to obtain calibrated voltage and current waveforms for an enhanced knowledge of the nonlinear operating behaviors of transistors of MMICs power amplifiers.

A. A time domain measurement system : the heart of the measurement setup

At microwave frequencies, three time domain measurement setups are usable : the sampling scope, the microwave transient analyser (MTA) and the large signal network analyser (LSNA). Nevertheless :

- the scope requires a long acquisition time and consequently produces significant time base distorsions due to inherent jitter ;
- the MTA enables only 2 channels.

The LSNA is a fully calibrated network analyser and represents the most suitable instrument right now, available through 'Maury microwave'[1].

On wafer waveform measurements by using classical reflectometers (bidirectionnal couplers) connected at the input and output ports of power devices under tests are now quite mature.

Nevertheless, measurements at the internals node of multistage-multicells MMICs reveal to be very usefull for in depth investigations or reability tests on large power amplifiers. Such measurements are made possible by the use of high impedance probes.

A key aspect for accurate measurements concerns the calibration and measurement procedures which is the main focus of this paper.

B. Basic considerations

Let us consider a quasi-TEM waveguide. The physical quantities which are measured by the LSNA are the voltage traveling waves (or voltage normalized pseudo-waves) such as :

$$\begin{cases} a = V_+ \\ b = V_- \end{cases} \quad \text{and} \quad \begin{cases} v = a + b \\ i = \dfrac{a - b}{Z_0} \end{cases}$$

where a and b are the pseudo-waves, v is the total voltage, i the current and Z_0 the caracteristic impedance of the waveguide [2]. According to the telegraphists equations, we can deduce the forward and reverse pseudo-wave from 2 simultaneous voltage measurements (v_1 and v_2) as follow :

$$\begin{cases} V_+ = \dfrac{v_1.e^{+\gamma.L} - v_2}{2.\mathrm{Sinh}(\gamma.L)} \\ V_- = \dfrac{v_1.e^{-\gamma.L} - v_2}{-2.\mathrm{Sinh}(\gamma.L)} \end{cases}$$

where γ is the propagation constant of the waveguide and L the distance between v_1 and v_2 probing locations.

Thus, from the 2 voltage measurements of a waveguide, we need the propagation constant to obtain the voltage travelling waves and both the propagation constant and the characteristic impedance to get current travelling waves.

C. Previous works

The first works about this topic have been realized by J.C.M. Hwang. He has used for that purpose a Microwave Transcient Analyser (MTA) [3] [4] [5]. The results have illutrated the great interest of this kind of measurement setup but the calibration procedure was not fully described. Indead, the high impedance probe have to be preliminary characterized. The MTA is not a fully calibrated mesurement instrument and introduces phase distortion which is neglected but not negligible [6].

In [7], U. Arz describes a classical and a new optimized method to get the S-parameters of a HIP with a VNA. Those S-parameters provide a practical mean for correcting raw measurements. In [8], P. Kabos illustrates and validates calibrated time-domain oscilloscope measurements using these previous HIP S-parameters. He comes to the following expression :

$$V(f) = V_{OSC}(f).[\delta_1(f) + \delta_2(f)] \quad \text{with } \delta_1(f) = \frac{1 - S_{22}(f).\Gamma(f)}{S_{21}}$$

$$\text{and } \delta_2(f) = S_{11}(f).\delta_1(f) + S_{21}(f).\Gamma(f).$$

V(f) is the corrected voltage at the tip of the HIP. Γ(f) is the reflexion coefficient of the scope and the S parameters are the HIP's ones. Thus, mesurements from a time domain setup associated with a HIP can be corrected as :

$$\tilde{V}_{\text{Tip of HIP}}(f) = \tilde{K}(f).\tilde{V}_{\text{Raw Measured}}(f)$$

At last, theses methods (with the MTA or the scope) are complex and require several measurements and connections / disconnections. The LSNA architecture enables more flexibility with the use of HIP. Then it becomes very easy to determine the value of $\tilde{K}(f)$ in the above equation.

II. Configuration of the measurement setup

Basically, the calibration procedure of the LSNA creates an error-matrix making the links between the voltages and the currents at the reference planes and the raw-data (sampled down-converted signals) [9]. The proposed measurement setup consists on substitute the test-set port 1 with 2 HIPs directly connected to the downconverter box. Using such a system arrangement means that we have to create the suitable error-matrix before measurements.

III. Calibration Procedures

The calibration procedure is performed in 3 steps.

The first step consists in calibrating the LSNA with a probe station in a classical way (LRRM process). This calibration gives us α_2^{CAL}, β_2^{CAL}, γ_2^{CAL} and δ_2^{CAL} in the final error-matrix as depicted in figure 1. After this calibration, we disconnect the input channels 1 and 2 of the downconverter box from the test-set and connect to connect HIPS as illustrated figure 1.
Measurements at port 2 remain calibrated. Then, the error corrected voltage at the Port 2 RF reference plane can be considered as a voltage standard to calibrate HIPs.

The second step consists in probing sequentially the thru line of the calibration kit with the HIPs at the port 2 reference plane. Then we can define $\tilde{K}(f)$ as the ratio of the following quantities : v2 (the error corrected measurements provided by port 2) and the down-converted raw data (r1 and r2) corresponding the HIP. $\tilde{K}(f)$ represents the response of the

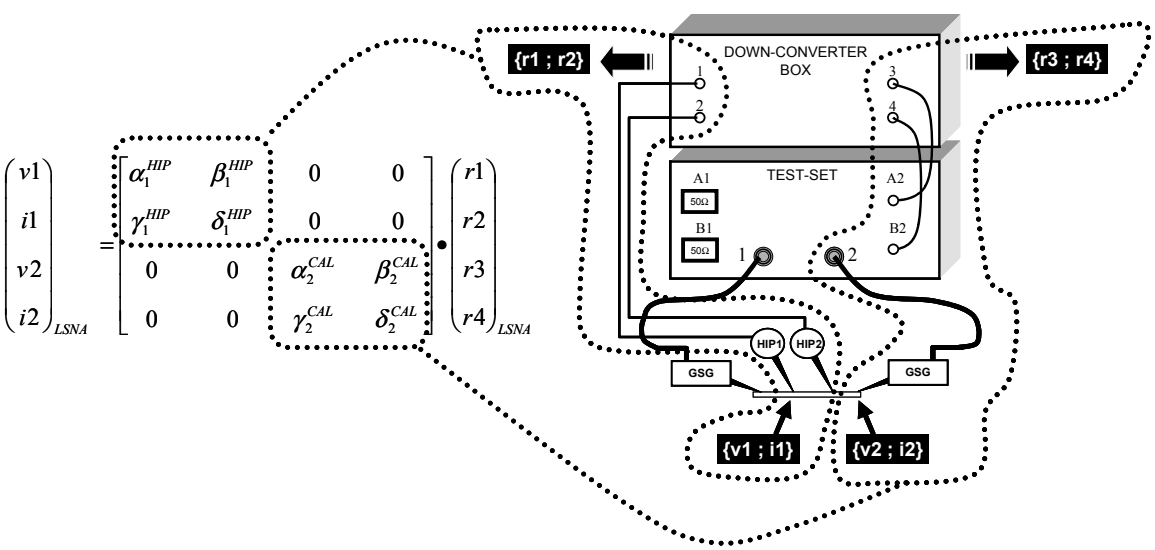

Fig 1 – LSNA associated with HIPs : the measurement setup and its correspounding error-matrix.
r1 to r4 represent downconverted sampled raw data.
v1, i1 are the real values at a RF reference plane (the tip of one HIP probe).
v2 and i2 are the real values at another RF reference plane (the tip of the GSG probed connected to Port 2).

measurement chain including the HIP, a bias "tee" (which has to be placed first to protect the down-converteur box from DC current, and secondly to enable the DC measurement with a classical voltmeter), and the downconvertion channels. With 2 HIPs, we define $\tilde{K}_1(f)$ and $\tilde{K}_2(f)$.

The third step is the generation of a new error-matrix. We have to define the terms α_1^{HIP}, β_1^{HIP}, γ_1^{HIP} and δ_1^{HIP} as indicated in figure1.

A. Method 1

The easiest process is to fix $\alpha_1^{HIP} = \tilde{K}_1(f)$, $\gamma_1^{HIP} = \tilde{K}_2(f)$ and $\beta_1^{HIP} = \gamma_1^{HIP} = 0$. Then, with this new calibration matrix, we can obtain the voltage at the tips of both HIP but not the currents : in the LSNA software, the i1 waveform is the voltage at the tip of the second HIP. This method has to be used when we require independents HIPs.

B. Method 2

Some applications require the measurement of the current. Then, a second possibility has been implemented in the software to fix the errors terms consequently. According to the telegraphist equations, the user have to know the distance between the 2 HIPs, the propagation constant of the probed line and its characteristic impedance. But the use of the $\tilde{K}(f)$ ratio cancel any coupling effect between the 2 HIP ($\beta_1^{HIP} = 0$). To take into account this coupling effet, we have to proceed to a new second step in the calibration procedure and define a sub-matrix instead of the $\tilde{K}(f)$ ratio.

C. Method 3 : Calibration of coupled HIPs

To perform measurements with 2 HIPs simultaneously, one HIP has to be placed on the reference plane during both the calibration and the measurements. To find out the 4 errors terms associated to the HIPs, we have to solve 2 equations with 4 unknown factors, so we need 2 different voltage/current standards. Its possible by removing the classical 50 ohms termination at the output of the test set (port 'RF IN 2') with an 'Open' or a 'Short'. The corresponding modified voltage and current standards are measured at the reference plane with the calibrated port 2. This procedure provides additive measurement necessary to determine the 4-terms error matrix relative to the HIPs.
During the measurements, the distance between HIPs, the propagation constant and the characteristic impedance must be equal to the ones used (but unknown) during calibration.
This restriction implies that we have to use the same substrat during calibration and measurements.

D. Method 3 : Measuring on a substrate different from the calibration one

To proceed a HIP calibration on a substrat and perform some measurements on another subtrat, we need to know all the characteristic parameters during the calibration and the measurements which are the propagation constants, the characteristic impedances and the distances between HIP of both substrats. Then, according to the telegraphist equations and assuming that 2 HIPs behave like a lumped-coupler with 4 wave-coupling factors as illustated figure 2, we can create a new sub-matrix error from the one obtained during the calibration procedure and the characteristic parameters values by extracting theses 4 coupling factors values.

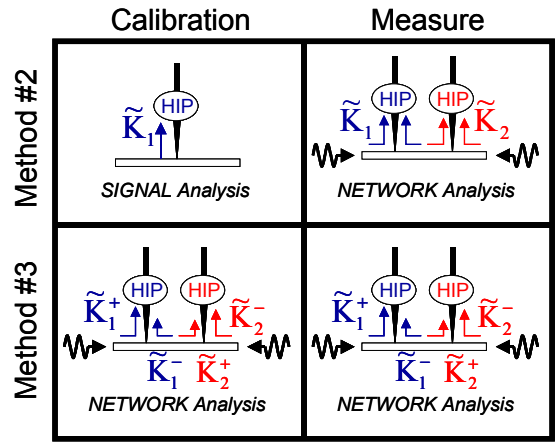

Fig 2 – Calibration and measurements with methods 2 and 3. Method 2 does not take into account the coupling effect between the 2 HIPs : the incident (+) and reflected (-) waves have the same transfert function.

IV. Calibration comparison (GSG and HIP)

The method number one has been used, first to measure the voltage along a line and secondly to test the design of a power amplifier.

Several voltage measurements have been made on a 50Ω line during a 'sweep-sin' excitation (different power levels and frequencies of the RF source). Figure 3 shows the voltage mapping at different locations and presents comparisons between measurements at the tip of the GSG probes (classical LSNA system) and measurements done with calibrated HIPs located close to these planes. Notice that all measured waveforms (whatever the frequency) are synchronized to the phase measured on port 2 (which is null). The comparison is quite good.

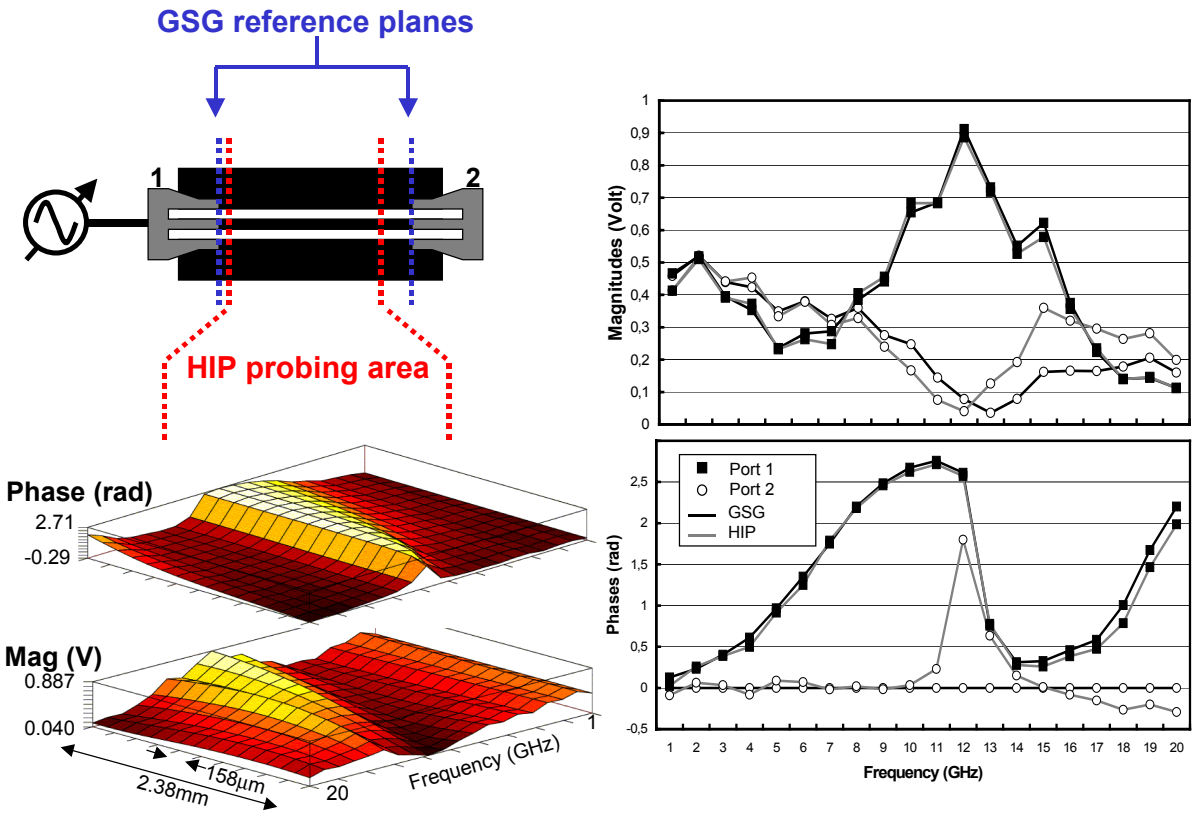

Fig 3 – Comparison between calibrated GSG and HIP voltage measurements

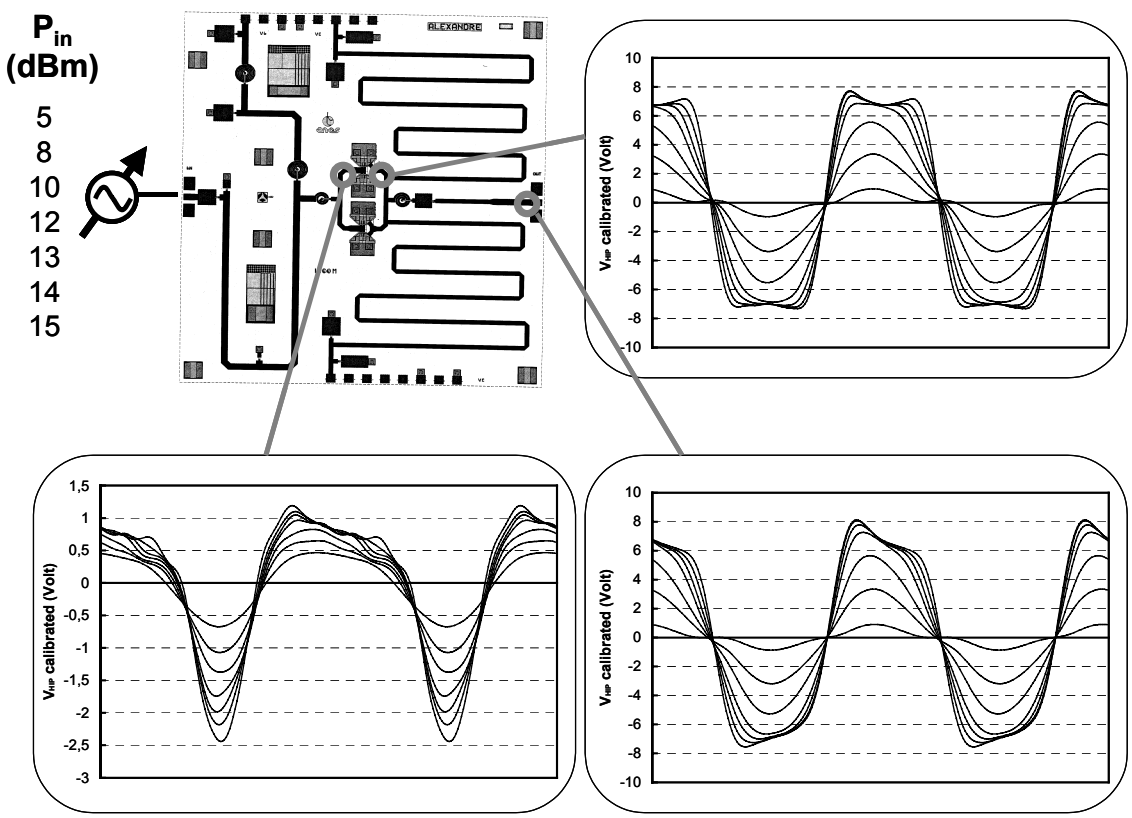

Fig 4 – Layout of the amplifier under test and internal calibrated waveforms measured with HIPs for differents input power.

V. Application to the Characterization of a Class-F Power Amplifier

A class-F power amplifier has been measured. Basically, an optimized class-F amplifier have to present a square voltage waveform at the output of the transistors but not necessarily at the output of the amplifier because of the filtering effects of the matching and the power combining networks. Internal waveform probing is the lonely experimental way to check the pertinent and successful design and realization of such topology.

A. The device under test

The device under test is a MMIC S-band one-stage power amplifier. The circuit is built in HBT technology. Design goal was to produce an optimized class F for a fundamental frequency equal to 2.15 GHz [10]. The bias are V_{be0} = 1 volts and V_{ce0} = 9 volts. Because of the class F, the expected efficiencies of the transistor are about 70%.

We probed the voltage at differents location on the MMIC for several input power. Figure 4 illustrates the measurements results.

B. Measurement Results

The output of the MMIC has been measured with both a GSG probe (LSNA's port 2) and a calibrated HIP. The time domain waveforms are strictely the sames. The measurements at the input of the transistors lead to typical waveforms. At high input power, we can see a quasi-square voltage waveform at the output of each transistor which validate the design topology and method for this class-F amplifier demonstrator.

C. Pictures of the setup

Figure 5 and 6 show two pictures of the last experiment. We have used one dual positioner (FPD 100 : Fine-Pitch Dual Positioner) to handle 2 high impedance probes (Cascade FPS-20X : Fine Pitch Signal) [11]. The probes are not connected to the ground, neither during calibration nor measurements [8].

VI. Conclusion

High impedance probe calibrations and measurements procedures have been described and implemented in the LSNA software (a single 'Mathematica' module). This module has to be linked to the original 'Mathematica' kernel of the LSNA driver. This tool provides a friendly and easy way to investigate waveforms at internal nodes of MMICs.

An application has been presented concerning the validation of an high efficiency amplifier design. This measurement system is expected to be essential for the stability analysis of MMIC because it offers an unique experimental verification of even and odd ocillation modes [12].

As a conclusion, the common use of the LSNA with HIPs strongly reinforces the links needed between the measurement and the simulation environments. It enables a better understanding of nonlinear effects and contributes to improved optimized designs of reliable MMICs.

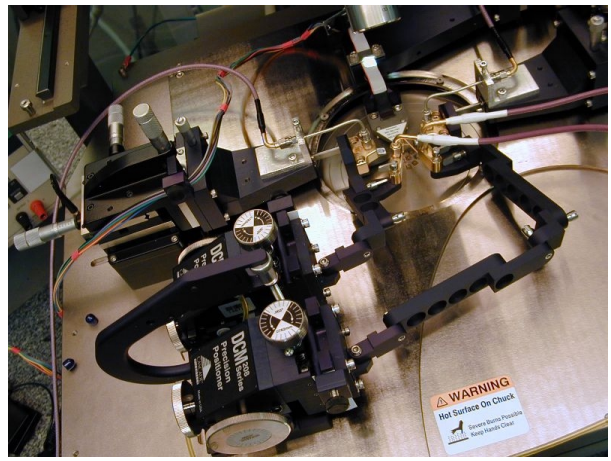

Fig 5 – Measurement setup : the dual positioner and the 2 high impedance probes.

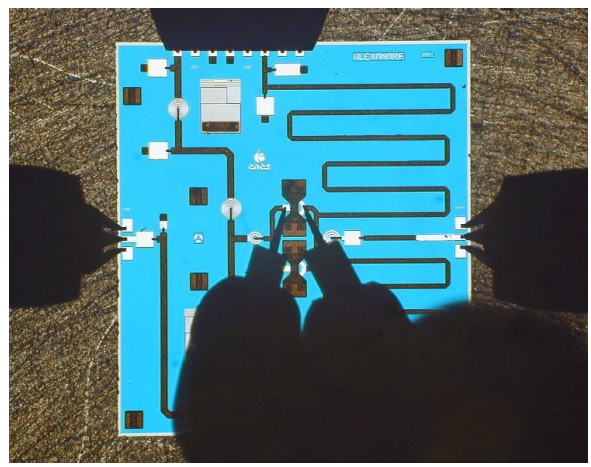

Fig 6 – Measurement setup : microscope view of the probing on the class-F MMIC.

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