A New Characterization Technique of "Four Hot S parameters" for the Study of Nonlinear Parametric Behaviors of Microwave Devices.

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Abstract **— This paper presents a new characterization system which enables calibrated "Hot S parameter" measurements of power transistors in a load pull environment. The device under test (DUT) is driven by a large signal at a frequency f_0 while a small signal at a frequency f is injected as a perturbation signal. A frequency sweep of the perturbation tone is performed (basically from 300MHz up to f_0 (ie lower sideband)). Upper sideband, from f0 up to $2f_0$, can be extended in a same manner.**

The four "Hot S parameters" measured at f are dependent on the nonlinear regime of the DUT forced by the large signal at f_0. The aim of this experimental purpose is to investigate nonlinear parametric behaviors like nonlinear stability. A description of the proposed measurement set-up is done. Calibration and measurement procedures are described and significant S band measurement results of HBTs are reported and discussed.

I. INTRODUCTION

When designing optimized and reliable solid state power amplifiers, one has to face to several main challenges. A suitable choice must be done between maximizing the RF output power and the power added efficiency as well as the design architecture which must be right to meet the performances in terms of power gain and frequency bandwidth. In order to be compliant with linearity aspects, proper solutions concerning biasing conditions and circuit topology have to be implemented. Moreover a specific attention on thermal aspects is also important.

Dealing with these quite complex aspects, general stability issue must be checked in order to avoid in band and out of band linear and parametric oscillations.

Focusing on these features early in the design process, that means on elementary multi-finger active cells, is of prime importance. For a successful design of power amplifiers, both electro-thermal modeling and large signal characterization are achieved. Nonlinear models of transistors are generally derived from multibias S parameters and I/V measurements which are then implemented in libraries of CAD packages.

The large signal characterization makes traditionally use of a load pull set-up in which CW test signal are used. Sometimes, additive load-pull contours are made with different test signals like two-tone signals or standard stimulus to characterize linearity aspects. A lot of works on both aspects (modeling and large signal characterization) have been carried out during the past decades. One comes generally to the conclusion that the large signal behavior and performances (power, gain, PAE) of transistors driven by CW signals are pretty well predicted by nonlinear models and confirmed by experiments.

To provide additive information for nonlinear model validations, the study of complex problems like nonlinear stability or major aspects governing the linearity of transistors is necessary. In this domain of interest, the derivatives of the non linearity are of prime importance. This paper focuses on an experimental characterization for this purpose.

Firstly, the set-up architecture and its calibration procedure are described. In a second part, "Hot S parameter" measurements of a transistor (HBTs 6 fingers) are reported. The four "Hot S parameters" are measured on a frequency bandwidth (400MHz-1400MHz) and for different power levels of a 2.5GHz carrier which drives the DUT from a linear regime to a nonlinear state. In a third and last part, results of four "Hot S parameter" measurements obtained from a transistor (HBT) upon an instable state are shown.

II. DESCRIPTION OF THE MEASUREMENT SYSTEM.

All the set up is automated and controlled through a GPIB bus. Before measurements, a calibration procedure is necessary at both f_0 and f frequencies.

The architecture of the set-up is shown. on Fig[1].

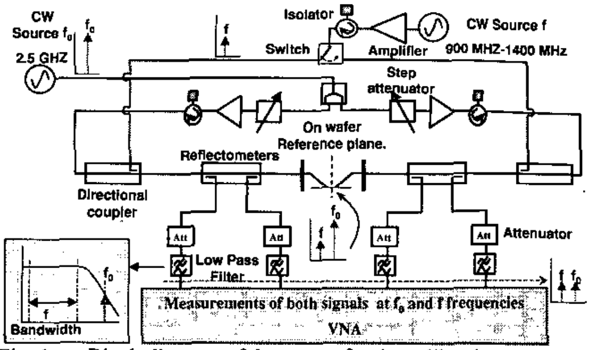

Fig. 1. Block diagram of the set-up for the calibration.

For that, the path which provides the pump that is to say the large signal at f_0 frequency is composed mainly of a RF power splitter and two amplifiers associated with step attenuators. It permits to route the signal with a controlled RF power level toward the measurement reference planes in a forward or a reverse mode. This enables a classic on-wafer SOLT calibration. In a same manner, a second path composed of an amplifier and a switch is used to route the signal at f frequency. As a result, a portion of the incoming and outgoing power waves at both f_0 and f frequencies are simultaneously fed through reflectometers to the VNA which operates in a receiver mode.

It is very important to notice here that the measurements at f_0 and f frequencies remain accurately calibrated while the signal level of the pump and the load impedance are varied. The calibration procedure described by D.Rytting [1] needed to be evolved to perform a full 16-term error correction. For this, in a first time, a classical standard reflection calibration (Short Open Load) is done. Then the additional procedure consists in connecting the thru standard on the on wafer reference plane while other Short Open Load standards are connected behind the reflectometers. This permits to take into account the mismatches presented by the generator and load impedances. The calibration procedure of our set up has been validated by a comparison between [S] parameter measurements obtained by the use of a conventional VNA and [S] parameters measured with our set up when the signal of the pump at f_0 is turned off whatever the generator and load impedance tuning.

Nevertheless, the limited dynamic range of the VNA test set forbids a wide RF power difference between the two signals (at f and f_0). In our study to overcome this difficulty, an appropriate low pass filter is used between the reflectometers and the VNA test set. The choice of these filters is driven by the need of our measurements. They mustn't attenuate the coupled small signal at f frequency to prevent noisy measurements of the "Hot S parameters". On the contrary, they have to reduce the RF power level of the coupled large signal at f_0 frequency to a quite acceptable power level for the VNA test set

An absolute power calibration at f_0 frequency is also made with a power meter. In such a way to get an error corrected value of this power at the reference planes for on-wafer probe contact, the power sensor is connected along the input of the reflectometers and reciprocity relationships are used to determine power levels at the DUT plane[2].

The way to perform "Hot S parameters" at frequency f while a load pull large signal characterization is performed at f_0 is now explained. By using the set up configuration sketched in Fig.2, the transistor under test can be driven from a linear to a nonlinear state by increasing the power level of the pump at f_0 frequency. Furthermore the load impedance can be tuned as a classic load pull characterization procedure.

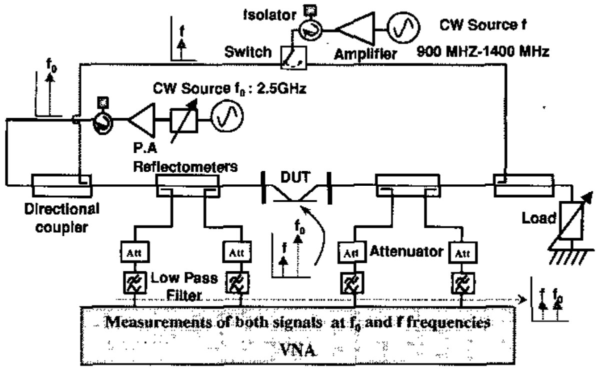

Fig.2.Block diagram of the set-up for measurements

In a same time, a small signal which keeps a constant low RF power level is switched in forward or reverse measurement mode toward the DUT to achieve "Hot S parameter" measurements at any f frequency within the 300MHz-1400MHz bandwidth.

II. ON WAFER "HOT S PARAMETERS" MEASUREMENT RESULTS

Firstly, as an example of the capabilities of our characterization system, we will show the influence of the transistor biasing point on "Hot S parameters" when a load impedance of 50□ is applied. Secondly, for a fixed bias condition, the impact of the load impedance and the power level of the pump on these "Hot S parameters" will be shown.

A. Measurements of HBTs "Hot S Parameters" versus collector voltage.

Here the aim is to show the RF power level impact of the pump (a large signal at f_0 frequency : 2.5GHz) on "Hot S parameters" measured at f frequencies (900MHz and 1400MHz) for different collector biasing voltages. The base-emitter voltage is fixed at 0V and the collector-emitter DC voltage is swept from 9V to 12V. Firstly, on Fig.3, as indication, traditional power measurements at f_0 are shown.

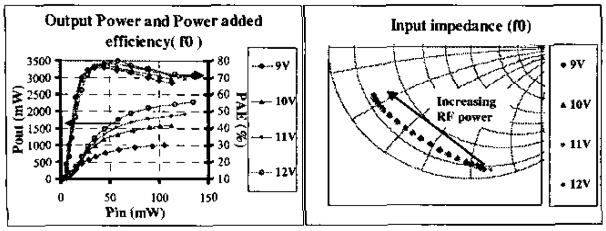

Fig.3. Power measurements at f_0=2.5GHz versus collector voltage.

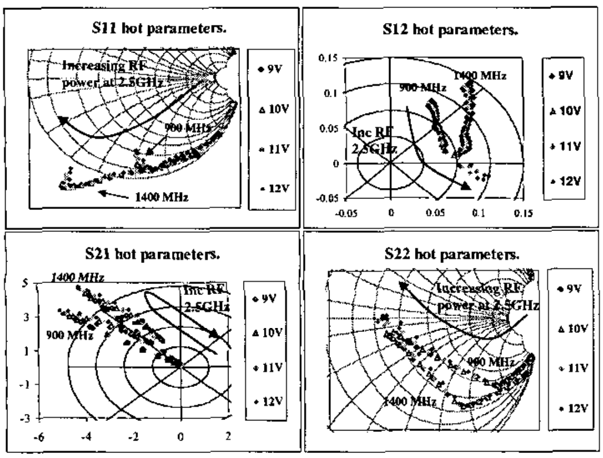

Fig.4. "Hot S parameter" measurements at f=900MHz and f=1400MHz versus collector voltage.

This results highlight the fact that here the collector biasing influence is more appreciable concerning the RF performances at f_0 frequency than concerning the evolution of the "Hot S parameters". Furthermore, we can see significant differences for the "Hot S parameters" curve deviations versus the RF power level of the pump.

B. Measurements of HBTs "Hot S Parameters" versus the load impedance.

The aim in this part is to show the influence of the load impedance at f_0 on "Hot S parameter" measurements. The transistor is loaded on five different impedances. The set up kept the same configuration, the base-emitter voltage is still fixed at 0V and the collector-emitter DC voltage is set to 9V The five arbitrary load impedances are sketched on Fig.5. Results for the large signal measurements at 2.5GHz are given on Fig.6.

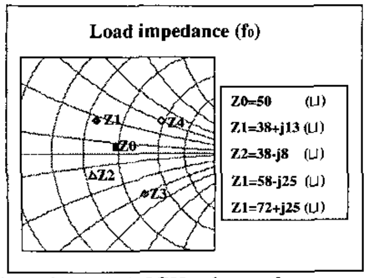

Fig.5. Load impedance at 2.5GHz chosen for measurements.

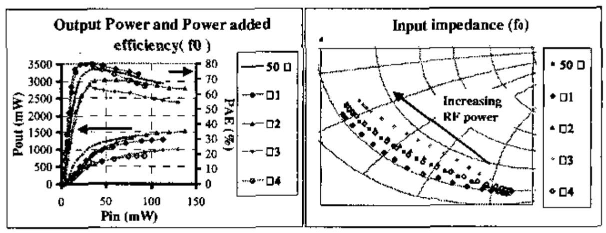

Fig.6. Power measurements at f_0=2.5GHz versus load impedance.

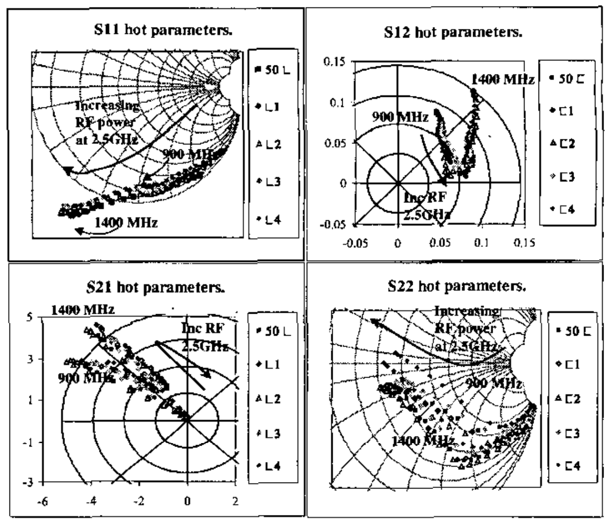

Fig.7. "Hot S parameter" measurements at f=900MHz and f=1400MHz versus load impedance.

Once again, both RF power level of the pump and frequency of the perturbation signal (f) mainly determinate the curve deviations of "four Hot S parameters". We can notice a significant difference in the curve deviation of S11 (it goes out of the Smith chart at f=1400MHz) while it stays within the Smith chart at f=900MHz.

Further and in depth investigations concerning nonlinear stability aspects can be considered. Along with the experimental study of non linear parametric behaviors of microwaves devices, the setup architecture has been improved specifically in order to increase the dynamic range. For that purpose, two VNA are coupled, one is dedicated for power measurements of the pump while the other one is only used to measure the "Hot S parameters" at f frequencies. The principle is sketched on Fig.9

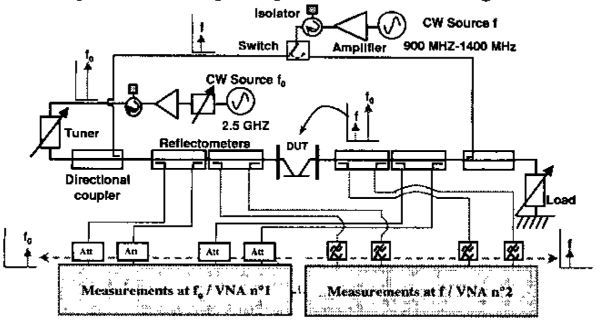

Fig.9. New "Hot S parameter" measurements set-up.

With this system, an unfavorable environment for the stability of a transistor (HBT) is obtained by tuning the load impedance at the pump frequency (f_0=2.5GHz). In this context, when the output power of the transistor at f_0 frequency varies between 6mW and 110mW,an oscillation occurs at 373.6MHz. After measuring the four "Hot S parameters" and measuring the both generator and load impedances around the oscillation frequency, the output reflection coefficient of the transistor (S22') multiplied by the reflection coefficient of the load ($\square_{LOAD}$) could be calculated. Fig.10 represents the product ($|S22'|*|\square_{LOAD}|$) and the spectrum before the unstable state of the transistor (low output power at f_0 frequency).

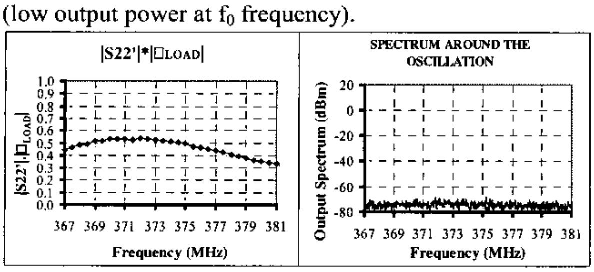

Fig.10. Measurements when the transistor is stable.

By increasing the power level of the pump, the transistor becomes instable. It is important to notice that for the frequency bandwidth where the parametric oscillation exists, the formalism of linear equations for S parameters couldn't be used any more, that means the measurements are not reliable. Nevertheless, extrapolation of measurements results (Fig.11) where there is no oscillation show that the value of the product $|S22'|*|\square_{LOAD}|$ tend to be higher than 1. This can explain this parametric oscillation.

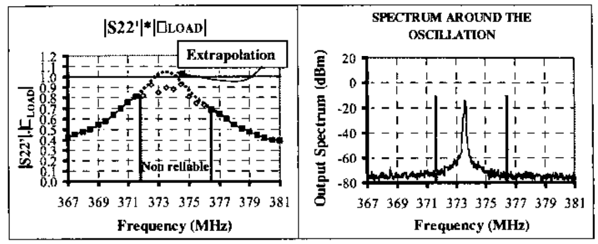

Fig.11. Measurements and extrapolation for an unstable state.

IV. CONCLUSION

A new characterization system which enables calibrated "Hot S parameter" measurements of power transistors in a load pull environment has been presented. We saw that the four "Hot S parameters" measured at f frequency are accurately measured under the nonlinear regime of the DUT forced by the large signal at f_0. A description of the proposed measurement set-up was done. Calibration and measurement procedures were described and significant S band results of HBTs were reported. This novel measurement approach and set up configuration are also expected to be useful for in depth and strong validation of nonlinear models of transistors specifically for the analysis of small signal nonlinear interactions.

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