Characterisation in 26 - 40 GHz band of HEMT's with an active load pull system

C. GAQUIERE, E. BOURCIER, B. BONTE, Y. CROSNIER

Institut d'Electronique et de Microélectronique du Nord
U.M.R. - C.N.R.S. 9929 - Avenue Poincaré - B.P. 69
59652 VILLENEUVE D'ASCQ CEDEX - FRANCE
Email : Christophe.Gaquière@iemn.univ-lille1.fr

ABSTRACT :

An active load pull system is presented for measuring devices from 50 µm to 1 mm gate width in Ka Band. It permits in a first configuration to measure the scattering parameters in small- and large-signal conditions. In the other configuration, it permits to extract all gains, power levels, impedances of interest, average currents and efficiencies for a given device, even for very large gate width. It can scan automatically the interesting area of the Smith chart. The system protects the tested devices because the impedance is presented at the output of the device only if the gate current is lower than a fixed value.

INTRODUCTION

The development of television, phone, automotive applications results in an increasing demand for millimeter wave range power devices and integrated circuits. DC measurements and S parameter measurements alone are not sufficient to qualify transistors regarding microwave output power. It is desirable to use on wafer testing to check the large signal performance of the device. For this purpose load pull measurement setups have been developed using vector error correction techniques to provide accurate load reflection coefficient and RF power data for the measured device. Two kinds of benches are classically used to study the device under power conditions.

Firstly the passive systems, where mechanical tuners are used. The main advantages are minor risk of oscillations, strictly linear behaviour and independent adjustment of magnitude and phase of the load. The main drawback is the limitation of the maximum load reflection coefficient which be simulated at the output of the device. Several societies market tuners covering the 0.8 to 100 GHz range.

Secondly, the active systems which are divided in two families based either on the TAKAYAMA principle (1) or on the active loop principle a bench based on this principle has been published by Demmler et al (2). The main advantage of these benches is the no limitation of the load magnitude presented at the device compared to passive systems. But, at the opposite, these systems are more expensive and more difficult to use (risk of oscillation, difficulty to keep constant the output load versus the injected power level by example). A comprehensive and fair comparison between active and passive systems was given by Muller et al (3).

In our labs a new active load-pull bench based on the Takayama principle has been developped. It differs from the other systems in many points:

- the WR28 waveguide structure allows high power density, limits the bandwidth to Ka band but benefits from the very high directivity of the reflectometer couplers;

- the system can determine small and large signal scattering parameters or active load-pull measurements for devices having 50 µm to several millimetres gate width without any modification;
- all the measurements are fully automated and the area of interest of the Smith chart is automatically scanned;
- the impedance is presented at the output of the device only if the gate current is less than 1 mA/mm

Indeed, it has been proven that gate current is one of the main limitation factors of the power capability, particularly for very small gate length devices Gaquiere et al.(4). So a limitation of the gate current density is always fixed in order not to degrade the DUT. Due to the bandwidth of the system (from 26 to 40 GHz), no harmonic termination can be controlled. In fact, it is very difficult to set up a system which can operate both with fundamental in Ka band and harmonics. To our knowledge, any result has been published with harmonic control in this frequency range. Moreover, this point is less important than at lower frequency, because the device under test may not be as efficient in generating harmonics.

We will explain the structure of our system, then the calibration procedures will be describe C. Gaquiere (5,6). After that the automation of the system will be explained, and some results will be presented.

DESCRIPTION OF THE SYSTEM :

Its simplified block diagram is shown in figure 1. The major part of the system makes use of wave guides. Two TWTA's are necessary to obtain enough power level to synthesise any load impedance at the output of the device whatever its total gate width and whatever the power level under investigation. The core of the measurement system includes a Wiltron 360B network analyser, a 3630 frequency down converter and an outside transfer switch. This transfer switch is the key component which allows to use the system either as a Sij parameter measurement set up or as an active load pull set up:

A synthesiser has been chosen due to its high frequency stability. It allows very accurate calibration, but especially it could be driven (in the case of low RF power) owing the external 10 MHz signal which phase locked the system (specific set on procedure of the VNA Wiltron 360). In these conditions this system allows us to measure small gate width devices (50 µm) and highly mismatched large gate width devices (> 1 mm) under linear and non-linear operation without changing anything in the system. This means that the system has a large dynamic range of 45 dB fixed by the linear operating range of the down converter mixers between -10 dBm and -55 dBm.
The phase shifter and attenuator can be driven manually or automatically. The attenuator has 60 dB dynamic, with a step of 0.1 dB. The whole phase shifting is 720°, with a step of 0.2°. Both components have good reproducibility and speed (less than 1 second for all the dynamic).

CALIBRATION OF THE SYSTEM :

This step is crucial because it determines the accuracy of the different measurements.

Impedance calibration

Upon inspection of the signal flow graphs for both standard S_{ij} parameters and active load pull configurations, it is observed that the causes of the systematic error coefficients are identical. So the Wiltron 360B TRL or SOLT internal calibration procedure is used to determine the error terms. In the VNA configuration, Sij parameters are available using the usual 360B computation software.
The calibration quality has been successfully checked by a comparison of Sij parameters of the same device realized firstly by a HP 85107 network analyzer and secondly with our system.

In load pull configuration, the RF signal is injected simultaneously at each port of the DUT and consequently the previous correction formulas are not applicable. According to the flow graph, specific expressions have to be used. They are based on the systematic error terms previously determined and on the reflection coefficient of the load. Acquisitions of the raw data and error coefficients are performed by an external computer which displays the corrected data of the device.

Power calibration

To reach a very good accuracy in the measurements, the power correction method is not scalar-corrected but vector-corrected. This calibration is realized in two step. The first step consists of the measurement of the injected power to the probe input plane with a power meter (to obtain an absolute power level), under the $a_{1m}/1$ procedure. A one port calibration is also done with the Wiltron 360B in this plane to determine the error terms e'00, e'11 and $e'_{10}e'_{01}$ as shown in figure 2. The reflected coefficient Γ_ε of the power probe is also measured. According to the flow graph of this configuration, it is possible to extract the magnitude of e'_{10} term using the following equations:

$$a'_1 = \frac{e'_{10} a_{1m}}{1 - e'_{11}\Gamma_\varepsilon}$$

$$P_\varepsilon = |a'_1|^2 \left(1 - |\Gamma_\varepsilon|^2\right)$$

which lead in the equation :

$$|e'_{10}|^2 = \frac{P_\varepsilon |1 - e'_{11}\Gamma_\varepsilon|^2}{|a_{1m}|^2 \left(1 - |\Gamma_\varepsilon|^2\right)}$$

where P_ε is the absorbed power.

The second step consists of translated the reference plane from the input probe plane to the input device plane. Which implies to take into account the systematic errors of the input probe. For all that, a TRL cascade calibration has been achieved which allows to determined the error terms of the input probe. This correction is realised using the error terms of the input probe and the source mismatch. Finally, the incident wave a_1 and the corresponding incident power P1 can be obtained using:

$$a_1 = \frac{e'_{10}\, e_{01} a_{1m}}{1 - e'_{11}\, e_{00} - e_{11}s'_{11} + e_{11}e'_{11}\, e_{00}s'_{11} - e_{10}e_{01}e'_{11}\, s'_{11}}$$

$$P1 = \frac{|e'_{10}|^2 |e_{01}|^2 P_{1mes}}{|1 - e'_{11}\, e_{00} - e_{11}s'_{11} + e_{11}e'_{11}\, e_{00}s'_{11} - e_{10}e_{01}e'_{11}\, s'_{11}|^2}$$

where S'_{11} is the reflection coefficient in the DUT input plane.At this stage of the procedure, it is then possible to determine all the injected and absorbed power level at the input and at the output of the DUT. Only one reference power measurement (a1m/1) is performed and all the powers (available and absorbed) relevant to the DUT are deduced from computation.

AUTOMATION OF THE SYSTEM :

To our knowledge, the procedure that has been established to fully characterize a device is the first one to provide so much convenience and safety. The requirement of a full automation of the system is made necessary for two main reasons. The first one concerns time saving and the second concerns the device failure (i.e. avoiding oscillations, high gate current areas and manipulation errors). The Labwindow CVI software (National Instrument trademark) has been chosen for driving the elements of the system (ammeter, DC power supply, attenuator, powermeter, phase shifter, TWTA and the vector network analyser).

The use of the bench is as follows :

Firstly, the bench is used as a classical vector network analyser to determine the scattering parameters of the DUT at the bias power conditions. This allows to determine the optimal load pull area (where the device presents an interesting gain) and also to avoid instability zones. Secondly, the operator chooses the load pull configuration (by changing the 50Ω load of the transfer switch by an RF jumper) and the interesting area, (define by the user) is described automatically, at different injected power levels. This area can be shifted if the optimal load impedance moves with the injected power level. Moreover the gate current is systematically checked and always limited at a density fixed by the operator. If the gate current is very low (at low input power level), the only limitation of the described area will be the equation of the minimum gain circle chosen by the operator . If the gate current is high the studied zone is automatically reduced (fig. 3) depending on the gate current magnitude fixed by the operator (in order to avoid damage of the device).

RESULTS :

In order to present some possilities of our system the evolutions of the optimal power load impedances versus the injected power level have been compared for two devices one on InP and the other on GaAs substrates (with the same total gate width and gate length (2x50x0,2 μm^2)) at 38 GHz. A more important phase shift of the optimal power load impedance for the InP device has been established than for the GaAs device at a same level of power gain compression (Fig. 4). At the present time, specific analysis are realised to find a correlation between these evolutions, the electrical equivalent small signal schemes and the process steps. Our system allows also to mesure the S'_{11} parameter, which is very important for the designer. From this point of view, a more important evolution of the S'_{11} parameter versus the injected power level is established (Fig. 9) in class AB compared to class A whatever the kind of substrate (InP or GaAs). This example presente the effect of the total gate width on the optimal power load impedances at 35 GHz. The evolutions of these impedances decrease when the total gate width increases. It could be established that the optimal power load impedance for the high total gate width is located near the edge of the smith chart so, it will be impossible to realise this impedance with a passive tuner.

CONCLUSION :

An original active load pull system, has been developed in the 26-40 GHz band. It permits to accurately extract all gains, all power levels and impedances of interest for a given device even for large total gate width. This system allows to make links between physical effects and power measurements. In these conditions we have the possibilities to perform reverse technological engineering in order to improve the design of our devices (recess topologies or development effects). Furthermore all these informations are very important to robustly verify the validity of non linear models and so, it is a very interesting tool for MMIC design.

REFERENCES :

(1) M. Demmler, B. Hughes and A. Cognata
"A 0.5-50 GHz on wafer, intermodulation, load-pull and power measurement system"
IEEE-MTT-S 1995 Int Microwave Symposium Dig. pp 1041-1044

(2) Y. Takayama
"A new load pull characterisation method for microwave power transistors"
IEEE-MTT-S 1976 Int Microwave Symposium Dig. pp 218-220

(3) J.-E. Müller, B. Gyselinckx, "Comparison of active versus passive on-wafer load-pull characterisation of microwave and MM-Wave Power Devices" IEEE MTT's Digest, 1994.

(4) C. Gaquière, B. Bonte, E. Bourcier Y. Crosnier
"Correlation between gate current and RF power performances of millimeter HEMT's"
26th European Microwave Conf., pp 33-36, Prague 1996.

(5) C. Gaquière
InP and GaAs power HEMT characterization with a Ka band active load pull system
IEEE Workshop Experimentally based FET device modelling & Related nonlinear circuit design, Kassel, Germany, July 1997.

(6) C. Gaquière, E. Bourcier, B. Bonte, Y. Crosnier
"A novel 26-40 GHz active load pull sytem"
25th European Microwave Conf., pp 334-338, Bologna 1995.

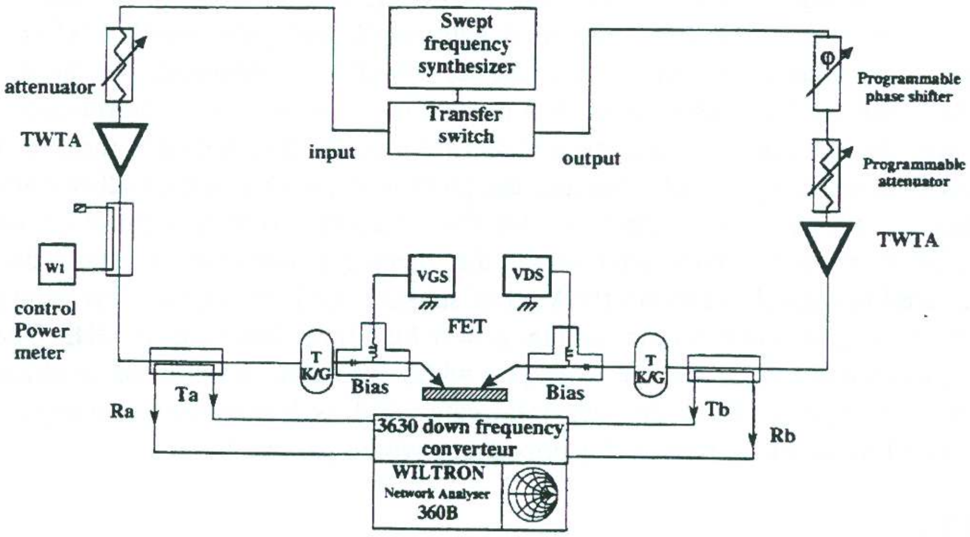

Figure 1 : Simplified block diagram of the active load pull system in the Ka band.

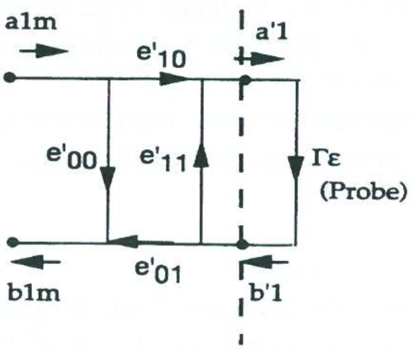

Figure 2 : Flow graph used for the first part of the power calibration in load pull configuration.

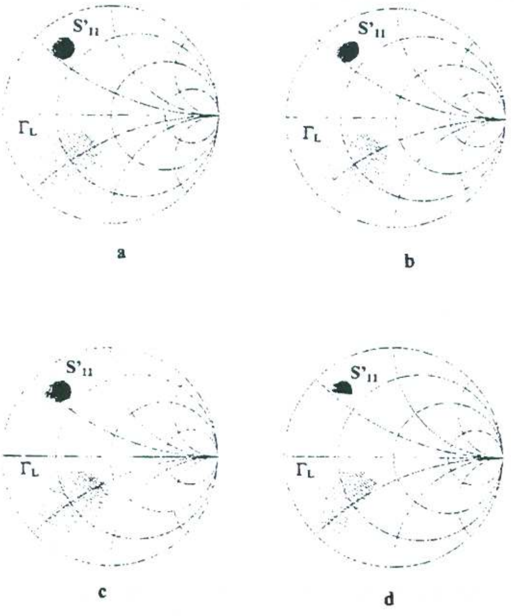

Figure 3 : Evolution of the scanned area in the Smith chart for 4 injected input power levels. (a): 5.5 dBm ; (b) : 7.5 dBm ; (c) : 11 dBm ; (d) : 11.6 dBm. S'_{11} and G_L are represented.

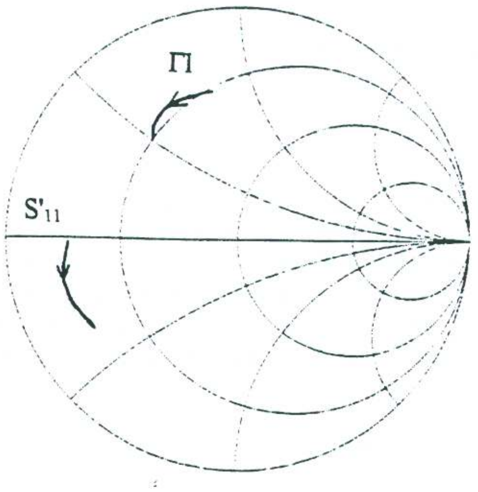

Figure 5 : Evolution of the Γl and S'_{11} parameter versus the injected power level for a HEMT device biased in class B at 38 GHz.

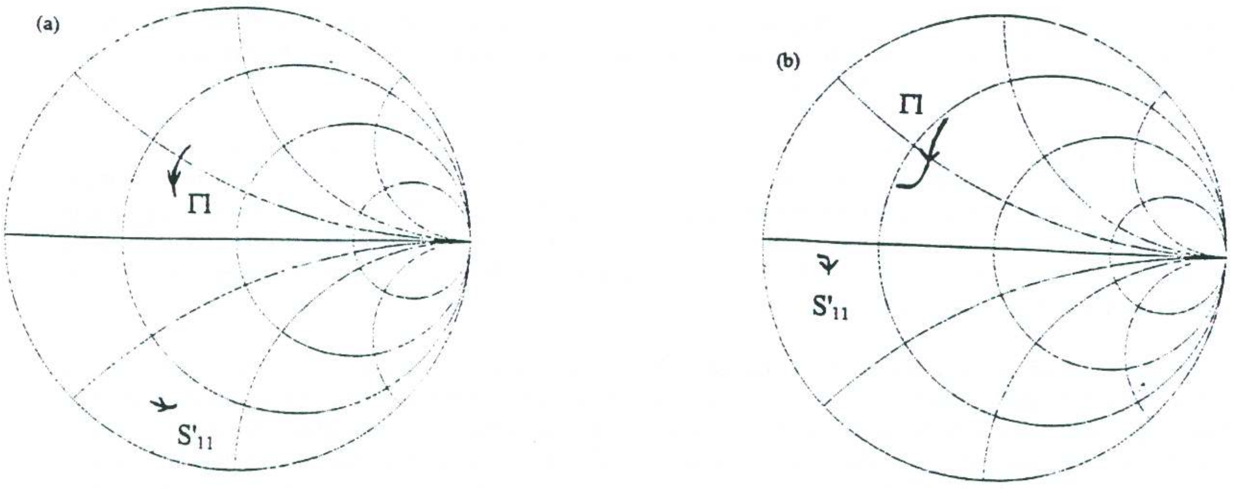

Figure 4 : Behaviour of the optimal power load impedance versus the injected power level for a GaAs substrate HEMT (a) and for a InP substrate HEMT (b) biased in class A at 38 GHz.