Jan Verspecht bvba

Mechelstraat 17
B-1745 Opwijk
Belgium

email: contact@janverspecht.com
web: http://www.janverspecht.com

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Fabien De Groote, Olivier Jardel, Jean-Pierre Teyssier, Tony Gasseling˜, Jan Verspecht*, Vince Mallette°, Christos Tsironis°

XLIM CNRS, University of Limoges, IUT GEII, 7 rue J. Vallès, 19100 Brive, France
Email: degroote@brive.unilim.fr ; olivier.jardel@brive.unilim.fr ; teyssier@brive.unilim.fr

˜AMCAD Engineering, ESTER Technopole BP 6915, 87069 Limoges, France
Email: gasseling@amcad-engineering.com

* Jan Verspecht BVBA, Mechelstraat 17, B-1745 Opwijk, Belgium
Email: contact@janverspecht.com

° Focus Microwaves, 1603 St. Regis, Dollard-des-Ormeaux, Quebec, Canada H9B 3H7
Email: info@focus-microwaves.com

Abstract — **This paper describes an on-wafer measurement setup based on several up-to-date features: the LSNA time domain measurement system; the new Multi-Purpose Tuner from Focus Microwaves with fundamental F0 and harmonic 2F0 and 3F0 tuning capabilities from 1.8 to 18GHz; and the so-called 'wave probe' coupling method. The combination of all these equipments allows extensive load-pull investigations with the direct view of the transistor output port load lines. The result of the 2F0 and 3F0 tuning on load lines is demonstrated on a power GaN FET up to 3.4Watts at 2.4GHz. It is also shown that different load impedances can provide the same efficiency, but with dramatically different load cycles resulting in a reduced transistor reliability.**

I. INTRODUCTION

The designers of best RF high power amplifiers are making an intensive use of the plot of the transistor load cycles. These slopes (plotted as time domain curves in the Vds/Id or Vce/Ic output plan) give them the paramount information about the matching of their load designs and the efficiency of the transistor nonlinear regime. The accuracy of these slopes depends on the quality of the nonlinear model of the transistors, and it is well-known that the model accuracy is sometimes not so good in nonlinear areas of operation. So there is a request for a measurement system with the capability to explore and get all the real transistor information for any biasing, frequency, amplitude or matching condition.

Many systems already available are giving partial information or incomplete tuning capabilities. The classical load-pull systems are useful, but they offer only power meter or VNA information, thus the time domain slopes cannot be reconstructed. Moreover, most systems are usually based on fundamental tuners, so the matching capabilities at harmonic frequencies are either poor or null. But the matching at harmonic frequencies has proven to be essential for the design of optimized power amplifiers [1] [2].

The system we are presenting provides efficient solutions for most of the drawbacks of regular load-pull systems. Although harmonic active load-pull is available [3], this system is a synthesis of the best solutions available today for passive load-pull. We will first describe its main features, and then we comment a set of measurement results achieved on a GaN transistor, with 3F0 tuning in addition with the 2F0 tuning [4].

II. THE SETUP FEATURES

A. THE WAVE PROBE

The wave probe concept has already been presented in [5]. This coupling method, based on a very old work carried out in the forties [6], provides the equivalent functionality of a reflectometer, with a coupling factor of –40 to –60 dB, and a directivity about 15 dB. As these wave probes are very small and introduce negligible losses in the main RF path, they can be installed between the passive tuners and the wafer probes without significant reduction of the matching capabilities.
A drawback of this coupling method is that it generates common mode currents excited on the feeding semi-rigid

cables. Electromagnetic radiation between the two wave probes can be consequently observed. This issue requires the design of a shield and a clever ground management.
The LSNA calibration algorithm works fine with a directivity factor as small as 15 dB, but the main advantage of the wave probe couplers is the short path between the DUT and the sampling heads of the LSNA. As a direct consequence, the best information about the DUT behavior is acquired (especially the harmonic components as results of the DUT nonlinearities), and the LSNA calibration does not need to be corrected when the mechanical tuners are moved.

B. THE TUNER "MPT"

The new iMPT 1818 (from 1.8 to 18 GHz) tuner from Focus Microwaves has been presented in January 2007 [7]. This very new and impressive equipment makes use of 9 stepping motors and a powerful controlling software in order to reach nearly any combination of F0, 2F0, 3F0 complex impedances in its frequency range. Several modes of operation are available, including a very smooth mode with only vertical movements of slugs for vibration-free on-wafer measurements.

C. THE COMPLETE SETUP

The main RF measurement unit is the LSNA. This equipment has been introduced 10 years ago and has been described many times[8]. The key point to notice here is that the combination of a on-wafer setup, a LSNA coupled with wave probes and the iMPT tuner allows nearly any kind of DUT electrical investigation. A classical fundamental tuner is installed at the input of the device, and a traveling wave amplifier helps the RF source to feed RF power in the DUT.The simplified setup is described on Fig. 1, and 2 photographs are proposed on Fig.2.

III. MEASUREMENTS RESULTS

The measurement results have been obtained on a GaN HEMT from Daimler-Chrysler processed in 2003, the device width is 12*100µm. The fundamental frequency is f0=2.4GHz, the LSNA calibration takes into account harmonic components up to 19.2GHz. All along this paper, the bias point is Vgs0=-3.4V, Vds0=22V and the drain current is close to 220mA (it changes slightly with the RF level and with the matching conditions, it has been measured each time for accurate PAE computation). The LSNA calibration is performed at the RF probe planes. The source impedance is set to 50 Ohms (no tuning at all) in order to reduce the instabilities [9].For the same reason, we have only considered load areas in the Smith chart that induces a positive real part of the small signal device input impedance.

The Fig. 3 presents a set of time domain output characteristics in the Vd/Id plan of the device in addition with the time domain slopes of Vds and Id. The plot 3)a proposes the load line when only the F0 matching is optimized for output power. One can notice that the device is driven in nonlinear regime. The PAE reached is 50.6%.
The plot 3)b of Fig.3 shows the improvements when an optimum has been searched with F0 and 2F0 load impedances, the 3F0 load is very close to 50 Ohms. The plot 3)c presents the same result when only F0 and 3F0 have been optimized. Finally, the plot 3)d proposes a full optimization of F0, 2F0 and 3F0 load impedances. With both harmonic optimizations on Fig. 3)d, a PAE close to 60% has been reached, with a drain voltage excursion up to 40 Volts. It is extremely interesting to notice that the optimization with only one harmonic load (2F0 or 3F0) has given nearly the same result in terms of PAE (53.2%) for that transistor, but a closer look at the load lines shows a much more unsafe slope up to 48 Volts with the 2F0 harmonic optimization. This information is of great importance for the long term device reliability: each RF cycle overdrives the DUT it in the breakdown area. The Fig.4)a and 4)b show 2 tuning points with the same output power (28.8 dBm), approximately the same gain (13.9, 15.3dB), approximately the same PAE (18.9%, 20.0%). Without the time domain slopes, one cannot decide which point is the best. But with a examination of the Vds slope, the 4)a slope is much more dangerous for the device as is goes deeper in the high Vds area.

IV. CONCLUSION AND PERSPECTIVES

Our setup reaches a new level in load-pull technologies. Its new capabilities are extremely useful for many tests and verifications: test of device capabilities, test of device matching reliability versus overload or mismatch, test of nonlinear models, optimization of load for efficiency in combination with reliability…
We now plan to make use of this setup in pulsed mode. The pulsed mode of the LSNA [10], compatible and synchronized with our DC/pulsed biasing system, is a key point for the deep investigations of unsafe operation areas of the transistors. With the combination of the LSNA pulsed mode and all the setup presented here, we will be able to observe some extreme load cycles of transistors before their destruction. This work will be of great importance for the design of more robust power amplifiers. Note that pulsed load-pull measurements are extremely difficult to achieve with active tuning loops for obvious stability reasons, so the availability of high gamma multi-harmonic passive tuners like the new MPT is mandatory for such studies.

ACKNOLEDGMENTS

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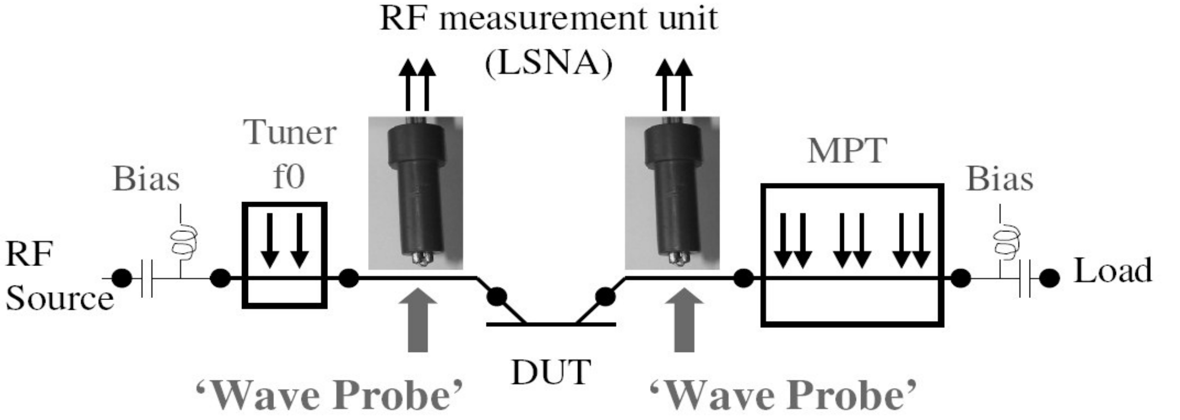


Fig. 1 : Simplified setup organization

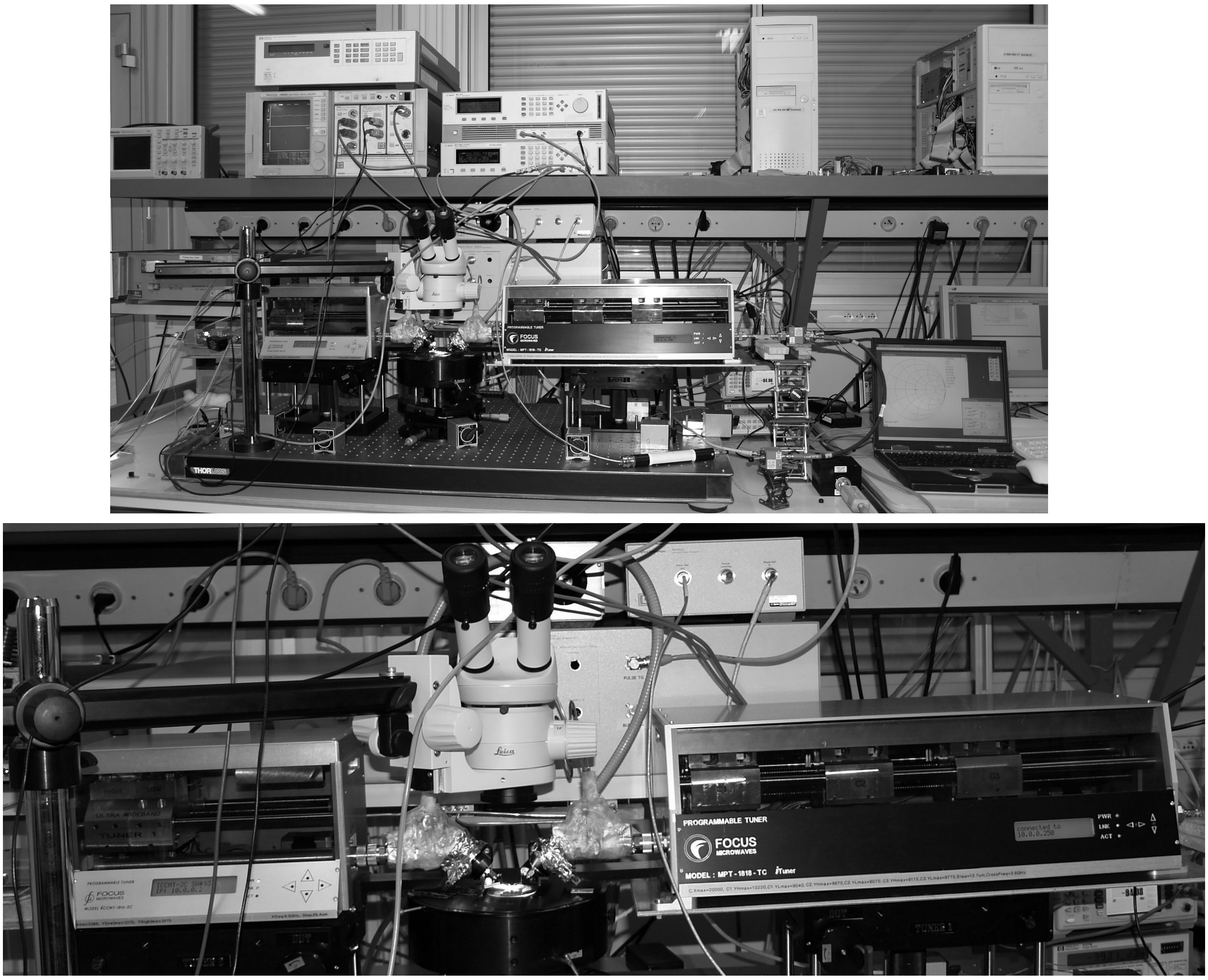
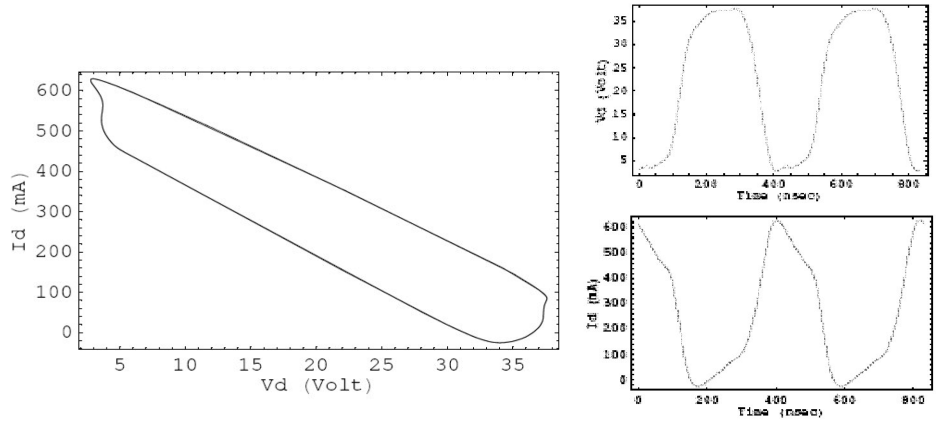
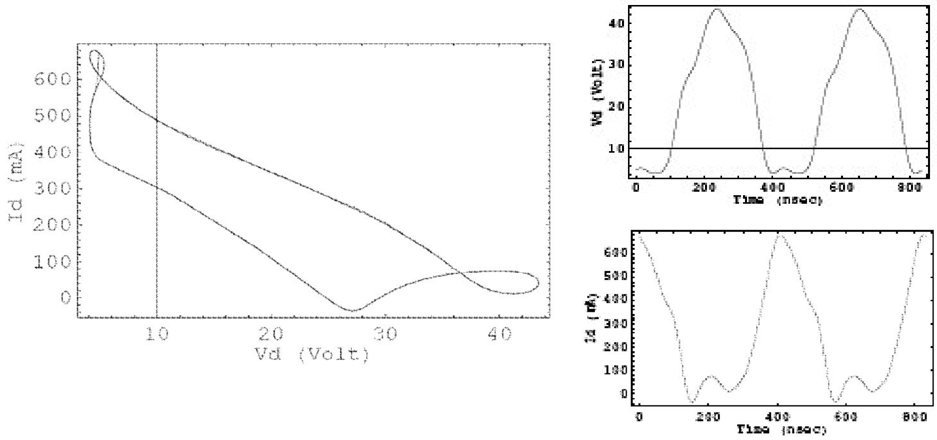


Fig. 2 : Photographs with the MPT associated to the LSNA



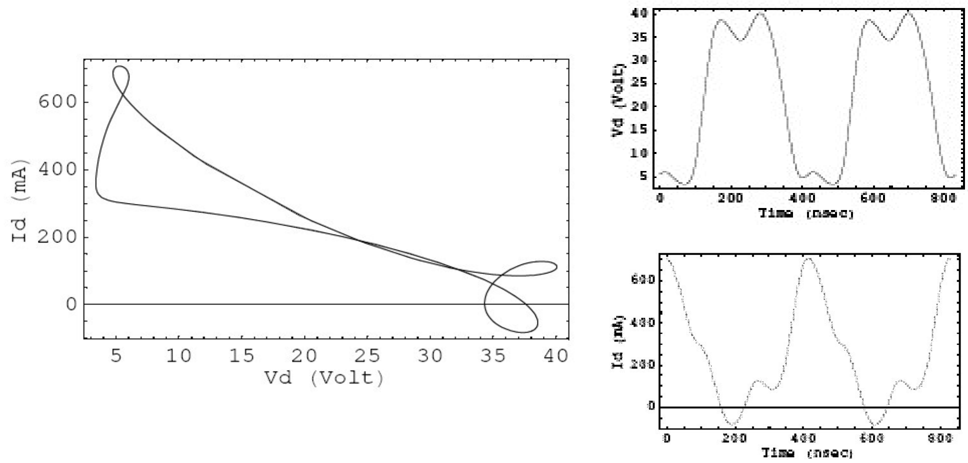
Zload = (58 – j20)Ω
Pout = 34.7 dBm
PAE = 50.6 %
Power gain = 21.1 dB
Abs(Gamma_2f0) = 0.05
Abs(Gamma_3f0) = 0.06

Fig. 3)a : load lines and power characteristics for F0 optimal matching



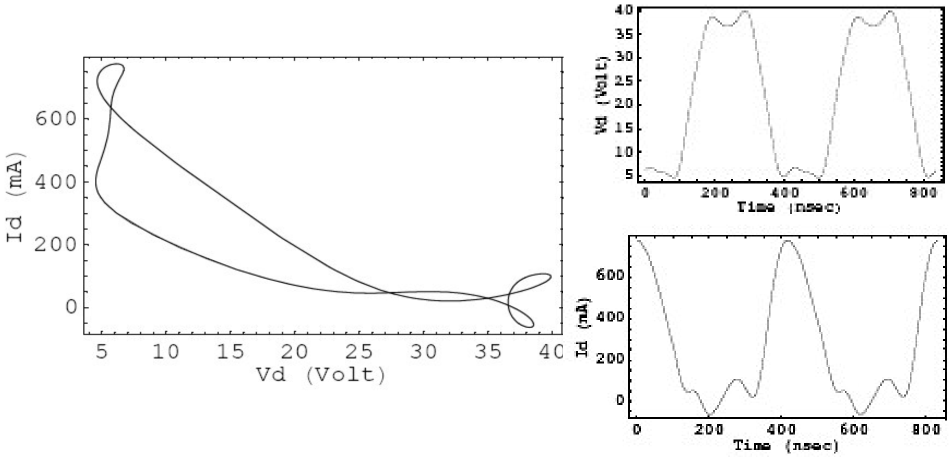
Zload = (60 – j23)Ω
Pout = 34.9 dBm
PAE = 53.1 %
Power gain = 21.1 dB
Abs(Gamma_2f0) = 0.88
Phase(Gamma_2f0) = 154.3°
Abs(Gamma_3f0) = 0.06

Fig. 3)b : load lines and power characteristics for F0 and 2F0 optimal matching



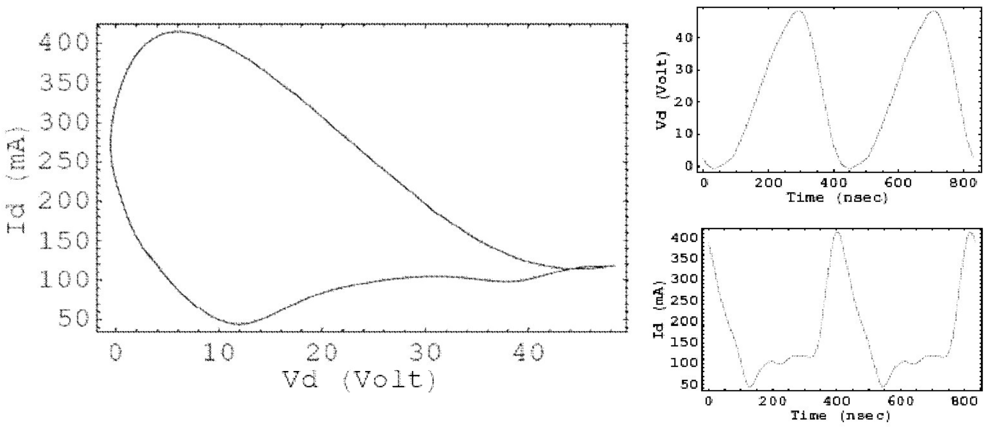
Zload = (58 – j18)Ω
Pout = 34.8 dBm
PAE = 53.3 %
Power gain = 21.5 dB
Abs(Gamma_3f0) = 0.88
Phase(Gamma_3f0) = 80.7°
Abs(Gamma_2f0) = 0.05

Fig. 3)c : load lines and power characteristics for F0 and 3F0 optimal matching



Zload = (51 – j14)Ω
Pout = 35.4 dBm
PAE = 59.7 %
Power gain = 21.4 dB
Abs(Gamma_2f0) = 0.90
Phase(Gamma_2f0) = 179.4°
Abs(Gamma_3f0) = 0.86
Phase(Gamma_3f0) = 68.9°

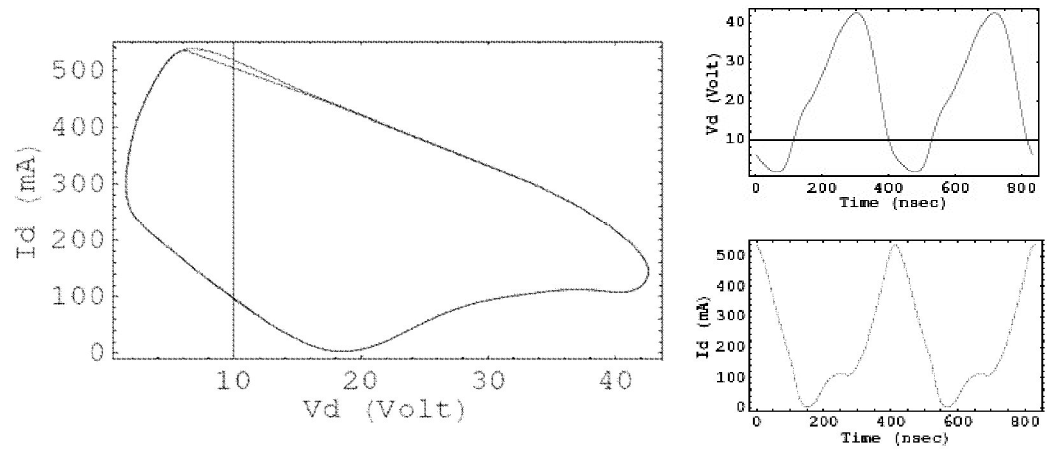
Fig. 3)d : load lines and power characteristics for F0, 2F0 and 3F0 optimal matching



Zload = (93.5 – j168.3)Ω
Pout = 28.8 dBm
Power gain = 13.9 dB

PAE = 18.9 %

Fig. 4)a : load lines and power characteristics for M1 matching conditions



Zload = (39.5 – j81.1)Ω
Pout = 28.8 dBm
Power gain = 15.3 dB

PAE = 20.0 %

Fig. 4)b : load lines and power characteristics for M2 matching conditions