Comparison of Load-Pull Measurement Results of a 4W pHEMT Involving Five European Laboratories

Jonathan Lees[1], Johannes Benedikt[1], Bernd Bunz[2], Christophe Gaquiere[3], Damien Ducatteau[3], E. Marquez-Segura[4], T.M. Martin-Guerrero[4], Alain Barel[5]

[1] Cardiff University, UK, [2] University of Kassel, [3] IEMN University of Lille , [4] University of Malaga, [5] University of Brussels

E-mail: Leesj2@cardiff.ac.uk Tel: +44 2920 339836, Fax:

Abstract — Load and source pull measurement data has for some time now been a critical and integral part of the power amplifier design process, offering accurate performance data of the actual device that is to be used. This data can be used directly to generate graphical representations of key parameters such as output power, efficiency and gain as functions of source and load impedance, for model verification or perhaps more interestingly as the basis of a model itself. There are a number of excellent research groups across Europe looking into these interesting areas, however until recently, collaboration and dissemination of information has been limited. TARGET, a network of excellence has provided a close working relationship between these groups where, for the first time these key capabilities have been compared and contrasted.

I. INTRODUCTION

It is well known that there is extensive research conducted throughout Europe looking closely at the microwave PA (Power Amplifier), and particularly in the areas of characterisation, modelling, design, and linearization[3][4][5][6]. Historically, this expertise has remained dispersed and fragmented however, with limited collaboration or communication between research groups. TARGET[7] is an exciting European initiative that aims to overcome these problems by improving collaboration and creating progressive and durable integration of research capabilities of the network partners.

The project involves 12 EU member countries and some 47 research groups with activities organised as a collection individual work packages, each addressing specific areas of microwave PA design. There are currently 28 work packages arranged into different groups; integration, prototyping, classical design, strategy, scientific coordination and dissemination. The prototyping work package group is termed '*Quick-Shot*' and considers large-signal characterisation, amplifier design and characterisation together with device and circuit model comparisons. The final objective of TARGET Quick-shot is the design and realisation of complete power amplifiers.

This paper focuses on the large signal characterisation element of the Quick-Shot work package group, and aims to discuss and compare the measurements involved in this activity. Although the significant comparison will ultimately be that of load-pull measurement data, there are a number of other critical measurements and processes that need to be compared, which are always necessary before accurate load-pull measurements are possible. For example, in order to present specific impedances to the input or output of a device, the measurement system used must be carefully calibrated such that the input and output phase reference planes are well defined[8]. It is important therefore to consider the device fixtures and the calibration verifications used by each group. Comparison of bias dependent s-parameters of the same device type allows some insight into the consistency of this process across a selection of different laboratories, which is a useful exercise in itself.

II. SUITABLE DEVICES

One of the initial requirements identified within Quick-Shot was the identification of suitable device technologies to support 4W and 30W power amplifier designs. As different laboratories would be exposing the devices to a variety of often hostile measurement and design environments[9][10], the selected device technologies needed to be both mature and robust. This requirement was also important from a device repeatability perspective. To address the increasing industrial role in the development of device and power amplifier technologies, it was also essential that the devices were commercially relevant. With these requirements in mind, medium power pHEMT and high power LDMOS devices were chosen, which were kindly supplied by Filtronic plc and Philips Semiconductors respectively. As more laboratories have been involved in

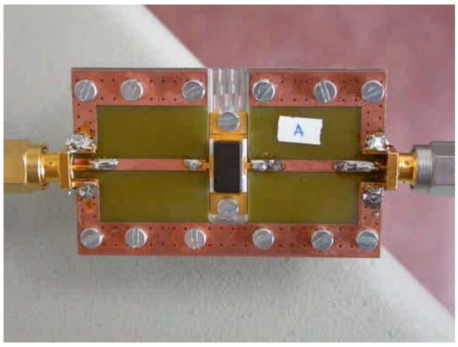

Figure 1 – Example Test Fixture courtesy of the University of Malaga

the measurement and characterisation of the pHEMT, the measurements of this device have been used as the basis for comparison for this paper. The pHEMT is of type FPD4000AF, a packaged depletion mode AlGaAs/InGaAs pseudomorphic High Electron Mobility Transistor (pHEMT), optimized for power applications in L-Band.

The data-sheet published performance for this 4W device at 1.8 GHz is summarised as: 36.5 dBm Output Power (P1dB), 10.5 dB Power Gain (G1dB), 49 dBm Output IP3, 10V Operation, 45% Power-Added Efficiency and Usable Gain to 4GHz.

III. EXPERIMENTAL TEST FIXTURES

The usual and traditional approach in characterising a packaged device is through the use of a custom built test fixture along with accompanying calibration standards[11].

The fundamental requirement of the test fixture was to allow accurate and repeatable measurement between 0.6 and 6.0 GHz. This would in turn allow measurement of the fundamental behaviour at 900 MHz, along with the following six harmonics. As the device is a medium power type, some thermal management would be required so the fixtures needed to be of suitable mass, or ‘heat-sinkable’ for the higher power measurements.

A number of laboratories manufactured their own test fixtures and calibration standards, and all adopted a similar approach employing various TRL (Thru–Reflect-Line) calibration techniques [1][2].

Figure 1 shows an example of one of these test fixtures kindly supplied by the University of Malaga. One laboratory adopted an approach where one test fixture was used to accommodate both 4W and 30W devices, which involved the addition of copper pads at the end of each port. Although effective, the minor disadvantage associated with this approach is the effect of these pads needs to be de-embedded from the measured data.

This highlights a problem worth noting: There is an ambiguity that can arise when defining the phase reference planes of the test fixture. The original measurement requirement specifies these reference planes should exist at the end of the package leads. It must be remembered that there are two possible solutions to this requirement, i.e. the lead / package interface, and the outer lead end, both being valid interpretations. This ambiguity can and has lead to differences in measured results. For this reason, it is very important to clearly and unambiguously define and communicate this information.

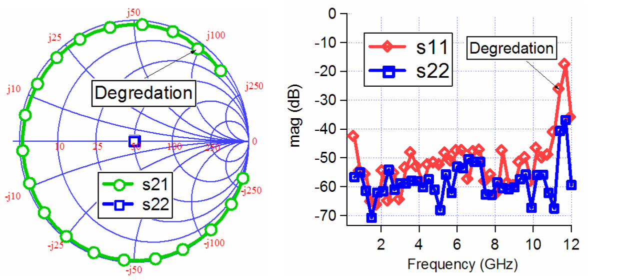

Figure 2 – Typical verification of test fixture

Verification and traceability of calibration is another difficult issue to address, and is considered a weakness of the custom test fixture approach[12]. With this type of measurement, it is the case that the only way to gain confidence in the calibration approach and the measured data is through re-measurement of calibration and verification standards and comparison of similar device measurements on different systems ideally across different labs.

Figure 2 shows a typical verification measurement where one of the calibration standards, typically the ‘line’ standard is re-measured. This measurement was conducted following the calibration of the test fixture shown in *Figure 1*, and shows behaviour that begins to degrade at roughly 11 GHz. This is due to a combination of frequency limitations of the directional couplers used within the particular measurement system and the repeatability / quality of the SMA connectors used. Since the degradation occurred at the 12th harmonic the obtained results were deemed more than suitable.

IV. DC MEASUREMENTS

The measurement requirement was to sweep gate voltage between -1.4V to 0V in steps of 0.2V, whilst sweeping drain voltage between 6V to 12V in 1V steps.

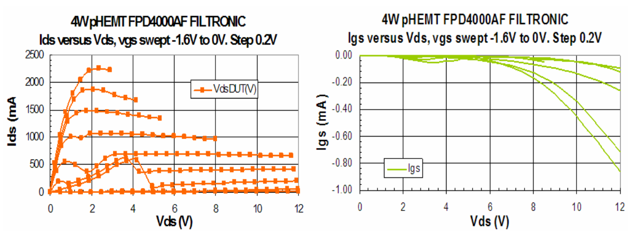

Figure 3 – Example DC-IV measurement courtesy of IEMN University of Lille.

Due to extensive low frequency gain, the device exhibited a strong tendency to oscillate in a 50Ω environment. Different laboratories had varying success in dealing with this measurement obstacle, and this was considered most probably due the different low frequency impedance environments within the measurement set-ups used at the sites. On investigation, it became apparent that there are significant differences in the bandwidth of the DC/IF channels, ranging from 10kHz to 0.5GHz. The laboratories having the most success possessed either a very wide bandwidth for the DC/IF channel or were possessing an IF load pull system allowing the control the impedances independently at IF frequencies.

Good communication between labs at this stage ensured an optimum outcome, and all measured results compared well. One example courtesy of IEMN, Lile is shown in *Figure 3*.

V. S-PARAMETER MEASUREMENTS

Bias dependent s-parameters were required on a grid with Vgs ranging from -1.4V to 0V in steps of 0.2V and Vds ranging from 6V to 12V in 1V steps. The maximum dissipated power was not to exceed 10W. The frequency range should be 0.6 to 6GHz. It was important to specify these measurements tightly to allow inter-comparison of results at a later date.

Although there were some initial problems with stability and some of the specified points could not be measured due to excessive DC power dissipation, most laboratories were able to measure the specified s-parameters. A sample of these measurement results from three different labs is presented in *Figure 4* and *Figure 5*.

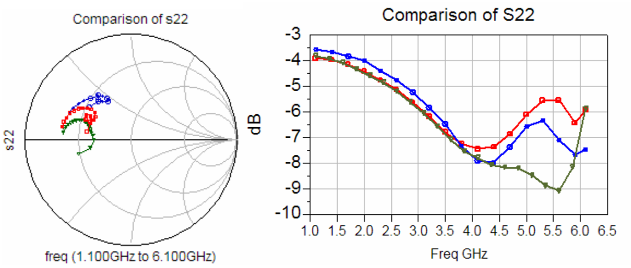

Figure 4 – Comparison of measured s22 at a single bias point from 3 labs

The comparison shows a good agreement in the measured s22 magnitude up to 4 GHz, at which point, one of the traces diverges. There is a noticeable s22 phase error between all three labs, which at this time is considered due to differences in phase reference plane definition between laboratories, although this will need to be verified. It is important to point out that an error of unknown magnitude can be expected due to different physical devices being used, the possibility of device degradation / stressing during various measurements and different thermal environments.

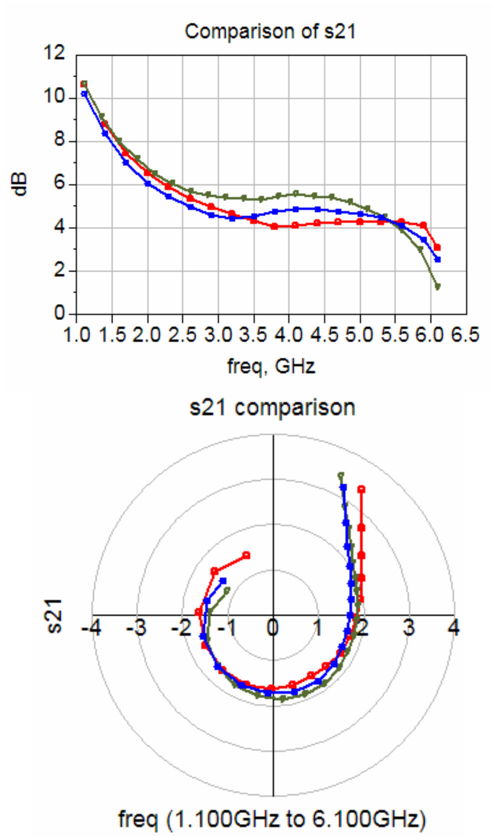

Figure 5 – – Comparison of measured s21 at a single bias point from 3 labs

In spite of these unknowns, there remains a reasonably good agreement between measurement results.

Note that all of the s-parameters presented in *Figure 4* and *Figure 5* were measured under a bias condition of Vds=10V and Vgs=-1.2V.

VI. LOAD PULL MEASUREMETNS

The measurement procedure involved firstly identifying two bias points (Vd=10;Vg=-0.9 and Vd=10;Vg=-1.2) and at each, sweeping the fundamental load across a specified impedance plane. Although the definition of this sweep area remained flexible, it was important that the highest point density existed around the impedances for maximum efficiency, gain, and output power. At each point of this sweep, a power sweep was to be performed during which the gain compression shall not exceed -1dB.

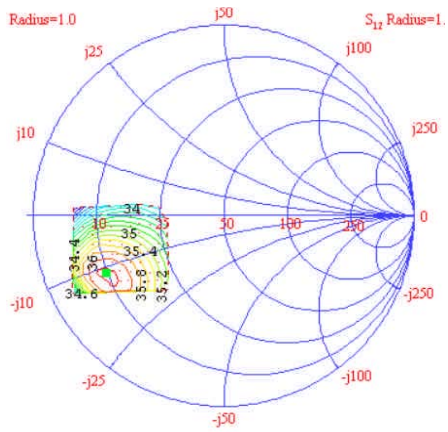

Figure 6 – Example load-pull contour for Pout

Figure 6 – shows one example of how the load-pull measurement data can be presented. Load-pull contours are used here to provide the information to allow optimal design, in this case, contours of constant power. These would generally be used in conjunction with similar contours of constant efficiency and possibly gain.

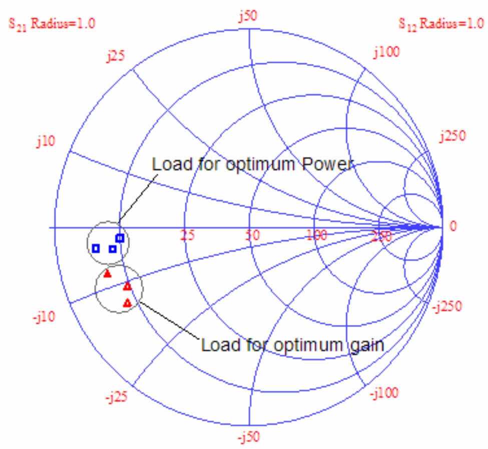

Figure 7 – Comparison of identified loads for optimum power for different groups

Figure 7 is a definitive comparison of the load-pull measurements conducted by three laboratories. The plot shows the small variation in loads for both optimum power and optimum gain at a similar drive level (1dB compression point) and bias. Considering the very different measurement systems used by these labs, and the relatively sparse measurement grid employed, the measurements show good agreement with any differences being thought due to interpolation error and small differences in the defined phase reference planes.

VII. Discussion

The groups participating within this TARGET measurement comparison exercise all have strong expertise in measurement and characterisations of on-wafer devices, which have generally well defined reference planes. This situation changes however for the measurement and characterisation of packaged devices where the reference plane is less well defined, and has the potential to vary from site to site depending, on the test-fixtures utilised. Taking this into consideration, the comparison has shown a good agreement between the data obtained within the participating labs.

One intermediate solution to this problem would be a "standardisation" of device test-fixture and appropriate calibration and verification standards within TARGET. Still, this intermediate solution does not guarantee that the standards will conform to internationally recognised and traceable standards. The solution to this problem is not straightforward as the development of standards is rather time-consuming and involves the participation of national standardisation bodies. This is however worth considering as packaged devices represent a large section of the market, e.g. mobile handsets and mobile base-stations.

An additional and important observation is the fact that the measurement systems within the participating groups exhibit large differences in the impedances presented to the device under test at IF frequencies. This became apparent during DC characterisation where the devices tended to oscillate at IF frequencies. It was interesting that those measurement systems with a large IF bandwidth tended to have less severe stability problems.

VIII. Conclusions

There are many excellent research groups across Europe using and developing load-pull measurement techniques for PA characterisation. Until recently however, collaboration and dissemination of information has been very limited. This paper has demonstrated that TARGET, as a network of excellence has provided a close working relationship between these groups where for the first time these key capabilities have been compared, contrasted and validated.

Although there are some small differences in the measurement results, these are considered due to known causes, which have been identified and highlighted as issues to be addressed.

It was noted that a wide system DC/IF bandwidth offered a higher flexibility in tackling low frequency stability problems. This observation is in contrast with the popular opinion that the DC/IF channel bandwidth should be as narrow as possible, as is the case with many commercial bias networks.

Acknowledgements

The authors would like to thank Filtronic plc and Philips semiconductors for the devices, and TARGET for the opportunity to carry out this work.

References

[1]. **G.F. Engen, & C.A. Hoer, "Thru-Reflect-Line: An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer"** *Microwave Theory and Techniques, IEEE Transactions on,* Volume 27, Issue 12, Dec 1979 Page(s): 987 - 993.

[2]. **R. A. Soares, P. Gouzen, P. Legaud, G. Follot, "A unified mathematical approach to two port calibration techniques and some applications**", *IEEE Trans. Theory and Techniques*, vol. 37, no. 11, pp. 1669-1674, November 1989.

[3]. **Jean-Pierre Teyssier, Denis Barataud, Chriophe Charbonniaud, Fabien DE Groote, Markus Mayer, Jean-Michel Nébus & Raymond Quéré,"Large Signal Characterization of Microwave Power Devicese"** *IEEE 12th GAAS Symposium,* Amsterdam., Oct. 2004.

[4]. **Ahmed Alabadelah, Tomás Fernandez, Angel Mediavilla, Bart Nauwelaers, Alberto Santarelli, Dominique Schreurs, Antonio Tazón & Pier Andrea Traverso , "Nonlinear Models of Microwave Power Devices and Circuits"** *IEEE 12th GAAS Symposium,* Amsterdam., Oct. 2004.

[5]. **M. S. O'Droma, J. Portilla, E. Bertran, S. Donati, T. J. Brazil, M. Rupp & R. Quay, "Linearisation Issues in Microwave Amplifiers"** *IEEE 12th GAAS Symposium,* Amsterdam., Oct. 2004.

[6]. **Paolo Colantonio, Josè Angel Garcia, Franco Giannini, Ernesto Limiti, Emigdio Malaver & Josè Carlos Pedro, "High Linearity and Efficiency Microwave PAs"** *IEEE 12th GAAS Symposium,* Amsterdam., Oct. 2004.

[7]. The official website of TARGET NoE: http://www.target-net.org/

[8]. **Tucker R.S. & Bradley P.D., "Computer-Aided Error Correction of Large-Signal Load-Pull Measurements"**, *IEEE Transactions on Microwave Theory and Techniques,* Vol. 32, Issue 3, Mar. 1984, pp. 296-301.

[9]. **Benedikt, J.; Gaddi,R.; Tasker, P.J.; Goss, M.; "High-power time-domain measurement system with active harmonic load-pull for high-efficiency base-station amplifier design",** *IEEE Transactions on Microwave Theory and Techniques,* Vol. 48, Issue 12, Dec. 2000, pp. 2617-2624.

[10]. **Bunz, B.; Kompa, G.; "Active load pull with fourth harmonic tuning based on an IQ modulator concept",** *33rd European Microwave Conference,* Vol. 1, Oct. 2003 pp.359 – 361.

[11]. **"In-Fixture Measurements Using Vector Network Analyzers",** Agilent, Application Note 1287-9.

[12]. **Fleury, J.; Bernard, O.;, "Designing and Characterizing TRL Fixture Calibration Standards for Device Modeling"**, Applied Microwave & Wireless, October 2001, pp. 26-42.