# Vector Corrected Non-Linear Transistor Characterization

Paul J. Tasker and Sean S. O'Keefe
*University of Wales Cardiff, Cardiff School of Engineering, P.O. Box 689, Cardiff CF2 3TF, UK*
Gareth D. Edwards and W. Andrew Phillips
*GMMT, Caswell, Towcester NN12 8EQ, UK*
Markus Demmler
*IAF, Freiburg, Germanny*
María del Carmen Currás Francos and Mónica Fernandez Barciela
*Universidad de Vigo, Vigo, Spain*

## Abstract

*An on-wafer microwave characterization system has been developed that allows for both 'frequency domain' swept frequency fixed power small signal s-parameter measurements and 'time domain' swept power fixed frequency large signal power measurements of transistors from 0.5 GHz to 40 GHz. The 'time domain' measurements are fully vector corrected to allow for the determination of both magnitudes and phases of the harmonisc generated in the non-linear regime. Such measurement capability allows for the measurement of the large signal voltage and currents waveforms present at the transistor terminations under large signal microwave excitation. The availability of these waveforms not only provides detailed insight into the operation of the transistor under large signal conditions, but is also revolutionizing the development, optimization and extraction of non-linear models and circuits design techniques. The charcterization techniques are illustrated through measurements on 0.25μm gate transistors fabricated using the H40 process at GMMT having a 4x60μm gate width.*

## Introduction

A major application area for GaAs transistors is in high efficiency power amplifiers at microwave and millimeterwave frequencies. Present HFET transistors are capable of providing high power densities, up to 1W/mm of gate width, at frequencies up to W-band. At present there is considerable development of the non-linear design concepts, simulation tools and transistor models that are necessary for large signal MMIC power amplifier designs, particularly when high power added efficiencies are a key design goal. However, most of the circuit understanding and basic design concepts used as well as the non-linear models implemented in the more complex CAD approaches are often based either on static I-V measurements or small signal microwave/millimeter wave s-parameter measurements. Improved understanding of the circuit operation under large signal conditions and the realization of optimized transistors requires the development of new large signal measurement techniques that will allow for detailed large signal characterization of transistors at microwave frequencies. Ideally these measurements should be performed in the 'time domain'. As a consequence, the development of microwave 'time domain' measurement systems is a very active area of research and development at the present [1-4].

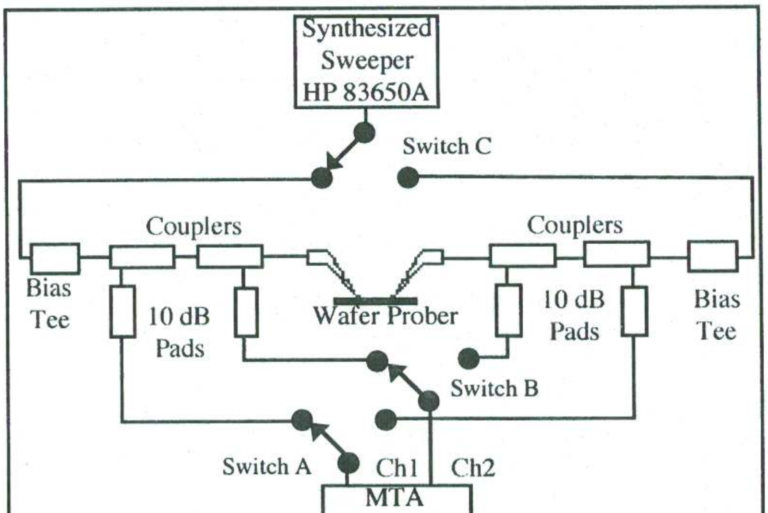


Figure 1. Two-port large signal on-wafer measurement system based on the HP Microwave Transition Analyzer.

## Measurement System

Figure 1 showss the full two-port large signal on-wafer measurement system, based on a one-path two-port system developed previously at the IAF in Freiburg [1], that has been developed at the University of Wales Cardiff. This microwave measurement system, based arround the HP Microwave Transition Analyzer (MTA), can perform measurements in the 'time domain' over a bandwidth from 0.5 GHz to 40 GHz. The integrated two-port test-set and wafer prober allows, via switch C, for the RF power to be switched from port 1 and 2, while switches A and B allow the two channel MTA to measure either in the 'frequency domain' all four s-parameters (ratio measurements are possible since the two channels have a common time base) or in the 'time domain' all four normalized travelling waves ($a_1$, $b_1$, $a_2$ and $b_2$). The 'frequency domain' measurement capability allows the system to be vector calibrated in a similar manner to a conventional Vector Network Analyzer. Hence, after calibration the system provides for vector corrected swept frequency small signal s-parameters measurements. Typical results acheived are shown in Figure 2. The measured s-parameters are compared with those computed using a conventional small signal model.

After additional 'frequency domain' calibration steps [1], the system then can then perform vector corrected 'time domain' measurements in which both the magnitude and phase of the fundamental and harmonic components of the normalized travelling waves are measured. This mode is used, for example, in swept power fixed frequency large signal power measurements of transistors. From these measurements input power, output power, gain and power added effeciency can be calculated. The data can then be displayed in a conventional manner as shown in Figure 3, which is similar to that provided by a more conventional power measurement system. However, what is significant is that since these measurements are performed in the 'time domain' where the magnitude and phase of the Fourier components of the normalized waves are measured and referenced to a single trigger channel, the large signal voltage and currents waveforms present at the transistor terminations under large signal microwave excitation can be computed, as shown in Figure 4. These waveform measurements can be performed in real time: an oscilloscope-like measurement mode, as so the system can display the waveforms, for example, during load or source pull.

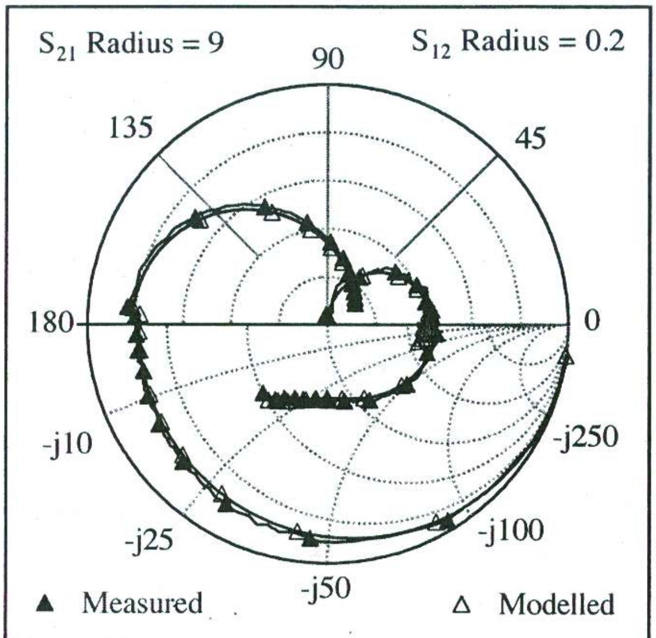


Figure 2. Measured s-parameters obtained using the MTA measurement system. Also shown are the modelled s-parameters computed from a model extracted from the measured s-parameters. Bias conditions were Vgs=-0.12 Vds=2.5 Ids=271mA/mm.

Non-Linear Model Verification

In the case of extraction and verification of non-linear models, this measurement system is an ideal tool. Both the s-parameters measurements, required for model generation, and the power measurements, required for model verification, are for the first time performed in the same system. Hence, when assessing model validity, measurement accuracy issues resulting from probe placement or different calibration approaches are eliminated. The measurements are performed in the same system using the same probe contact and the same calibration parameters. Figure 5 shows the comparison between simulated and measured power performance using a look-up table model [7] that was generated by using this system to perform bias dependent s-parameter measurements at a single frequency 4 GHz). Excellent agreement is seen indicating the validity of this modelling approach.

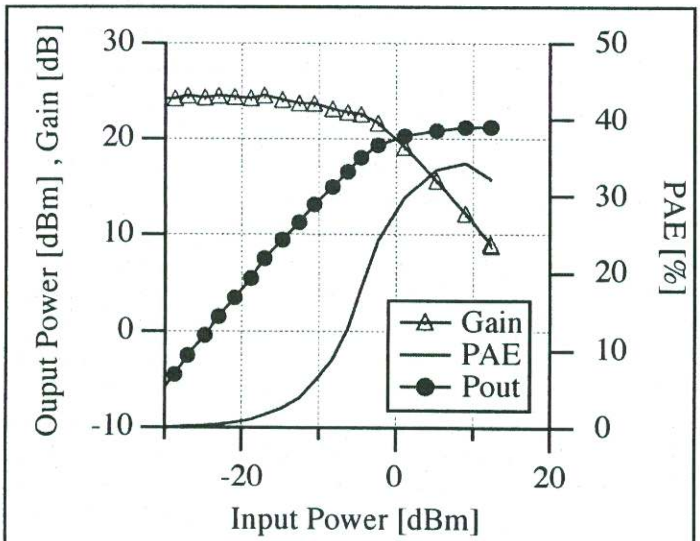


Figure 3. Measured large signal performance is obtained using the MTA measurement system at 4 GHz. Bias conditions were Vgs=-0.2 Vds=5.26 Ids=270mA/mm. Saturated output power is 553mW/mm.

Analysis

Detailed analysis of this measurement data also allows for improved understanding of the operation of the transistor under large signal conditions at microwave frequencies [5]. Study of the current and voltage waveforms, for example, allows the observation of forward gate conduction during the forward voltage part of the gate voltage cycle. Analysis of the output voltage indicates the clipping of the waveforms as a result of pinch-off (or breakdown) and current saturation (or drain knee). This is best observed if the output current is plotted against the output voltage, i.e. a dynamic load-line, as shown in Figure 6. If this measurement is repeated at different drain voltages, the boundaries confining the microwave current and voltage swing can be determined [5]. Analysis of this data allows for the determination of the optimum load and power performance. In this case it indicates that the optimum load is 15.6 Ω-mm into which a maximum output power of 600 mW/mm could be developed. The maximum performance measured into a 50 Ω (12 Ω-mm) load at 4 Ghz was 553mW/mm. Plotting contours of constant microwave output power on these characteristics allows for the determination of the effect of varying the microwave load impedance in a manner that can be more informative than conventional load-pull contour plots.

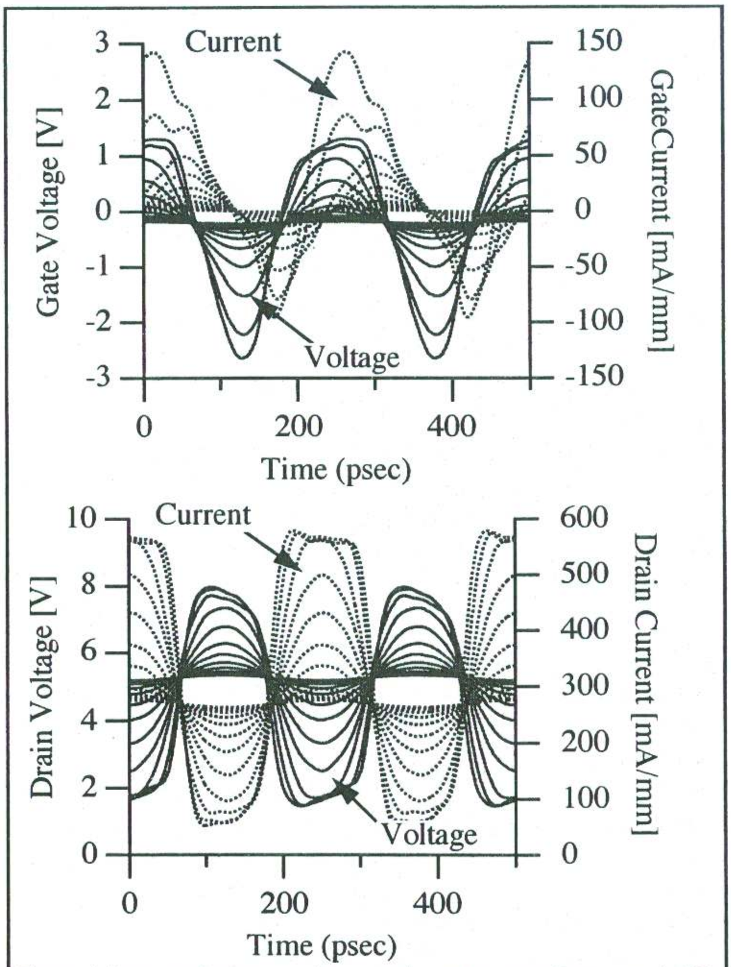

Figure 4. Input and output voltage and current waveforms at 4 GHz measured using the MTA measurement system with increasing input power level from which the power performance shown in Figure 3 was computed.

In addition, the four state functions ($I_g$, $C_g$, $I_d$ and $C_d$) necessary for modelling of the non-linear behaviour of the transistors [6,7] can also be extracted from these waveforms [5,8-10]. For example the microwave transfer characteristic, measured state function $I_d(V_g)$ is determined from the input voltage and output current waveforms. Comparison of this dynamic transfer function with the static DC transfer function allows transconductance dispersion to be quantified. By measuring the microwave transfer characteristic as a function of drain voltage and mapping selected points from this characteristic onto the dynamic load-line, allows for the determination of the microwave I-V characteristic [5], as shown in Figure 7. These I-V characteristics are conceptually similar to those determined using pulsed I-V measurements. As a consequence they can be analyzed to determine the effect of dispersion and self heating on the DC I-V characteristics. They provide for a direct measurement of the mcrowave breakdown characteristics. In this case it can be seen that there is very close agreement between the DC and microwave I-V characteristics

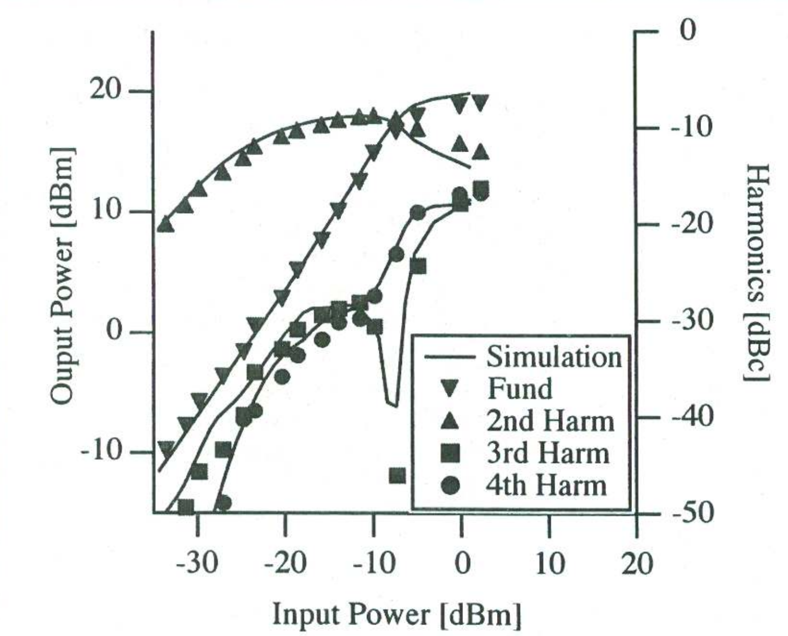

Figure 5. Comparision of measured and simulated power performance at 2 GHz using a look-up table model. Class B bias point is Vgs=-0.8V Vds=3.66V.

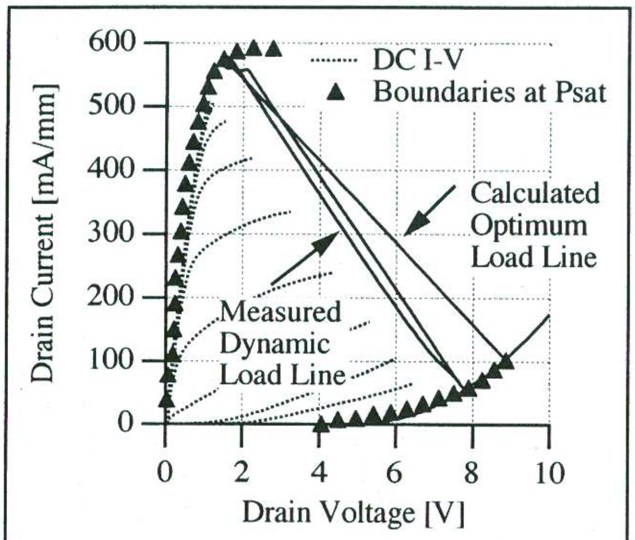


Figure 6. Measured dynamic load line at 4 GHz showing the clipping limits. By varying the DC bias conditions the clipping limit contours can be determined, hence optimum load line calculated.

indicating that these devices exhibit very little dispersive behavior. The eventual aim would be to use these large signal extracted state functions as the data set for look-up table models.


Summary

A fully comprehensive large signal measurement system has been developed. This measurement system allows for both conventional 'frequency domain' small signal s-parameter measurements as well as advanced 'time domain' large signal measurements and is ideal for non-linear model generation and verification. Analysis of the waveform data can also provide immediate insight into the large signal circuit performance of the transistor: maximum output power, optimum load impedance, efficiency, etc. The data also provides a direct measure of the non-linear behaviour of the transistor at microwave frequencies. It thus provides a measure of dispersive effects, microwave breakdown voltage, etc. In addition, analysis of this data can allow for the extraction of the non-linear I-V and Q-V characteristics required for accurate non-linear models. The output I-V characteristics have already been used for the extraction of an analytical non-linear CAD model [8].


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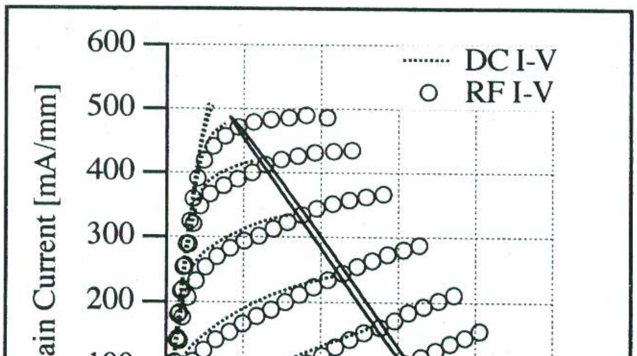


Figure 7. Microwave I-V characteristic extracted from 'time domain' large signal microwave waveform measurements.