# A VECTOR CORRECTED WAVEFORM AND LOAD LINE MEASUREMENT SYSTEM FOR LARGE SIGNAL TRANSISTOR CHARACTERISATION

J.G. Leckey, A.D. Patterson and J.A.C. Stewart

High Frequency Electronics Laboratory, The Queen's University of Belfast
Ashby Building, Stranmillis Road, Belfast BT9 5AH, N. Ireland.

## ABSTRACT

A vector corrected large signal measurement setup based on a Microwave Transition Analyser has been developed to enable device output harmonic and waveform measurement with variable drive level, frequency, DC bias and fundamental load impedance. A novel capability of this system is the ability to plot the device dynamic load lines during measurement so that nonlinear effects can be investigated as a function of bias and load impedance in real time. Load line results are shown for a MESFET and an HBT device and the effect of load impedance on device behaviour is described.

## INTRODUCTION

Vector harmonic measurement systems based on the Hewlett Packard Microwave Transition Analyser (MTA) have recently been reported for use in large signal transistor characterisation, nonlinear model parameter extraction and model verification[1-5]. The systems typically employ a single tone input signal and allow capture of large signal waveforms at different drive levels and DC bias conditions. This paper presents a newly developed MTA based system which includes a variable load tuner in its vector calibration so that waveform measurements may be obtained while a known load is presented at the device output terminal. The setup is an improvement over traditional VNA load pull systems [6] since device output current and voltage waveforms may be examined in conjunction with harmonic power levels, for arbitrary load impedances. The chief motivation for the development of the variable load system was to produce a nonlinear model verification facility with variable load termination, enabling the device to operate over a greater area of its output characteristics independent of applied DC bias conditions. The system provides a further dimension to the use of such measurements in nonlinear parameter extraction[7,8,9].

A further novel feature of this system is the ability to instantaneously measure, de-embed and display the RF dynamic load line so that the effect of particular load-bias-power level combinations can be observed in real time. Breakdown and forward gate conduction can be observed as causing load line compression, and the optimum load line for output power may be investigated. The system may be software configured to carry out standard load pull measurements and to measure DC characteristics thus forming a comprehensive power transistor characterisation tool.



## MEASUREMENT SYSTEM

The block diagram of the measurement system is shown in figure 1 and is a development of that described in [1-3]. The single tone input is applied by a microwave source which allows the input power level to be swept to 15dBm. Higher input power levels may be accommodated by adding an amplifier at this point. The MTA is used as harmonic receiver with a bandwidth for higher harmonics to 40GHz and a dynamic range found in practice to be around 70dB. Device bias is applied via a programmable DC source. The nonlinear waveform at the device incident port



CH3577-4/95/0000-1243$01.00 © 1995 IEEE

and the phase reference are monitored by 40GHz couplers, with the input channel to the MTA switchable between output transmission and input reflection measurements.

## CALIBRATION

The calibration requirement of the system is increased by the need to include a number of different load impedances and a software routine was developed to automate this process. The approach taken was to carry out an initial network analyser SOLT calibration of the measurement environment with the tuner set to a low reflection coefficient position. This routine produces the error boxes for the input and ouput circuits. The S-parameters of the total system are then measured for a selected number of tuner settings over its range of travel and the output error boxes for each position calculated and stored with the corresponding tuner control co-ordinates. This enables a selected reflection coefficient to be set at the device output terminal during the measurement procedure with known corresponding error boxes. The resultant two port S-parameter networks from the calibration are used to de-embed the measurements or may be included in nonlinear simulation for model verification.

## MEASUREMENT PROCEDURE

The measurement procedure utilises control software which enables **i)** Selection of input drive frequency, power sweep range and signal averaging **ii)** Selection of the required device DC bias **iii)** Selection of the fundamental frequency load termination, **iv)** Capture of harmonic data over the power sweep range and **v)** Display of dynamic load lines.

In order to calculate the load lines the measured harmonic data is converted into frequency domain vector voltages and currents for each harmonic at the MTA measurement port. The S-parameter output networks for each frequency are then converted to ABCD matrices so that the measured port voltages may be transformed to the device terminals. A fast fourier transform is applied to recover the time domain voltage and current waveforms at the device terminals. While this method allows a fast recovery of the load lines at the device terminals, for quantitative analysis the intrinsic waveforms may be calculated from a knowledge of device parasitics.

## MEASUREMENT RESULTS AND ANALYSIS

Figure 2 shows drain voltage waveforms for a Daimler Benz chip MESFET biased at 45 mA drain current and 3 Volts Vds for a 50 ohm load at 1 GHz. Compression in the output waveforms is caused by the presaturation knee region of the drain characteristics and also by pinch-off. The dynamic load line for this condition is plotted in figure 3, in this case an approximate straight line can be seen due to the antiphase nature of the drain current and voltage waveforms. The gradient of this line is due to the 50 ohm load effectively in parallel with the device ouput conductance.

The effect of varying both the angle and magnitude of the device load reflection coefficient can be investigated by examining the dynamic load lines produced for various load conditions. The reactance introduced by varying the load reflection coefficient angle causes the load line to become an ellipsoid rather than a resistive straight line. At a load angle of around 90 degrees the load line opens up to its maximum extent as can be seen from figure 4. At this point the voltage and current waveforms are approaching quadrature phase difference. The trajectory of the rf load line is clearly confined by pinch off at the lower current limit and by the knee region at the higher current limit.

For load reflection coefficient angles close to 180 degrees (towards a short circuit) as in figure 5 the dynamic load line tends to become less open. In this case the real part is less than 50 ohms and the gradient of the load line increases. The plot clearly shows the effect of gate conduction leading to hard output waveform clipping. At low reflection coefficient angles (towards open circuit) the real part of the load impedance is greater than 50 ohms causing the dynamic load line to have a reduced gradient as is shown in figure 6. On this plot the angle of the load line leads to operation into the breakdown region at high drain voltages. This measurement allows breakdown limits to be characterised under rf excitation.

Figures 7 and 8 show waveform and load line measurements performed on an HBT device. Figure 8 shows the collector voltage and current load line for a 240 $um^2$ Daimler Benz GaInP/GaAs HBT driven into a reactive load of angle 60 degrees and magnitude 0.5 at 1GHz (Ice=25mA, Vce=4V). The corresponding current waveform is shown in figure 7 showing soft compression effects at high drive levels.

## CONCLUSION

The measurement system described above allows a full range of single tone large signal measurements with variable frequency, bias and load impedance. The system is a useful tool in the characterisation of devices for power amplifier design, since the effects of load impedance and bias point on PAE and harmonic generation can be investigated. Breakdown and compression effects under large signal RF operation may also be monitored through examining the dynamic load lines which are now available during measurement.

## REFERENCES

1. F. Van Ray, G. Kompa, "A New On-Wafer Large Signal Waveform Measurement System with 40 GHz Harmonic Bandwidth", IEEE MTT-S Digest, pp.1435-1438, 1992.
2. J.A.C Stewart and J.G Leckey, "Verification and Extraction of Nonlinear Device Model Parameters from Harmonic Amplitude and Phase", High Performance Electron Devices for Microwave and Optoelectronic Applications, IEEE UK/ROI Section, Workshop Proceedings, Oct 1993.
3. M. Demmler et al. "A Vector Corrected High Power On-Wafer Measurement System with a Frequency Range for the Higher Harmonics up to 40 GHz.", Proc. 24th European Microwave Conference, pp.1367-1372, 1994.
4. T. Van den Broeck and J. Versprecht "Calibrated Vectorial Nonlinear-Network Analysers" ,IEEE MTT-S Digest, pp.1069-1072, May 1994.
5. U. Lott, "A survey of the error contributions in nonlinear network measurements at microwave frequencies", CAE Modelling and Measurement Verification, IEEE MTT/ED/AP Joint Chpt Workshop Proc., London, pp. 61-66, Oct 94.
6. A. Werthof, F. Van Ray and G. Kompa, "Direct Nonlinear Power MESFET Parameter Extraction and Consistent Modeling", IEEE MTT-S Digest, pp.645-648, June 1993.
7. J.E. Muller, M. Laudien, H. Muller, "On-wafer Load Pull Characterisation of Self-Aligned GaAs Power MESFETs",Proc. 21st European Microwave Conference, pp.1379-1384, 1991.
8. J.G. Leckey et al., "Nonlinear MESFET Parameter Estimation Using Harmonic Amplitude and Phase Measurements", IEEE MTT-S Digest, pp.1563-1566, May 1994.
9. P.J Tasker et al., "Novel Approach to the Extraction of Transistor Parameters from Large Signal Measurements", Proc. 24th European Microwave Conference, 1994.

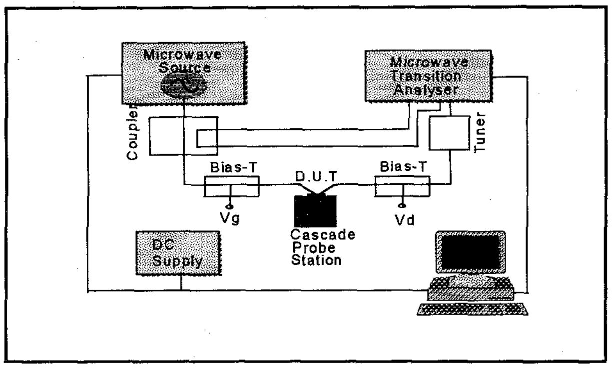


*Figure 1 The Large Signal Measurement Set-up*

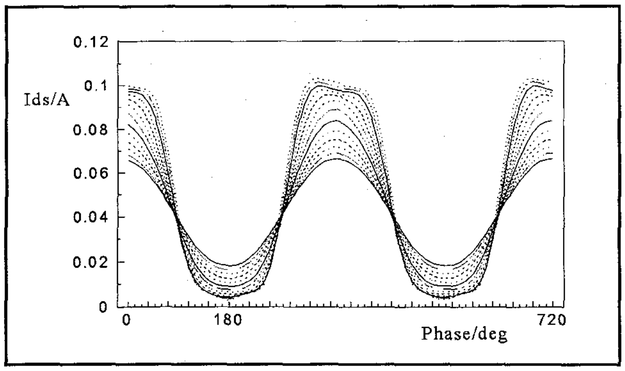


*Fig.2 MESFET Ids Waveforms for increasing input drive.*

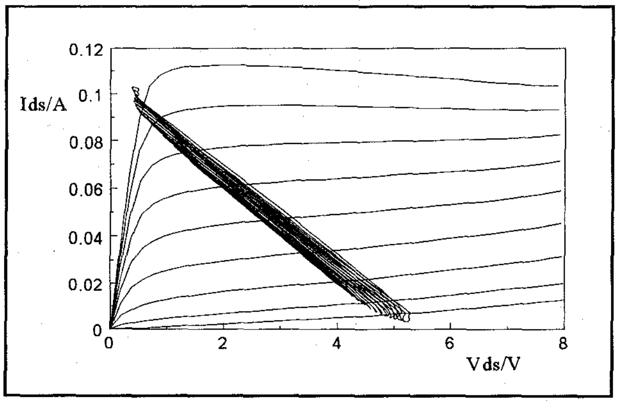


*Fig.3 MESFET Dynamic Load lines for Rl=50Ω*

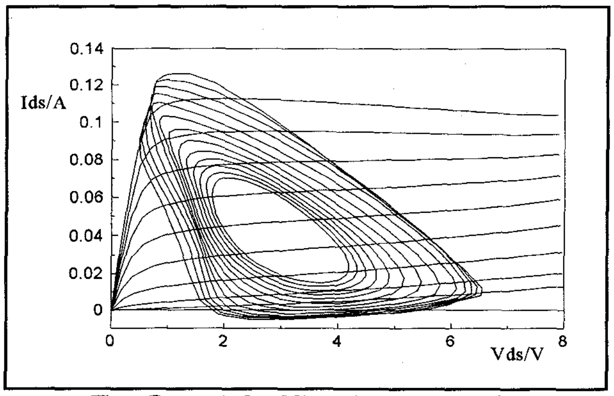


*Fig.4 Dynamic load lines for $\Gamma_L$=0.5,100deg*

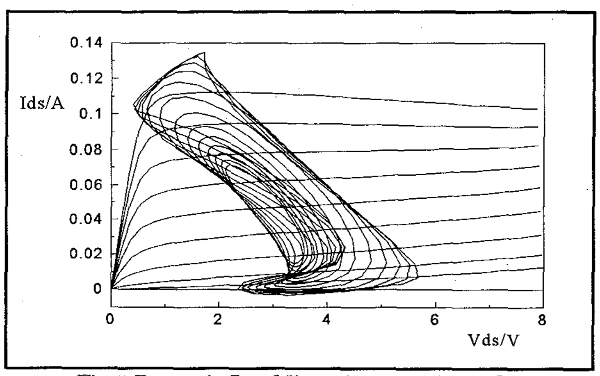


*Fig.5 Dynamic Load lines for $\Gamma_L$=0.5,150 deg*

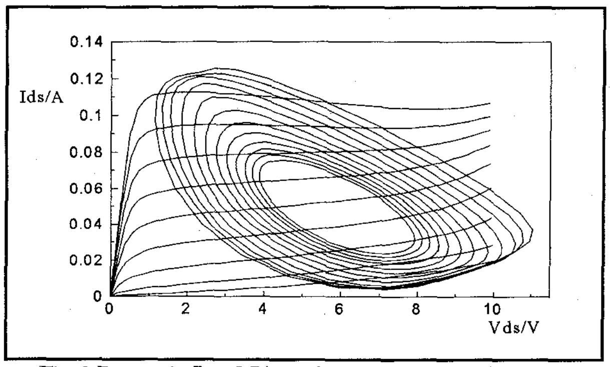


*Fig.6 Dynamic Load Lines for $\Gamma_L$=0.5,60 deg,Vds=6V.*

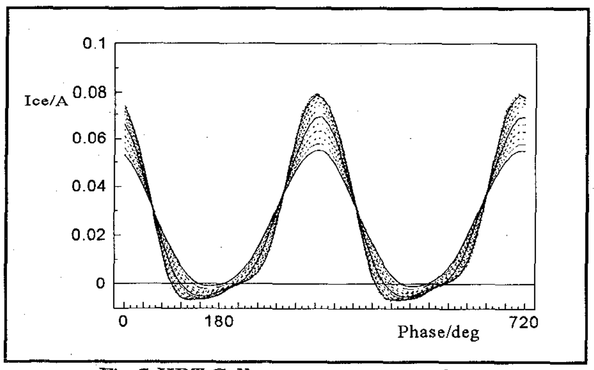


*Fig.7 HBT Collector current waveforms*

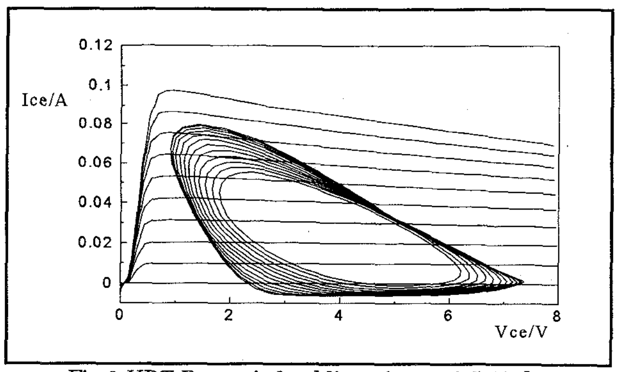


*Fig.8 HBT Dynamic load lines for $\Gamma_L$=0.5,60 deg*