AN AUTOMATED MEASUREMENT TECHNIQUE FOR MEASURING AMPLIFIER LOAD-PULL AND VERIFYING LARGE-SIGNAL DEVICE MODELS

Mark Pierpoint, Roger. D. Pollard and John. R. Richardson.

Microwave Solid-State Group,
Department of Electrical and Electronic Engineering,
The University of Leeds, Leeds, LS2 9JT, U.K.

ABSTRACT

A physical model has been used to characterise the large-signal behaviour of a GaAs MESFET terminated with a wide range of load impedances and a new, automated, load-pull system developed to make measurements in order to verify the performance of the model. The heart of the measurement system is a motorised slide-screw tuner which operates over 2-18 GHz with reflection coefficients greater than 0.93 above 3 GHz.

INTRODUCTION

Since the first microwave GaAs MESFETs were reported in the early 1970's they have been used extensively for providing small-signal amplification above 1 GHz. The development of GaAs MESFET power amplifiers, however, has been far less dramatic; devices operating in a non-linear fashion are difficult to characterise and designs are consequently far from exact and optimal.

This paper describes work carried out on the large-signal modelling of GaAs MESFETs and the automated measurement of their load-pull behaviour. The object is to facilitate the design of power amplifiers with power, gain, bandwidth and efficiency as design parameters.

MODELLING

The modelling is based on a two-dimensional physical simulation of a GaAs FET, configured as a two-port and terminated at its output with loads of known reflection coefficient (Fig. 1) thus simulating the experimental technique employed in load-pull measurements [1]. With a sinusoidal voltage impressed at the input, the resulting current and voltage waveforms at the loaded output are built up in time-step increments. Fourier analysis of these waveforms provides information on the output power at each harmonic of the impressed frequency. In this way the performance of a given device, for various input frequencies, drive levels, bias conditions and loads is simulated.

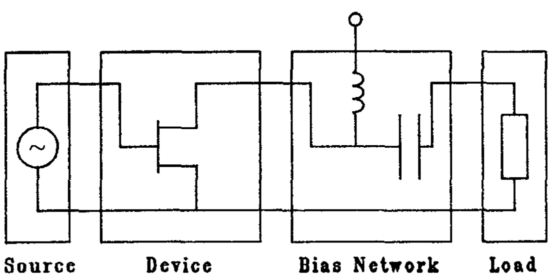

Fig. 1 Simulated Load-Pull Configuration.

A rectangular device geometry is used with a regular mesh overlay (Fig. 2) and the charge-transport equations are solved numerically using a finite difference scheme [2]. The high efficiency of the computer coding allows the simulation of steady-state large-signal (CW) operation over hundreds of pico-seconds.

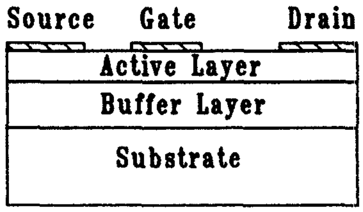

Fig. 2 GaAs MESFET Device Geometry for Model.

Passive microwave loads are modelled as lumped circuits, with the formulation of the time-domain differential and integral expressions being based on backward difference methods. For example, the two most commonly used circuit equations reduce to :-

$$V = L\frac{di}{dt} \rightarrow V^t = L\left[\frac{i^t - i^{t-1}}{\Delta t}\right]$$

$$V = \frac{1}{C}\int i dt \rightarrow V^t = \frac{L^t \Delta t}{C} + V^{t-1}$$

The load model includes a very small capacitor (about 10fF) in parallel with the load to filter out transient current changes between time-steps. These equations are then immune to the numerical noise on the simulated terminal currents and this ensures the stability of the device model.

The results from the simulation are post-processed to realise all the necessary graphical output and design information. Examples of this are shown in Figs. 3 and 4 which refer to the simulation of a low power test device but clearly show the parameters, such as the 1dB compression point at 10dBm output power and the optimum load impedance for a given input power, important in the design of power amplifiers.

LOAD-PULL SYSTEM

Verification of the model under large-signal conditions is undertaken using load-pull measurements. Manual systems are too slow and laborious for full device characterisation so the process has been automated using a computer-controlled, stepper-motor driven, slide-screw tuner.

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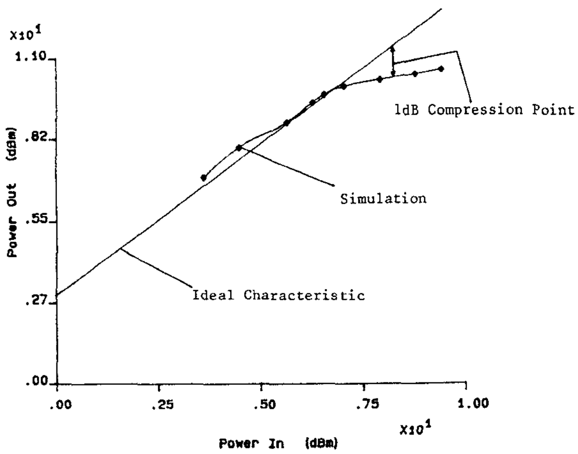


Fig. 3 Simulated Power Saturation Curve with the 1dB Compression Point Marked.

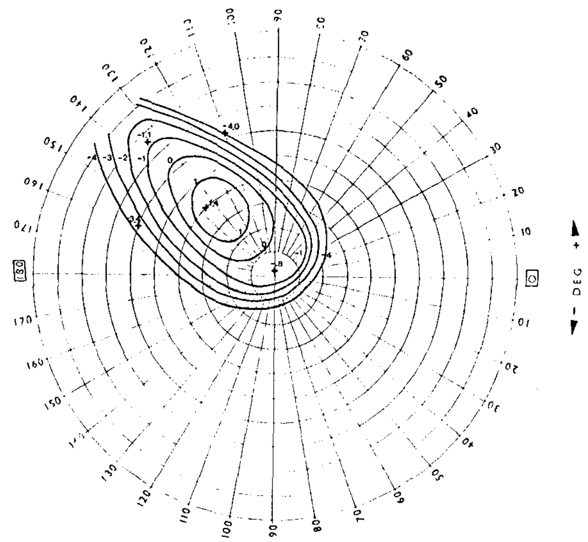


Fig. 4 Simulated Load-Pull Contours (values in dBm).

The Tuner

The tuner (Fig. 5) is designed to operate over a frequency range of 2–18 GHz. It is based on a length of 50 ohm slab-line which has an open structure allowing the insertion of a small metallic slug. The magnitude of reflection coefficient is varied by moving the slug in and out of the line, while moving it along the line, modifies the phase. Excellent tuner performance has been achieved through careful design of the slug and the stepper-motor drive mechanisms and the single tuning element provides reflection coefficients greater than 0.78 over 2–3 GHz and 0.93 over 3–18 GHz (Fig. 6).

The two stepper-motors which position the slug are referenced to "zero" points by means of high quality mechanical or optical micro-switches, so that any reflection coefficient is then defined by a number of motor steps from each reference stop. The repeatability with which the tuning element can be re-positioned is of the utmost importance in the measurement system and with this tuner it is possible to reproduce the magnitude and phase of the reflection coefficient to within 0.003 and 0.4° respectively.

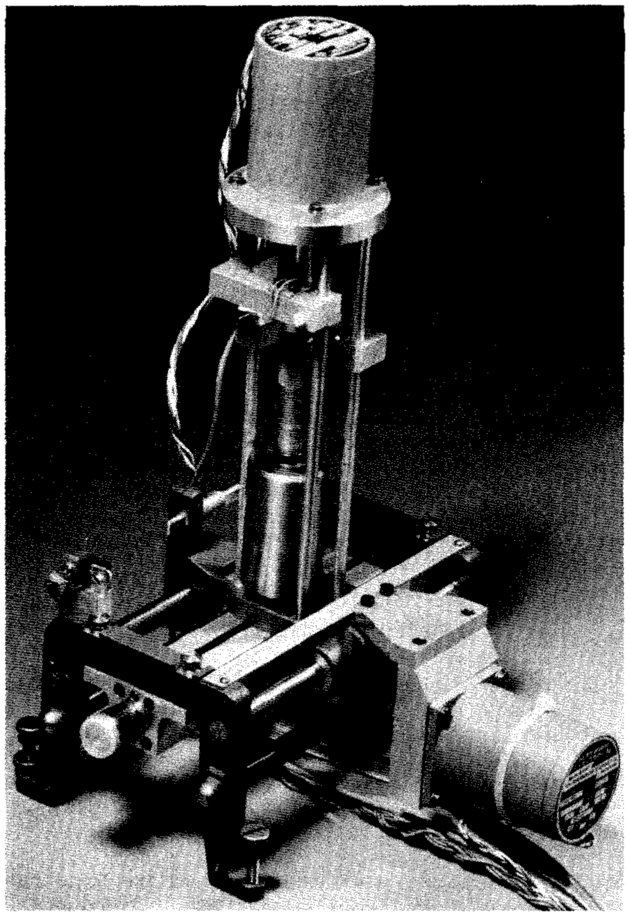


Fig. 5 The Automated Slide-Screw Tuner.

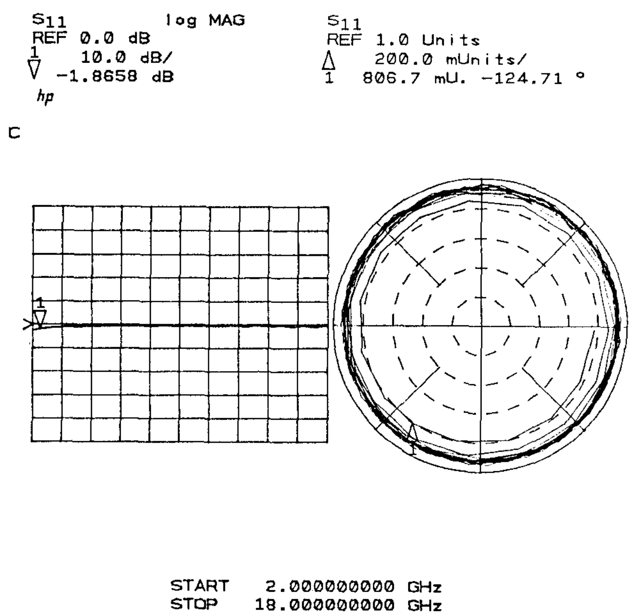
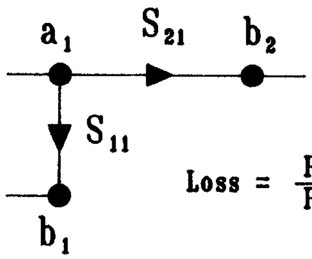


Fig. 6 Tuner Reflection Coefficient 2-18 GHz.

An expression for the loss of the tuner may be derived from a consideration of the signal flow graph in Figure 7. The tuner loss ranges from 3.1 dB for the very high reflection coefficients (slug fully in) to < 0.1 dB when the slug is completely withdrawn.



$$\text{Loss} = \frac{Po}{Pi} = \frac{|S_{21}|^2}{1 - |S_{11}|^2}$$

Fig. 7 Signal Flow-Graph and Expression for Tuner Loss.

Contour Plotting

In normal practice, the large-signal performance of a device is characterised by plotting contours of constant power output as a function of load impedance on a Smith chart. Techniques for plotting these often involve following contours [3,4]. This method has a number of disadvantages :

- The contour levels of interest must be chosen before the measurements are made.
- Finding different impedances giving the same power level using closed-loop control of the tuner is slow and difficult to implement.
- A large number of measurement points are required to determine each contour.

These disadvantages may be eliminated by using a generalised contouring algorithm on a fast desktop computer to plot smooth contours from a set of scattered data points. A program has been written which interpolates the data points onto a regular grid using least-squares fitting to a weighted parabolic function [5] and draws contours across the area of interest. Using this procedure as few as 30 data measurement points have been used to produce contours, with a computation time of five minutes on an HP9000 model 236U.

The System

A schematic of the Load-pull system is shown in Fig. 8. At present only the output tuner has been automated so the manual input tuner is fixed for each frequency of interest and then characterised together with the input bias-T and circulator so that the incident power on the device may be corrected for losses. Automatic operation involves changing the stepper-motor postions to repeat the exact points at which the output tuner, bias-T and circulator have been previously calibrated. The input and output power, frequency and bias are then recorded at each point in turn. A vector network analyser is not needed for each measurement but only to calibrate the tuner initially and subsequently for any periodic re-calibration.

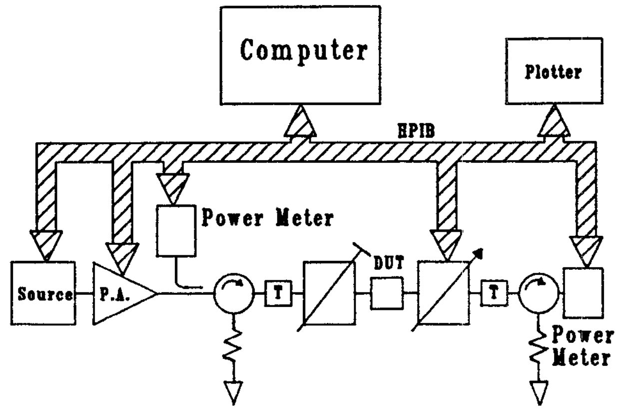


Fig. 8 Automated Load-Pull Measurement System.

The amount of information to be handled during the measurement sequence requires the use of a structured strategy for storing data. An output network calibration file for each frequency is used and contains the electrical performance at each tuner point. Likewise for the input network, one set of correction data for the preset tuner position is needed. Two measurement arrays store corrected input and output power for the tuner positions, frequencies and bias points used. Program outputs include power saturation curves, load-pull contours and overlay facilities for plotting load-pull contours with contours of constant gain and the locus of optimum load impedance over a frequency band.

Two sets of results for an NE9000 chip at 8V, 50 mA are shown in Figs. 9 and 10 for input powers of 0dBm and 12dBm (1dB compression point). These results illustrate how the near circular contours at small-signal levels become distorted as the drive level is increased into the non-linear region. The optimum region of the reflection coefficient plane for power matching is also clearly seen.

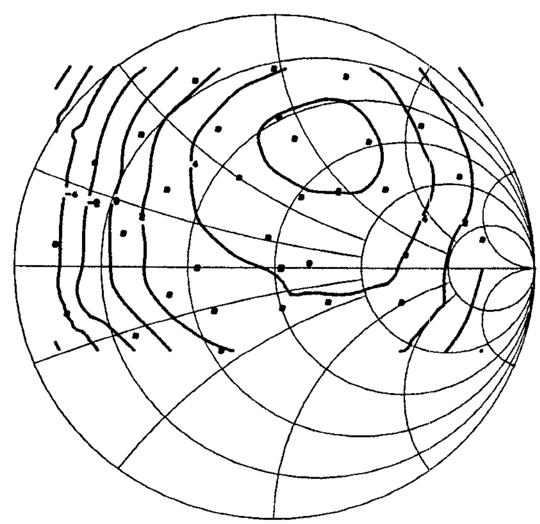


Fig. 9 Load-Pull Results at 0dBm Input Power at 10 GHz on Smith Chart Overlay.

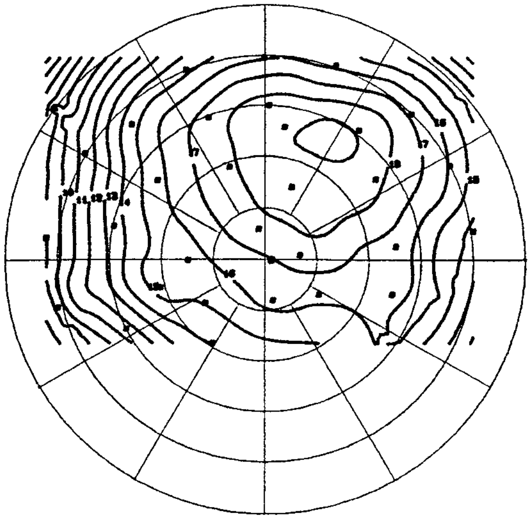


Fig. 10 Load-Pull Results at the 1dB Compression Point at 10 GHz on Polar Overlay.

Provision is made in the controlling software for the inclusion of an HP8510A network analyser (Fig. 11) and an automated input tuner which improves the system flexibility in two principal ways :

1) The positioning of the two directional couplers is such that, by combining the measured parameters "a" and "b" in different ways, both tuner and DUT non-linear measurements can be made simultaneously to a high degree of accuracy.

2) The system may be error corrected in a similar way to that described by Tucker and Bradley [6].

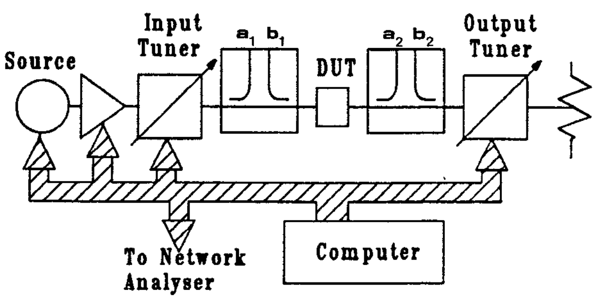


Fig. 11 Non-Linear Measurement System.

CONCLUSIONS

More complete information on the non-linear behaviour of GaAs MESFETs is the first and most fundamental step towards improving the power output and efficiency of solid-state power amplifiers. Two techniques for the comprehensive large-signal characterisation of GaAs MESFETs have been described.

A microwave tuner capable of producing very high reflection coefficients over 2-18 GHz has been used in a new automated load-pull system with excellent results.

The modelling may be expanded to incorporate the simulation of harmonic power and intermodulation distortion and the automated tuner may be used in any measurement system where a variable load impedance is required, such as, harmonic load-pull [7] and noise-figure characterisation.

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