High Frequency Sampling Technique for Microwave Active and Passive Device Characterisation

Dominic FitzPatrick, Tudor Williams
Dept of Electrical and Electronic Engineering, Cardiff School of Engineering, Cardiff University, The Parade, Cardiff, CF24 3AA, Wales, UK.
fitzpatrickdm1@cardiff.ac.uk, williamst5@cardiff.ac.uk

ABSTRACT - The most commonly used method for characterising microwave components is to measure the s-parameters of the device using a Vector Network Analyser. A problem with this method is that the VNAs are essentially narrow band down converters and cannot handle harmonic and distortion products. By directly measuring the incident and reflected waveforms on the device ports with wide bandwidth samplers and then processing these waveforms, not only can large signal s-parameters be extracted but also harmonic and compression characteristics. The flexibility offered by the direct access to the sampling heads allows for the construction of measurement systems which can, for example, directly measure the multi-port devices with all ports simultaneously excited (such as phased array elements).

This paper describes the basic waveform measurement system developed at Cardiff University, and then some of the applications to which this system has been applied including, small and large s-parameter measurement, DC-IV device characterisation, active load-pull including harmonic, and four port antenna match. The potential for 'waveform engineering' and accurate large signal device modelling is described.

I. Introduction

Fundamental to the measurement and characterisation of components at microwave frequencies are Scattering or S-parameters. There are many excellent texts on the subject[1] but in a brief summary; the s-parameter matrix is constructed from the signals output from the devices ports when one port is stimulated with a signal. The matrix takes the form $S_{1..i,1..j}$ with i denoting the measurement port and j the stimulated port (other ports terminated in the measurement impedance). Thus S parameters can be used to characterise multi-port devices. The measurement of one and two port devices has for a long time been easily accomplished by the use of Vector Network Analysers (VNAs), as shown in figure 1. The first of these measurement systems was introduced by Elliott Brothers in the 1950's[2], although it was the introduction of the Hewlett Packard 8409 which brought the measurements into general circulation. There has been little change in approach from that of the 1960's; indeed the main difference in the techniques employed has been in the use of increased computing power to handle the data. The original HP8409 automatic network analyser had a polar display on which

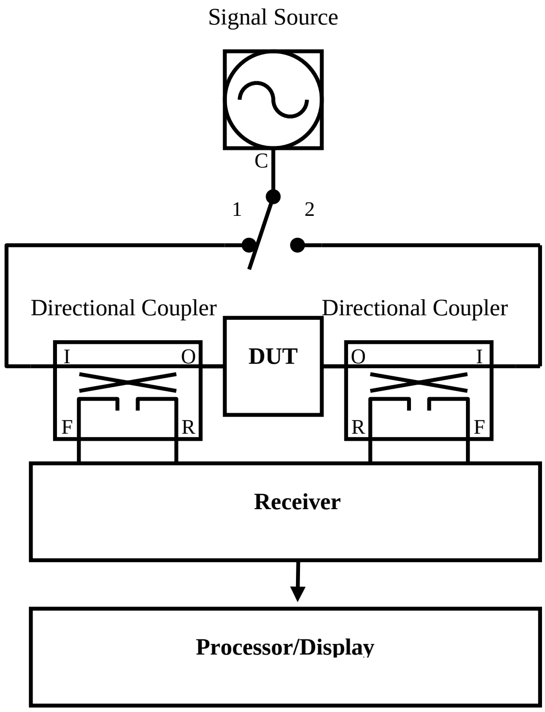


Figure 1. Basic VNA Block Diagram

the operator would, by adjusting the gain and phase of the system, setup the Smith chart display (a plastic overlay) so that it gave the correct impedances. The advent of the HP85 computer in 1980 brought low cost 'automation' to the measurement system. This was an important improvement, as in order to reduce the measurement uncertainties, an extensive calibration process is required. The systemic errors are caused by:

- Reflection and transmission tracking
- Source and load impedance mismatches
- Directivity and cross talk

Thus there are 6 error terms per port (which has lead to the common term twelve term error correction which refers to the common 2 port system). As these errors are constant with frequency they can be calibrated by the measurement of known standards, typically a short, open and match. Recent introduction of electronic calibration has eased and sped up the process.

VNA measurements are based in the frequency domain and thus are well suited to both the measurement and tuning of devices. A drawback comes however when the Devices Under Test (DUT) behave in a non-linear fashion. The receivers in the measurement system cannot distinguish between frequencies. VNA's can measure the gain compression in for example an amplifier, and cross calibration with a power meter can enable the instrument to display a power compression curve, however they cannot display the harmonic distortion. Thus the ability of VNAs to measure large signal conditions is limited.

A further restriction is in the measurement of multi-port devices. The most commonly available measurement systems are two ports. It is possible to measure multi-port devices and by mathematically manipulating the measurement to derive the multi-port s-parameters. However this relies on the device operation being the same when only 1 port is stimulated at a time. Methods have been developed, for example using frequency offsets for measuring mixers, but whilst these allow the conversion loss, match and delay of the devices to be measured, they cannot simultaneously do so on all ports or measure the breakthrough and mixer products.

II. SAMPLING MEASUREMENT TECHNIQUE

An alternative technique to the measurement of device characteristics including S–parameters has been developed at Cardiff University based upon a time domain measurement system. Fundamentally the S-parameters are still measured in the same way by sampling the forward and reflected waves using a direction coupler. The difference is that these sampled waves are measured in the time domain by a fast sampling scope, initially the Agilent Microwave Transition Analyser and now the Tektronix Digital Sampling Analyser. The captured waveforms can then be processed in software[*] to provide magnitude and phase information at each constituent frequency. Provided the waveforms captured are repetitive, the software can, through performing a Finite Fourier Transform (FFT) on a cycle, determine the magnitude and phase of each frequency in the spectrum. Thus not only can the linear characteristics based upon S-parameters be determined but also the non-linear and distortion effects.

[*] IGOR Pro, Wavemetrics Inc.

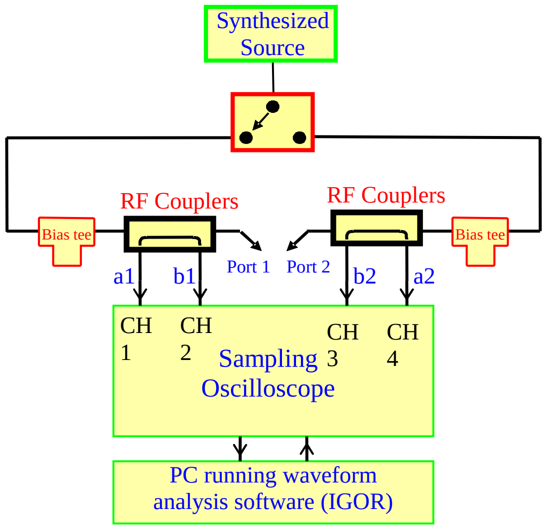


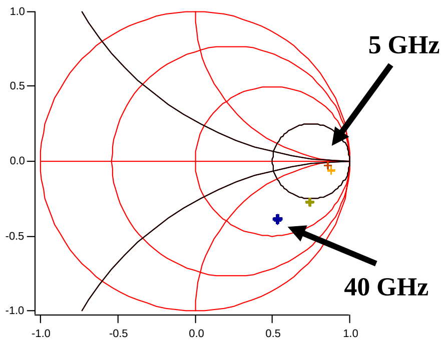
Figure 2, Basic Sampling System

The error correction procedure is the same as the 6 term per port correction applied with VNAs. The bandwidth limitations are defined by the frequency response of the RF couplers and the sampling heads of the oscilloscope. The latest system at Cardiff uses 1-40 GHz directional couplers and 60GHz sample heads (3dB bandwidth).

In order to improve the measurement accuracy averaging is used when acquiring the waveforms,

Figure 3, RF Coupler & Sampling Heads

this removes the unpredictable errors in the measurement system that cannot be removed by calibration. Figure 4 shows the repeatability of a 1 port reflection measurement between 5 and 40GHz and figures 5 and 6 show how the measurement accuracy varies with the number of averages. With 256 averages a phase accuracy of $< \pm 2°$ and a magnitude (of the reflection coefficient) of $< \pm 0.0025$ can be achieved. Above 500 averages the accuracy degrades



512 Measurements at each frequency

Figure 4, Reflection measurement

slightly due to phase drift between the signal source and the DSA (the two are locked via the 10MHz reference).

The dynamic range of the measurement system is ultimately limited by the maximum directivity, the ability to distinguish between a high reflection and the matched system impedance. Figure 7 shows that a directivity of >50dB can be achieved up to 40 GHz.

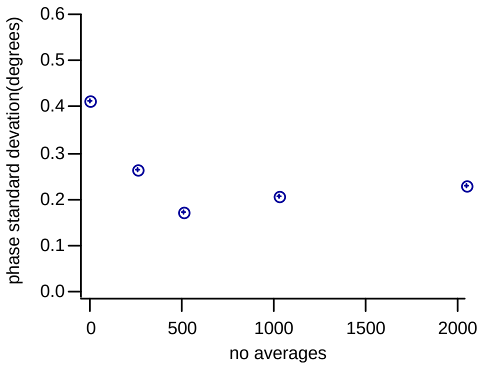


Figure 5, Phase variation vs. No. of averages

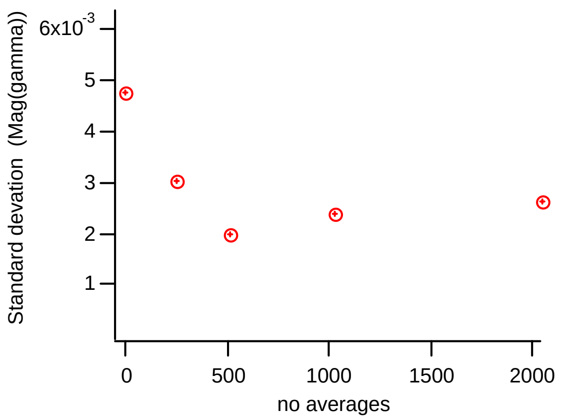


Figure 6, Magnitude variation vs. No. of averages

The measurement system is independent of power level up to the linear limits of the sample

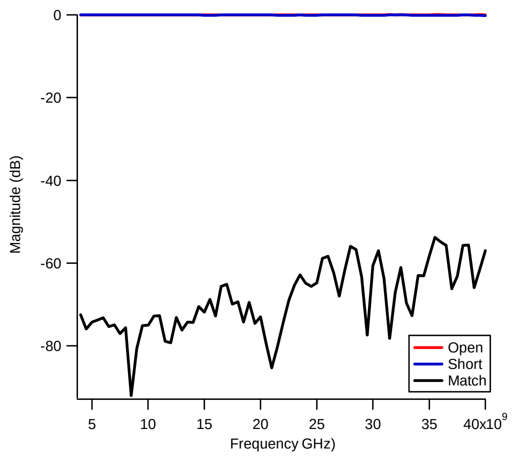


Figure 7, System Dynamic Range

heads. By fitting attenuators prior to the sampler the maximum signal level can be adjusted such that power levels up to the limits of the coaxial components can be measured[3]. Thus the system can be used to measure the effects of changing the power levels. This requires the addition of an extra switch which allows a power meter to be included in the system to calibrate the absolute power levels at the test ports. Figure 8 shows the

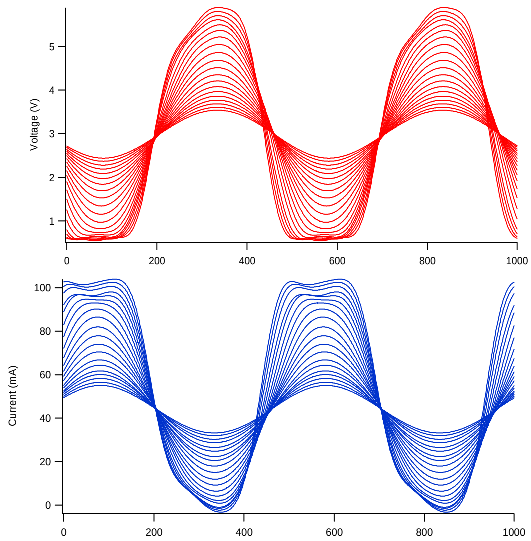


Figure 8, Output Voltage & Current Waveforms from transistor with input power

voltage and current waveforms measured on the output of a transistor with increasing power levels; and figure 9 shows the fundamental 1st and 2nd harmonic power levels in more conventional form.

Note the upper harmonic that can be measured is limited by the coupler response and the system noise floor.

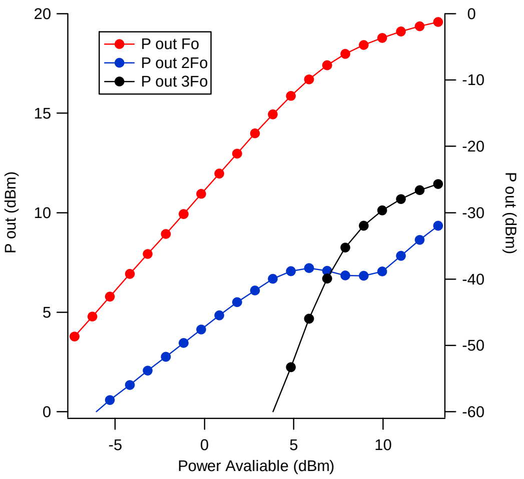


Figure 9, Fundamental, 1st & 2nd harmonic output power with increasing input power

III. Advanced Applications

The system was initially developed to characterise active devices, particularly microwave transistors. Hence the inclusion of bias tees on the test ports. Including controllable power supplies within the measurement system transistor bias curves can be plotted for the test device. Onto these can then be plotted the active RF load line.

Key to the development of high power microwave amplifiers is the use of load pull design techniques[4]. This method presents the appropriate impedance to the device (typically using mechanical tuners) and the output power is measured. Thus the optimum load impedance can be determined (for saturated power, linearity, efficiency, etc.), figure 10. In the Cardiff system the output from the device is passed through a circulator and dumped in a load. A new coherent signal of controlled phase and magnitude is passed through the circulator back to the device. Thus by adjusting this signal any load impedance across the Smith chart can be simulated. Further signals can be injected at the harmonics so that the fundamental and harmonic impedances can be separately controlled[5].

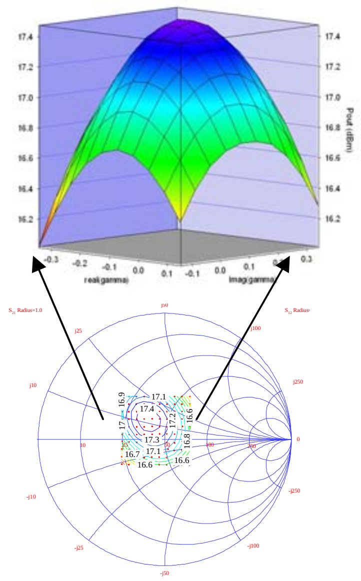


Figure 10, Load Pull Power Contours

As mentioned, multi-port devices which require more than one port to be stimulated simultaneously can pose particular problems. Using the high frequency sampling technique a 4 port antenna requiring all the ports to be driven in phase quadrature has been tested as shown in figure 11.

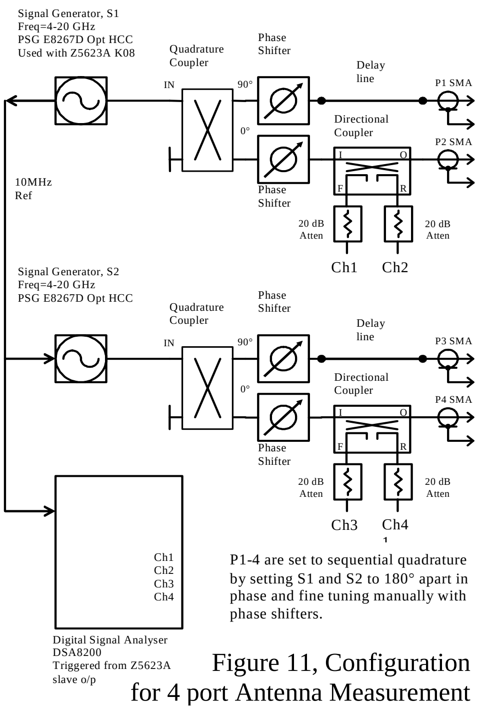


Figure 11, Configuration for 4 port Antenna Measurement

Due to the symmetry of the structure it was only necessary to measure 2 of the ports. To measure more ports 2 additional samplers (the DSA8200 can accommodate up to 8 samplers) and a directional coupler per port are required. To validate the measurements a single port was driven and measured on both the sampling system and an 8510 VNA, the measurements of amplitude and phase are shown in figure 12. The measurement of 2 ports with all 4 ports driven is shown in figure 13.

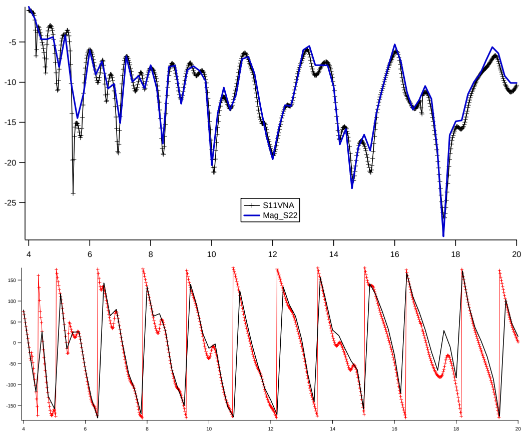


Figure 12, Comparison of Single Port Magnitude and Phase, VNA vs. Sampler

The positive return loss seen in figure 13 is due to the isolation of the antenna being low and the phasing from the other 3 ports being such that the return signal appears larger than the incident.

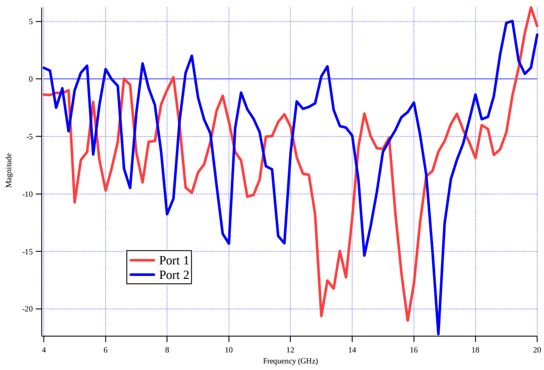


Figure 13, Antenna (anti-phase) port response

IV. Conclusion

An alternative S-parameter measurement system to the conventional VNA has been presented. The versatility of a time based system for characterising non-linear devices as well as the ability to configure the equipment to measure multi-port systems has been shown. As a development tool the system gives far greater insight into the intricate interactions between source and load impedance and device performance.

The high frequency sampling technique does not give the fast measurement speed that the standard VNA using swept frequency can deliver. Hence for production tuning and alignment of amplifiers and filters it is not well suited. However coupled with fundamental and harmonic active load pull; the ability to simulate source and load impedance can lead to very accurate characterisation of large signal devices.

[1] R. Anderson, HP Application note 95-1, original 1967.

[2] A.E.Bailey, “Microwave Measurements”, 2nd Edition, IET, 1989

[3] Z. Aboush, C. Jones, G. Knight, A. Sheikh, H. Lee, J. Lees, J. Benedikt, and P. J. Tasker, "High Power Active Harmonic Load-Pull.System for Characterization of High Power 100Watt Transistors," IEEE MTT-S Int. Microwave Symposium, 2005

[4] S. Cripps, “A Low-Budget Harmonic Load-pull System for High Power Amplifier Design”, ARMMS April 2006

[5] Benedikt, J; Gaddi, R; Tasker,P.J.; Goss,M; “High-Power time domain measurement systems 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