Radio Frequency and Microwave Measurements

# 2.1 Introduction

To characterise nonlinear behavioural models, the radio frequency (RF) response of a device to electromagnetic wave stimuli must be measured. When compared with DC (and low frequency) measurements, RF and microwave measurements present significant additional challenges.

For DC systems, it is desirable to transmit voltages through a circuit with minimal loss in magnitude. To achieve this effectively, components are typically designed with high input impedance and low output impedance. With RF systems, circuit components and interconnects can be of the order of a quarter-wavelength in length, and therefore signals must be treated as electromagnetic waves to account for different behaviour at these frequencies.

When a travelling wave encounters a discontinuity in impedance, such as a cable connector or on-wafer structure, some of the power in the wave is reflected. The amount of reflected power is proportional to the size of the impedance mismatch between each side of the discontinuity. Hence, for RF systems, the transmission of power is the focus of the circuit designer. The measurement of power flowing through a transmission line is complicated by three key factors. Firstly, because the waves are travelling, the instantaneous voltage at any point on the transmission line will vary between the peak-to-peak values of the wave. Secondly, there are waves travelling in both directions along the transmission line which must be measured separately. Finally, the power of the wave is a complex quantity which consists of both magnitude and phase.

To perform these measurements, a specialist instrument called a vector network analyser (VNA) can be used. In this chapter, the concepts and measurements associated with this instrument are introduced, which will be used later in the thesis to understand the uncertainty contributions from measurements to nonlinear behavioural models.

# 2.2 Electromagnetic Wave Parameters

# 2.2.1 Wave Definitions

To describe the power transmitted through a transmission line, several definitions are in use in industry and academia for either accuracy or convenience. To avoid confusion in this document, these will now be defined. Information presented in this section has been obtained from [1-5].

### **Travelling Waves**

Travelling waves represent a solution to Maxwell’s equations along a transmission line. They are physical and measurable via slotted line experiments or thru-reflect-line calibrations [6] (see Chapter X). Travelling waves are defined by the total transverse electric and magnetic fields Et and Mt of a single propagating mode at each frequency:

Et=c+e-yzet+c-e+yzet; Ht=c+e-yzht-c-e+yzht (1)

Where, following the notation of [5], et and ht are the unnormalized electric and magnetic fields of the modal solution of Maxwell’s equations in transmission line, y=a+ib is the complex propagation constant of the mode, z is the direction of propagation, and c+ and c- are complex quantities representing the unnormalized forward and backward amplitude of the mode, respectively.

### **Equivalent-Circuit Voltage and Current**

To represent travelling waves as equivalent low frequency circuit parameters such as voltage and current, a normalisation is chosen to derive a characteristic impedance for the transmission line. This normalisation takes the form

Et(z)=v(z)/v0\*et; Ht(z)=i(z)/i0\*ht (2)

Where v0 and i0 are normalisation constants that allow v and I to take units of root-mean-square voltage and current, respectively [5].

### 2.2.1.3 Pseudowaves

Equivalent voltages and currents cannot be used in lossy transmission lines where the electric and magnetic fields are out of phase. To account for this and provide a solution which can be used with conventional circuit design methodologies (e.g. Smith chart techniques [7]) and simulators, pseudowaves can be used. This representation is defined with a reference impedance, Zref, which can be chosen by the user, but is typically 50 Ohms in conventional measurements. The forward and backward pseudowaves a and b can be written as:

a(Zref)=|v0|/v0\*sqrt(Re(Z0))/2|Zref|\*(v+iZref); b(Zref)=|v0|/v0\*sqrt(Re(Z0))/2|Zref|\*(v-iZref) (3)

### 2.2.1.4 Power Waves

Finally, power waves are defined so that the relationship p = |a|2 - |b|2 is true for any reference impedance, where p is the power transmitted through the transmission line and a and b are the forward and backward power waves, respectively. They are defined as:

a(Zref)=(v+iZ)/(2(sqrt(Re(Zref)))); b(Zref)=(v-iZ)/(2(sqrt(Re(Zref)))) (4)

Data taken from Keysight NVNAs is presented in power wave format, with units of square-root Watts. To convert these values into decibels referenced to 1 milliwatt, the following formula is used:

P(dBm) = 10\*log(|P(sqrt(W))\*\*2) + 30

## 2.2.2 Derived Metrics and Figures of Merit

The behaviour of a linear microwave device can be completely defined by the complex ratio of electromagnetic waves which are scattered at each port to those which are incident at each port. The combination of these ratios constitutes the scattering parameters (s-parameters) of a microwave device and are used extensively in the design and measurement of microwave systems. The formal definition of the s-parameters for a two-port device is

S11=b1/a1|a2=0, S12=b1/a2|a1=0, S21=b2/a1|a2=0, S22=b2/a2|a1=0 (5)

Where both a and b can be expressed in either pseudowave or power wave representation. The term “scattered” can be interchanged with “transmitted” and “reflected” depending on if the scattered wave is output on a different port, or the same port, to the incident wave, respectively. A signal flow diagram is provided in Fig. 1 showing the relationship between equivalent-circuit voltage and current, pseudowaves/power waves and s-parameters for a two-port device.

Scattering parameters are often expressed in matrix form, where the column index is the scattered port, and the row index is the incident port. For a two-port device, the s-parameter matrix would be

S=[S11 S12;S21 S22]. (6)

The most interesting characteristic of a microwave device is often the effect which it has on a transmitted wave in the forward direction (S21 for a two-port device). If the device increases the magnitude of the incident signal this metric is called gain, otherwise it is called insertion loss. Typically gain is associated with active devices (those which are powered from an external source separate to the incident microwave signals) such as amplifiers and loss is associated with passive devices (those with no external power source) such as attenuators, splitters and mixers. The power gain (operating gain) and insertion loss relating to S21 can be calculated using

Power Gain = 10 log (|S21|2) dB, (7)

and

Insertion Loss = -10 log (|S21|2) dB, (8)

respectively.

Because optimal transmission in microwave systems require impedance matching between components, it is inevitable that some power will be reflected in a two-port device. Therefore, the match of a device is another important measurement, which is dependent on the voltage reflection coefficient (Gamma) of the device and can be related to the impedance of a source and load by

Gammaxx = Sxx = (ZL-ZS)/(ZL+ZS), (9)

where x is a port index.

A more thorough definition of voltage reflection coefficient for a two-port device includes any effect from the impedance seen at the other port, and for the case of input match is calculated as

Gamma11 = S11 + (S12S21GL)/(1-S22GL), (10)

where GS and GL are the voltage reflection coefficients of the source and load connected to the device.

For an active device such as an amplifier, it can be useful to consider the power reflected at the input when calculating the power gain of the device. The transducer gain of a device accounts for this potential loss of power at the input and provides a more portable metric which is not dependent on the impedance of the measurement setup. It is defined as

Gt = ((1-|GS|2)/|1-GinGS|2)|S21|2((1-|GL2|2)/|1-S22GL|2), (11)

where Gin is the input match of the device.

For nonlinear devices, which have

# 2.3 Vector Network Analysers

To measure the incident and scattered waves for a DUT and calculate the s-parameters as in (5), a vector network analyser (VNA) is typically used. The VNA is a quintessential piece of RF and microwave instrumentation and is found in most if not all such laboratories. Due to the challenging nature of measurements at these frequencies, it is a complicated instrument with many internal parts. This section explains how the VNA functions and the procedures behind its calibration. For a good history of VNA architecture and product development please see [Teppati Camb, Dunsmore Wiley].

## 2.3.1 Architecture

The reflectometer



Figure 8: A one-port simple reflectometer. a1 is the incident wave generated by the source, which is

admitted to the DUT while also being sampled by the directional coupler and sent to the reference

receiver via a1REF . The reflected wave, b1, is also sampled by another directional coupler and sent

to the test receiver as b1REF, with the remaining power dissipated at the matched source.

Designed in 1947 by Parzen and Yalow [x], the reflectometer was an invaluable tool for characterising transmission lines used in telecommunication systems. Shown in Figure x, the incident signal is generated by a swept signal source and passes through the directional coupler before arriving at the DUT. The voltage reflection coefficient of the DUT will cause an amount of incident power to be reflected, which passes back through the coupler before being absorbed by the source (which has very low reflection). The directional couplers allow the waves travelling between the source and the DUT to be sampled by complex receivers, filtering the two waves by their direction of travel thus allowing the incident and scattered waves to be separated for measurement. The limitation of a single reflectometer is that it can only measure waves at one port of a DUT, therefore preventing transmission measurements.

Double reflectometer

By adding a second reflectometer and synchronising the stimuli and measurements, it is possible to measure all s-parameters of a two-port device. This is the basic internal structure of a VNA. Many designs use an economical single source which is switched between both ports, although for versatility there are instruments available with two sources. These more versatile units often expose more connections between internal components (e.g. the couplers and receivers) to allow the user to perform non-standard measurements or to add attenuation or preamplification for extreme stimulus powers.

Modern VNAs also offer the option of measuring more than two ports, which are referred to as “multi-port” measurements. Several manufacturers offer four-port instruments which include four reflectometers (with usually two sources), although with external switching networks it is possible to expand this up to 48 ports [http://www.microwavejournal.com/articles/21785-vector-network-analysis-with-up-to-48-ports].

The basic block diagram of a modern two-port double-reflectometer VNA is shown in Fig. 9. To measure both stimulus conditions for the two-port S-parameter equations in (5), the sources alternate between delivering power and acting as a load for each measurement. As the source is swept the a and b waves for all ports are measured against frequency, from which the VNA software calculates the S-parameters. The receivers sampling the incident waves are known as the reference receivers and those sampling the scattered waves are called measurement receivers.

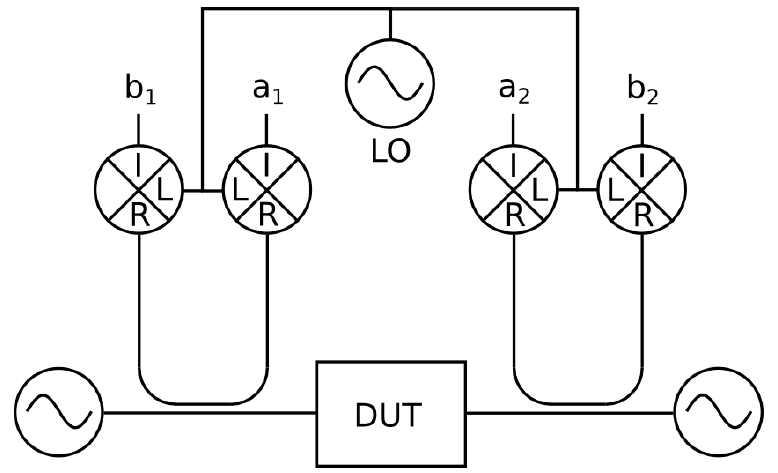


Figure 9: A modern two-source mixer-based VNA, which employs heterodyning to allow measurements at microwave frequencies. Two directional couplers are located between each source and the DUT and are connected back to back. These sample waves travelling in both directions and are connected to mixers which downconvert the microwave frequencies (R) into intermediate frequencies (I) which can be sampled by the complex receivers. The shared local oscillator (LO) feeding the mixers preserves phase coherence between the receivers. This configuration is known as a two-port double-reflectometer VNA. Figure adapted by author from [10].

To perform S-parameter measurements using a VNA, the user must set both the frequency span and number of frequency points. They may also change settings of intermediate frequency bandwidth (IFBW) and numerical averaging, both of which reduce measurement noise by applying digital filtering but can consequently increase acquisition time. The user will then perform a calibration, which corrects for any response present in the measurement setup that is not caused by the DUT. When the system is calibrated physical ‘measurement planes’ are defined, where only effects of the signal path on the DUT side of the planes are incorporated in the measurement results. This is illustrated in Fig. 10. Once this step is complete, the VNA is ready for use. However, it is good practice to first check that calibration was successful by measuring some known devices (verification), or to use techniques such as ripple extraction (discussed in Chapter 4) to measure the residual uncertainty. This process characterises remaining error which the calibration failed to correct.

## 2.3.2 Error Models

One-port model

Two-port models

X terms etc

## 2.3.3 Calibration

Three known loads

Sliding load

Self-calibrations

Thru-reflect-line

TRL Variants

# 2.4 Large Signal Vector Network Analysers

Previously avoided errors now present – need absolute wave measurements

## 2.4.1 Architectures

## 2.4.2 Absolute 8-Term Error Model

## 2.4.3 Power Meter Calibration

## 2.4.4 Phase References

# 2.5 Conclusions

# References

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