Vector Network Analyzer

1 Objectives

- To get acquainted with a vector network analyzer (VNA).
- To learn how to characterize networks at high frequencies.
- To learn how to measure scattering parameters.
- To explore the characteristics of microwave devices.

2 Background Theory

2.1 Transmission Basics

Electronic circuits which operate at high frequencies present some unique challenges for a proper characterization. At high frequencies the wavelengths of operation become similar in dimension to the physical properties of circuit elements. This results in circuit performance that is distributed in nature rather than describing the voltage and current at a specific circuit node. It is more appropriate to describe how waves in a transmission medium respond to a component in their path. Network analyzers are a class of instruments that have been developed to characterize Radio Frequency (RF) components accurately and efficiently as a function of frequency. Network analysis is the process of creating a data model of the transfer and/or impedance characteristics of a linear network through stimulus-response testing over the frequency range of interest. At frequencies above 1MHz, lumped elements actually become circuit consisting of the basic elements plus parasitic elements like stray capacitance, lead inductance and unknown absorptive losses. Since parasitic depend on the individual device and its construction, they are almost hard to predict. Above 1 GHz, component geometries are comparable to a signal wavelength, intensifying the variance in circuit behavior due to device construction. Network analysis is generally limited to the definition of linear networks. Since linearity constrains networks stimulated by a sine wave to produce a sine-wave output, sine-wave testing is an ideal method for characterizing magnitude and phase response as a function of frequency. This chapter discusses the key parameters used to characterize RF components, the types of network analyzer techniques used to make measurements and the considerations to be made in obtaining the most accurate results.

2.2 Component Characteristics

RF (frequencies less than 3 GHz) or microwave (frequencies in the 3 to 30 GHz range) energy can be likened to a light wave. Incident energy on a Device Under Test (DUT) (for example, a lens) is either reflected from or transmitted through the device (see Figure 1). By measuring the amplitude ratios and phase differences between the two waves it is possible to characterize the reflection (impedance) and transmission (gain) characteristics of the device.

2.3 Reflection and Transmission

There are many terms used to describe these characteristics. Some use only magnitude information (scalar) and others include both magnitude and phase information (vector). If an incident voltage and current waves on a device are denoted by $V_{incient}$, $I_{incident}$, the ratio of $V_{incient}$ and $I_{incident}$ is called the characteristic impedance Z_0, and a device terminating a transmission system has an impedance called a load impedance Z_L, then the device characteristics can be defined by:

Reflection terms:

$$\Gamma = \frac{V_{reflect}}{V_{incident}} = \frac{Z_L - Z_0}{Z_L + Z_0}, \ -1 < \Gamma < 1.$$

where Γ : reflection coefficient

$V_{reflect}$, $V_{incident}$: reflected, incident waves on DUT

Z_L, Z_0: load, characteristic impedances

$$\text{Return loss (dB)} = -20\log_{10}|\Gamma| = -20\log_{10}\rho$$

Standing wave ratio: $\text{SWR} = \dfrac{1+\rho}{1-\rho}$

Transmission terms:

Transmisson coefficient: $\tau = \dfrac{V_{trans}}{V_{incident}}$

Insertion loss(dB) = $20\log_{10}|\tau|$, Gain(dB) = $-20\log_{10}|\tau|$

V_{trans}: transmitted wave on DUT

2.4 Scattering (S) Parameters

Many component measurements are two-port networks, such as amplifiers, filters, cables and antennas. These component characteristics are typically used to determine how a particular device would contribute as a part of a more complex system. To provide a method that models and analyzes a full two ports device in the RF environment, scattering parameters (S parameters) are defined as follows:

$$S_{ij} = \left.\frac{b_i}{a_j}\right|_{a_k=0,\forall k\neq j}$$

where a_j denotes the wave *entering* the j^{th} port, and b_i denote the wave *exiting* the i^{th} port. Once all S parameters are obtained, the relationship between the incoming and outgoing waves can be written in terms of scattering matrix, [**S**], as:

$[\mathbf{b}] = [\mathbf{S}][\mathbf{a}]$, where [**a**],[**b**] are incoming, outgoing wave vectors, respectively.

This is a characterization technique similar to a lower-frequency Z or Y modeling, except that it uses incident, transmitted and reflected waves to characterize the input and output ports of a device as opposed to using voltage and current terms which are impossible to measure at high frequencies. The S parameter terms are related to other parameters with certain conditions. For instance, S_{11} is equivalent to a device input reflection coefficient under the condition the device has a perfect Z_0 match on its output. S parameter characterization of devices plays a key role in the ability of measuring, modeling and designing complex systems with multiple components. By definition, S parameters can be measured with a network analyzer.

3 Vector Network Analyzer

A network analyzer measurement system can be set of four major parts: a signal source providing the incident signal, signal separation devices to separate the incident, reflected and transmitted signals, a receiver to convert the microwave signals to a lower Intermediate Frequency (IF) signals, a signal processor and a display section to process the IF signals and display detected information, as shown in Figure 1.

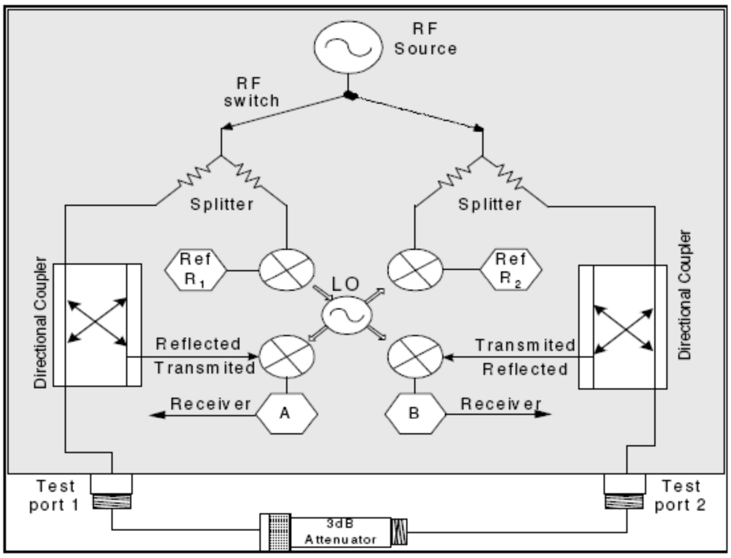

Figure 1: The major elements of a network analyzer.

The receiver performs the full S parameters which defined as:

$$S_{11} = \frac{\text{reflected wave}}{\text{incident wave}} = \frac{A}{R_1};\ S_{22} = \frac{\text{reflected backward wave}}{\text{incident backward wave}} = \frac{B}{R_2};$$

$$S_{21} = \frac{\text{transmitted wave}}{\text{incident wave}} = \frac{B}{R_1};\; S_{12} = \frac{\text{transmitted backward wave}}{\text{incident backward wave}} = \frac{A}{R_2}.$$

3.1 Signal Source

The signal source (RF or microwave) produces the incident signal used to stimulate the Device Under Test (DUT). The DUT responds by reflecting part of the incident energy and transmitting the remaining part. By sweeping the frequency of the source the frequency response of the device can be determined. Frequency range, frequency stability, signal purity, output power level and level control are factors which may affect the accuracy of a measurement. The source used for the network analyzer measurements, is a synthesizer, which characterized by stable amplitude frequency and a high frequency resolution (less than 100 Hz at microwave range).

3.2 Signal Separation

The next step in the measurement process is to separate the incident, reflected and transmitted signals. Once separated, their individual magnitude and/or phase differences can be measured. This can be accomplished through the use of wideband directional couplers, bridges or power splitters. A directional coupler is a device that consists of two coupled transmission lines that are configured to couple energy to an auxiliary port if it goes through the main port in one direction and not in the opposite direction. Directional couplers usually have relatively low loss in the mainline path and thus present little loss to the incident power. In a directional coupler structure (see Figure 1) the coupled arm samples a signal traveling in one direction only. The coupled signal is at a reduced level and the relative amount of reduced level is called the coupling factor. For instance a -20dB directional coupler means that the coupled port power level is 20 dB below the input, which is equivalent to 1% of the incident power. The remaining 99% travel through the main arm. The other key characteristic of a directional coupler is directivity. Directivity is defined as the difference between a signal detected in the forward direction and a signal detected in the reverse direction (isolation between the forward and reverse signals). A typical directional coupler will work over several octaves with 30 dB directivity. The two-resistor power splitter (see Figure 1) is used to sample either the incident signal or the transmitted signal. The input signal is split equally between the two arms, with the output signal (power) from each arm being 6dB below the input (power). A primary application of the power splitter is for producing a measurement with a very good source match. If one side of the splitter output is taken to a reference detector and the other side goes through a DUT to a transmission detector, a ratio display of transmitted to incident has the effect of making the resistor in the power splitter determine the equivalent source match of the measurement. Power splitters are very broadband, have excellent frequency response and present a good match at the DUT input. Separation of the incident and reflected signals can be accomplished using either a dual directional coupler or a splitter.

3.3 Receiver

The receiver provides the means of converting and detecting the RF or microwave signals to a lower IF or DC signals. There are basically two receiver techniques used in network analysis (see Figure 2).

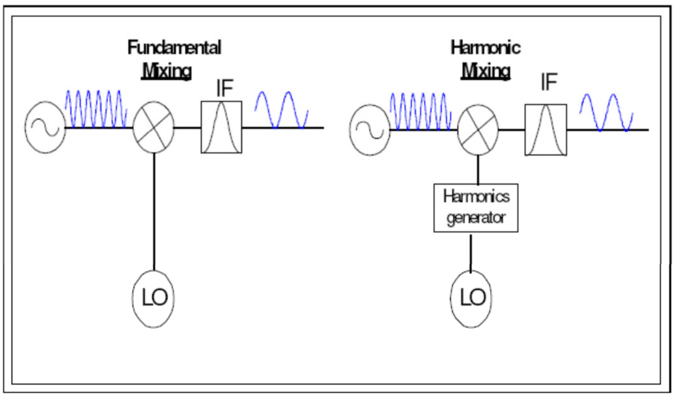

Figure 2: Fundamental and harmonics mixing receiver

The receivers are broadband tuned receivers that use either a fundamental mixing or harmonic mixing input structure to convert an RF signal to a lower-frequency IF signal. The tuned receivers provide a narrowband-pass Intermediate-Frequency (IF) filter to reject spurious signals and minimized the noise floor of the receiver. The vector measurement systems (tuned receivers) have the highest dynamic ranges, are less suspect from harmonic and spurious responses, they can measure phase relationships of input signals and provide the ability to make complex calibrations that lead to more accurate measurements.

3.4 Analyzing and Display

Once the RF signals have been detected, the network analyzer must process the detected signals and display the measured values. Network analyzers are multichannel receivers utilizing a reference channel and at least one test channel. Absolute signal levels in the channels, relative signal levels (ratios) between the channels, or relative phase difference between channels can be measured by the network analyzer. Relative ratio measurements are usually made in dB, which is the log ratio of an unknown signal (test channel) with a chosen reference signal (reference channel). For example, 0 dB implies that the two signal levels have a ratio of unity, while +/-20 dB implies a 10: 1 voltage ratio between two signals. All network analyzer phase measurements are relative measurements, with the reference channel signal considered to have zero phase. The analyzer then measures the phase difference of the test channel with respect to the reference channel.

4 Operator Calibration

4.1 General

All real measurement systems are affected by three types of measurement errors:
* Systematic errors.
* Random errors.
* Drift errors.

Calibration is a set of operations which improve measurement accuracy by means of compensation for systematic measurement errors (repeatable measurement variation).

4.2 Systematic Errors

Systematic errors are caused by non-perfect devices. We assume that these errors do not change over time, therefore they can be characterized and mathematically removed during the calibration process. Systematic errors are related to (see Figure 3):
* Frequency response errors during transmission or reflection measurements.
* Signal leakage within or between components of the system, directivity and crosstalk errors.
* Impedance mismatch due to unequal input and output impedance of the DUT and the network analyzer.

Manufacturers assume that the operator takes care of random errors that are caused by connectors repeatability and by the cables.

4.3 Random Errors

Random errors vary randomly as a function of time (amplitude and phase). Since there is no way to predict them, they cannot be removed. Sources of random errors are:
* Internal noise of the instrument.
* Connector and adapters.
* Cables.

As it mention above it is impossible to remove these errors, but it is possible to minimize their effects by:

Internal noise:
* Increasing source power.
* Narrowing IF filter.
* Using trace averaging.

Connectors and adapter care Connector repeatability is a source of random measurement errors. For all connectors and adapters, you have to frequently do the following:
* Inspect all the connectors for damage or visual defect.
* Clean the connectors.
* Use high quality, well known and preserved connectors and adapters.

Cables Care Coaxial cables connecting the DUT to the analyzer. Cables can cause random errors, you have to frequently do the following:
* Inspect for unusual lossy cables.
* Inspect for damage cable connectors.
* Inspect for cables which change response when flexing (this may indicate for damage near the connectors).
It is strongly recommended to use known high quality and well preserved cables, if high accuracy measurement is needed.

4.4 Drift Errors
Drift errors occur when the test results of measurements change, after calibration has been performed. They are primary caused by temperature variation. These errors can be minimized by frequently calibration or use the equipment in a controlled temperature range, such as 25±5°C.

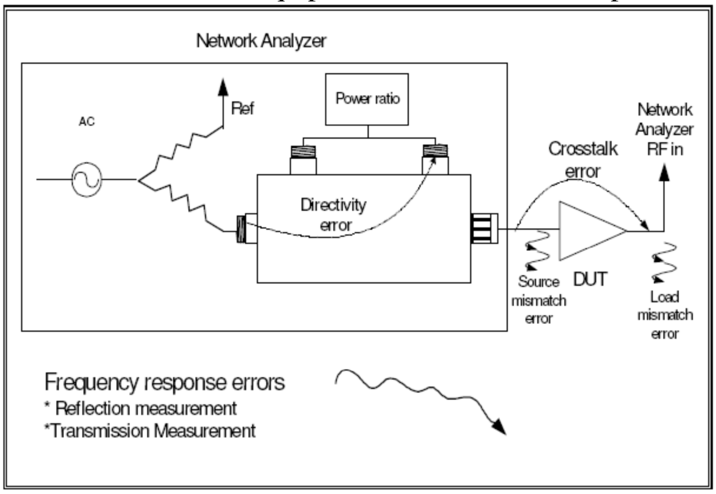

Figure 3: Error correction due to calibration

5 Measurements

5.1 Calibration

Before performing measurements, calibration is required to improve the accuracy of the measurements. The one-path 2-port calibration[1] provides directivity, source match, load match, isolation and frequency response vector error correction, in only forward direction for transmission and reflection measurements of two-port devices. This calibration provides the best magnitude and phase measurement accuracy for both transmission and reflection measurements of two-port devices.
One-path 2-port calibration procedure (See figure 4 and also the manual for the reference)
1. Turn on the Network Analyzer.
2. Press Cal.
3. Click Cal Kit to select Calibration Kit.
4. Click Calibrate.
5. Click One Path 2-Port Cal.
6. Click Select Port to select a test port (and corresponding S parameter) on which 1-port calibration will be performed.
7. Connect an OPEN calibration standard to the selected test port (connector to which the DUT is to be connected).
8. Click Open to start the calibration measurement. Also observe the S_{11} on the display.
9. Connect a SHORT calibration standard to the selected test port (connector to which the DUT is to be connected).
10. Click Short to start the calibration measurement. Also observe the S_{11} on the display.

[1] For both forward and reverse directions, “the full 2-port calibration” is required.

11. Connect a LOAD calibration standard to the selected test port (connector to which the DUT is to be connected). Click Load to start the calibration. Also observe the S_{11} on the display.
12. Make a between the selected test ports (between the connectors to which the DUT will be connected).
13. Click Thru to start the calibration measurement.
14. Click Done to terminate the One Path 2-Port Calibration calibration process. Upon pressing this key, calibration coefficients will be calculated and saved. The error correction function will also be automatically VNAbled.

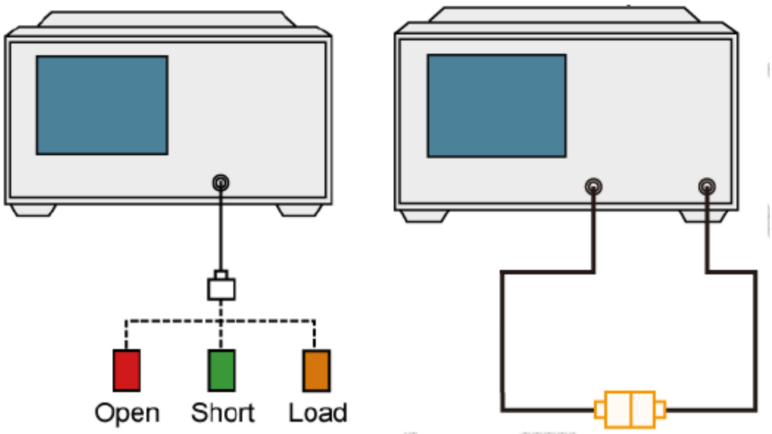

Figure 4: One-path 2-port calibration

5.2 S-parameter Measurements

1. Connect the antenna (1-port device) to port 1, and measure both magnitude and phase of S_{11}. Record the frequency response and find the 3-dB bandwidth.
2. Connect the bandpass filter (2-port device) between port 1 and port 2, and measure both magnitude and phase of both S_{11} and S_{21}. Record the frequency response and find the 3-dB bandwidth.
3. Make sure that the attenuation is set to be 0 dB, then connect the attenuator (2-port device) between port 1 and port 2, and measure both magnitude and phase of both S_{11} and S_{21}. Record the frequency response. Then change the attenuation to 10 dB, 20 dB, and 30 dB, respectively, and record the frequency response for each case.
4. Connect the coaxial cable (RG58) between port 1 and port 2, and measure both magnitude and phase of both S_{11} and S_{21} at 10,20,30,50,100,200,300,500,1000,1300 MHz to be used in characteristic impedance (Z_0) and propagation constant (γ) analyses.

NOTE Change frequency range and scale for proper measurements.

6 Final Report

1. Show all the measurement results. Also convert dB unit to linear magnitude scale.

2. Find the characteristic impedance and propagation constant from the measurement results and compare them with the data given in the data sheet file (rg58.pdf).

3. Summarize what you have found from the measurements.

7 Postlab Questions

1. Explain how to use this vector network analyzer to measure S-parameters of a device with more than 2 ports.

2. Explain how to obtain the parameters R, L, G, C of the RG58 coaxial cable.