

## **7 VECTOR NETWORK ANALYZER**

### **1. Introduction**

A vector network analyzer (VNA) is an instrument that allows precise and automatized measurements of the  $S$ -parameters vs. frequency and various terms that can be derived from the  $S$ -parameters (return loss, insertion loss, phase delay, group delay, device bandwidth...). Therefore, it enables straightforward characterisation of various microwave devices such as filters, cables, waveguides, amplifiers, resonators, antennas, etc. Moreover, as both the magnitude and phase in the frequency domain are known, it is possible to convert these results into the time domain using the Fourier transform. Often the transformation can be performed directly in the instrument and in real-time, so it can operate nearly as a TDR. In addition, VNAs typically allow power sweeps which is very useful for the characterisation of nonlinear devices. All these functionalities make the VNA clearly the most utilised instrument in microwave electronics.

### **2. VNA fundamentals**

#### **2.1. Block diagram**

Fig. 7.1 shows a simplified block diagram of a 2-port VNA [1]. A microwave signal (stimulus) necessary for the  $S$ -parameter measurement is delivered by the internal source (synthesizer) operating in a frequency band chosen by the operator (and limited by the VNA specification). The divider splits the signal into the reference signal (R) and the signal to be delivered to the device under test (DUT). The path of the latter signal comprises the attenuator allowing the power level adjustment at the test ports, and the electronic switch allowing the choice of the direction of measurement (forward:  $S_{11}$  and  $S_{21}$ ; reverse:  $S_{22}$  and  $S_{12}$ ). The directional couplers enable signal separation. For instance, in the forward direction, the directional coupler on the left-hand side provides the reflected signal (A), while the directional coupler on the right-hand side provides the transmitted signal (B). It is the opposite for the reverse measurement direction. The three microwave signals (R, A, B) are sampled and further processed, but in essence  $S_{11} = A/R$  and  $S_{21} = B/R$  (for the forward direction).

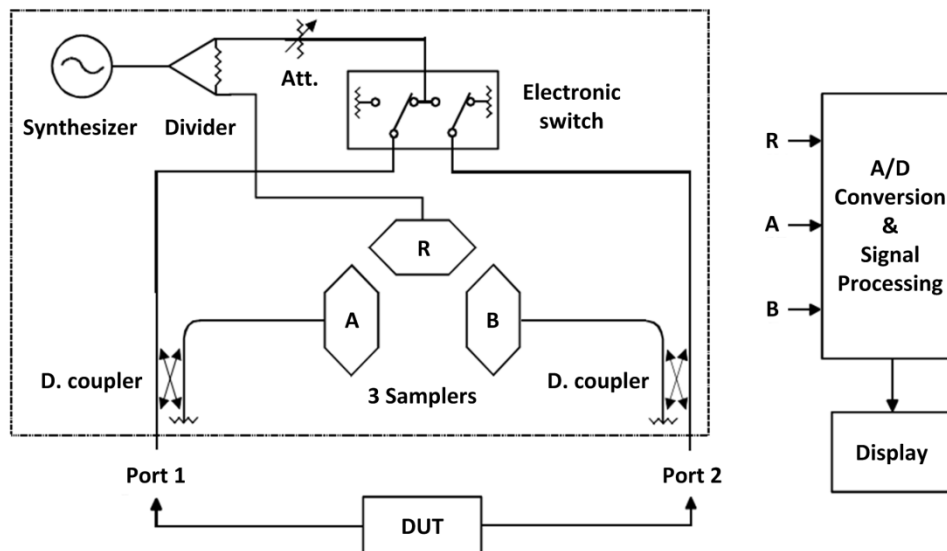


Fig. 7.1 Simplified VNA block diagram.

## 2.2. Calibration

The three basic types of measurement errors are: systematic, random, and drift. Systematic errors are due to imperfections in the VNA. They are repeatable and essentially time-invariant, so they can be characterised during the calibration process and mathematically removed from the raw measurements. Random errors are unpredictable errors caused by the noise and repeatability of the electronic switch and test port connectors. They cannot be removed by calibration, but can be minimised by using high-quality microwave components for the VNA fabrication. Drift errors are due to the VNA performance changing after a calibration has been done. Drift is primarily caused by temperature variation and it can be removed by a new calibration. Therefore, the timeframe over which a calibration remains valid is dependent on the environment in which one performs measurements.

The major systematic errors associated with network measurements are shown in Fig. 7.2. The error terms related to signal leakage are directivity and crosstalk. The error terms related to signal reflections are source and load mismatch. The final class of error terms are related to frequency response of the receivers, and are called reflection and transmission tracking.

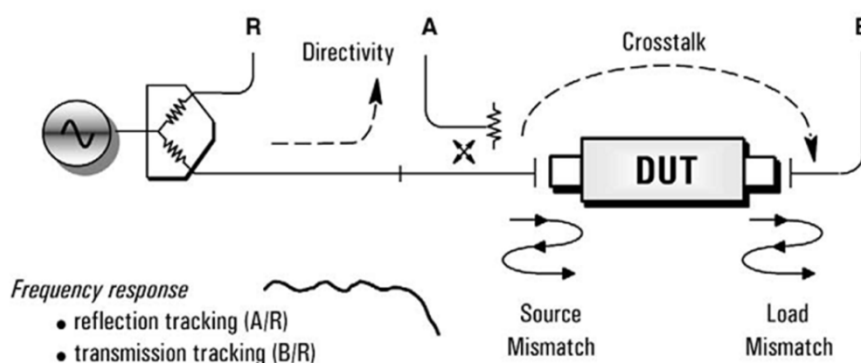


Fig. 7.2 Systematic measurement errors.

In order to account for the systematic errors, it is possible to perform a response correction (normalisation) and a vector correction. The response correction is essentially just a normalised measurement where a reference trace (e.g. the trace obtained for the two VNA test ports directly connected together, i.e. thru) is stored in the VNA memory, and subsequent measurement data is divided by this memory trace. Effectively, this process only removes the tracking terms (reflection or transmission). The vector correction is more complicated but it can remove all the error terms mentioned above. It requires calibration standards, i.e. very accurately defined devices whose exact electrical parameters are permanently written in the VNA memory and measuring of which contributes to the error terms determination.

In the case of the one port model (applicable for single port DUTs and generally when only the reflection is to be measured), the error terms to be corrected are  $E_D$  – directivity,  $E_S$  – source mismatch, and  $E_{RT}$  – reflection tracking, as illustrated in Fig. 7.3. It is clear that in order to obtain the actual (desired)  $S_{11A}$  from the measured (raw)  $S_{11M}$ , the three error terms must be known. They are calculated from the measurement results of the standards in the calibration process. For instance, the  $E_D$  term is directly obtained by connecting the matched load standard ( $S_{11A, load} = 0$ ) because in this case  $S_{11M, load} = E_D$ . Connecting two additional standards (short and open) will create two additional equations and the eventual determination of the remaining two error terms. These calculations are done internally in the VNA and the instrument typically displays the corrected results.

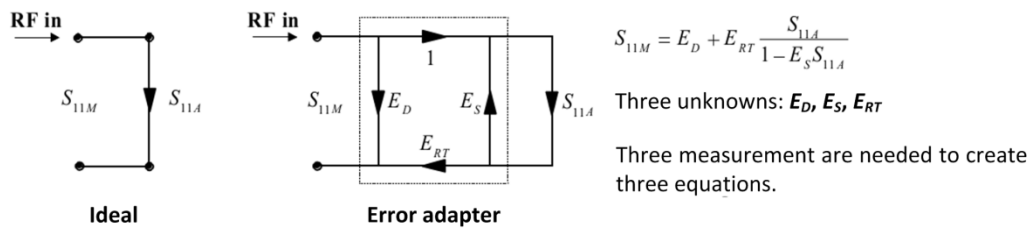


Fig. 7.3 One port calibration model.

For a two port measurement the model becomes more complicated, as now we have six error terms instead of three (see Fig. 7.4, the additional error terms are  $E_L$  – load mismatch,  $E_{TT}$  – transmission tracking, and  $E_x$  – crosstalk). Moreover, the six error terms are different for the forward and reverse direction. Therefore, there are twelve unknowns in total which is why the full 2-port calibration in principle requires twelve measurements. Typically, all the twelve measurements are performed by connecting the four known standards: short, open, load, and thru (which defines the typical name for this type of calibration: SOLT).

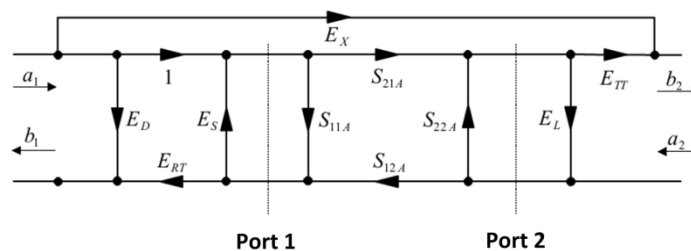


Fig. 7.4 Two port calibration model.

Fig. 7.5 shows the insertion loss of a filter and illustrates different levels of error correction. The uncorrected trace exhibits considerable loss and ripple. According to this result, the filter quality seems to be poor. However, this is only because this result is the combination of the filter's response and that of the test system. The response calibration already results in a significant accuracy improvement. Here tracking error terms are removed, which also compensates for the losses caused by the test cables. However, the result is still rather unreliable because most of the error terms remain uncorrected. For instance, the ripple in the pass-band is clearly observed (even goes above 0 dB, which we know is impossible for any passive device). This ripple is not a consequence of the filter design but stems from the interaction between the system's source and load match (as they are not corrected). Finally, the measurement after a full two-port calibration is the most accurate of the three measurements shown. Here we can see the filter's pass-band response with virtually no influence from the test system. Now we can be sure that the filter pass-band response is actually very good, with only  $\pm 0.1$  dB variation around its central frequency.

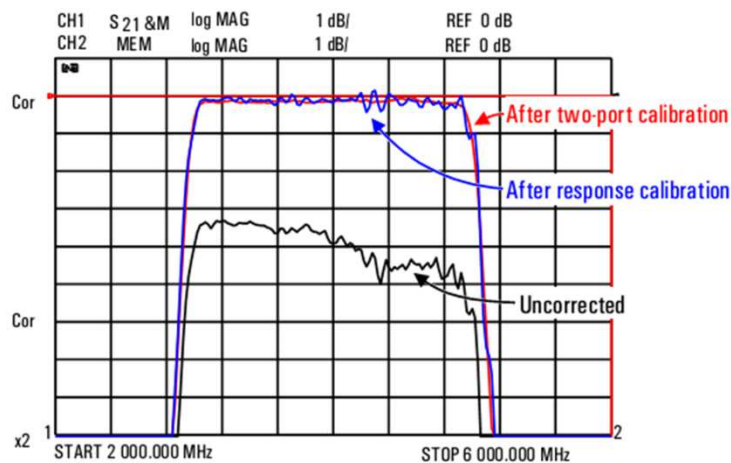


Fig. 7.5 Different levels of calibration.

While it is clear that the full two port calibration based on mechanical SOLT standards assures accurate results, it should be noticed that the calibration process requires many connections and disconnections. Therefore, the calibration quality depends to a certain extent on the operator skill. Furthermore, the properties of the mechanical standards deteriorate with time due to the connector wear and possible (often hardly visible) damage, which undermines the quality of calibration. One alternative to the SOLT calibration is electronic calibration (E-cal). The E-cal is a fully automatized calibration procedure where the operator is only required to connect the proper E-cal module and set the parameters such as the frequency range, number of measurement points, etc. The E-cal module essentially contains several pin-diode switches which shunt a transmission line that connects the two ports of the module. Electronic switching of the pin-diodes results in several repeatable impedance states. Measuring the E-cal module response in these states (that were previously accurately characterised in the factory and permanently written in the VNA memory) provides the results needed to obtain the twelve error terms, similarly as in the SOLT calibration. Because multiple connections are omitted (only one connection is needed, in fact), the E-cal makes the full two port calibration fast, easy, and far less prone to operator errors. In addition, the typical achieved accuracy is better than that of the SOLT calibration.

### 3. Experiments

#### 3.1. Utilised equipment

- Vector network analyzer *HP 8720D*
- SOLT calibration kit PC 3.5 mm *HP 85052A*
- E-cal control unit *HP 85060C*
- E-cal module 1 GHz – 26.5 GHz *HP 85062-60006*
- E-cal module 30 kHz – 6 GHz *HP 85093-60003*
- Tunable bandpass filter K&L 50140
- Chebychev bandpass filter
- Quadrature hybrid
- Cavity with various dielectric samples

#### 3.2. Important remarks

A VNA is a highly precise, however very sensitive and very expensive piece of equipment. The same observation can be made for the calibration kits. Therefore, a great care needs to be taken when manipulating them. In particular, the following points must be strictly obeyed:

1. The instrument is very sensitive to electrostatic discharge. Therefore, always be grounded during manipulation. Effective grounding is realised by wearing a wrist strap connected to the ground socket of the VNA.
2. While making a connection, always turn only the connector nut (typically located on the male connector) while simultaneously supporting the other half of the connection (and preventing it from any rotation) with an open-end wrench.
3. Never use excessive force when screwing the connectors (particularly calibration standards). In order to ensure the optimal and repeatable amount of force, use the torque wrench for final connections.

#### 3.3. Measurements

Convention used in this document: `HARD KEY`, `Soft key`.

##### 3.3.1. VNA calibration

Turn on the E-cal control unit and then the VNA. In general, the equipment needs to warm up for 20 min in order to reach a satisfying level of stability. The E-cal modules will not work until a stationary temperature is reached.

We will perform and store the following three calibrations:

1. 2 – 4 GHz with 401 points (classic SOLT calibration);
2. 3 – 4 GHz with 801 points (E-cal);
3. 2.3 – 2.5 GHz with 801 points (E-cal);

In all the three cases, we will work with the VNA in the 'step' mode, where the synthesiser is locked at each frequency point.

### VNA preparation

Press PRESET (green button). This puts the VNA in a predefined state with default settings (this button is frequently found on various instruments). Select the stepped sweep: MENU/Sweep type menu/Step swp: ON. Select the number of points: MENU/Number of points: 401. Select the frequency band: START/2G; STOP/4G. Now the instrument is prepared for Calibration 1.

### Calibration 1 (SOLT)

Select the calibration kit: CAL/Cal kit/3.5 mmD. Start the calibration procedure: CAL/Calibrate menu/Full 2-port. Connect the calibration standards according to the instructions on the VNA display.

*Note: The crosstalk (isolation) error term needs to be determined only when a very large dynamic range is required. As we do not deal with high-isolation devices (e.g. switches in open state) or high-dynamic range devices (e.g. some filter stop-bands) in this laboratory session, we will omit isolation during this calibration.*

Once the calibration is done, it is wise to store the correction data (cal set) in the internal memory. The name of the file is by default REGnn, but it can be edited: SAVE-RECALL/File utilities/Rename file (use the keyboard or the knob to give a convenient name).

### Calibration 2 and 3 (E-cal)

Press PRESET and prepare the VNA settings for Calibration 2 (stepped sweep, 801 points). Start the E-cal by pressing CAL/Ecal menu/Module A/Full 2-port. Save the corresponding cal set. Repeat this procedure for Calibration 3 as well.

At this point, the VNA should have the three cal sets stored in its internal memory. This data remains usable for a limited period of time (mainly due to the temperature drifts). It will be perfectly valid during this laboratory session or the next day, but it would already be in question the week after.

### **3.3.2. Measurements of the quadrature hybrid**

Recall the cal set for the 2 – 4 GHz band (Calibration 1). Observe the four interesting  $S$ -parameters of the quadrature hybrid:  $S_{11}$  (input matching),  $S_{41}$  (isolation),  $S_{21}$  (coupling to the port 2), and  $S_{31}$  (coupling to the port 3). In general, various  $S$ -parameters can be displayed on the VNA by pressing MEAS/..., while the data format and scale can be adjusted by pressing FORMAT/... and SCALE REF/..., respectively. Moreover, two traces can be simultaneously displayed by utilising the memory: DISPLAY/.... The softkeys following all the mentioned hardkeys are very intuitive. Evaluate the losses at the DUT operating frequency. What can be said of the bandwidth? Measure the phase difference between the two –3 dB outputs. For all these measurements, markers are available: MARKER/...

Save the measurement results in order to be able to prepare three graphs:  $S_{11}(\text{dB})$  &  $S_{41}(\text{dB})$ ,  $S_{21}(\text{dB})$  &  $S_{31}(\text{dB})$ , and the phase difference.

*Note: VNA test ports (after full two-port calibration) act as a matched load termination or a generator with its internal impedance equal to  $Z_0$ . In order to measure properly the S-parameters, the rest of the quadrature hybrid ports need to be terminated in matched loads as well.*

### **3.3.3. Measurements of the bandpass filters**

Keep the same calibration (Calibration 1) and connect the tunable bandpass filter K&L 50140 (set at 3 GHz) between the test ports 1 and 2. Observe the  $S_{21}$  and  $S_{11}$  parameters. Measure the bandwidth, insertion loss, maximum reflection within the pass-band, and the slope. Markers and particularly some intuitive marker functions (MARKER FCTN/...) can facilitate these measurements.

Save the measurement results in order to be able to prepare one graph showing  $S_{11}$ (dB) &  $S_{21}$ (dB).

Recall the cal set for the 3 – 4 GHz band (Calibration 2). Connect the Chebychev passband filter between the test ports 1 and 2. Observe the  $S_{21}$  and  $S_{11}$  parameters. Measure the bandwidth, maximum insertion loss, maximal reflection within the pass-band, and the slope. Markers and particularly some intuitive marker functions (MARKER FCTN/...) can facilitate these measurements.

*Note: The common practice of defining the edges of a filter bandwidth at  $-3$  dB is usually not applied to Chebychev filters; instead the edges are taken as the points at which the gain falls to the value of the ripple for the final time.*

Save the measurement results in order to be able to prepare one graph showing  $S_{11}$ (dB) &  $S_{21}$ (dB).

### **3.3.4. Measurements of the cavity**

The cavity to be measured is of cylindrical shape, operating in  $TM_{010}$  mode (see Fig. 7.6). The top and bottom are drilled in the centre. The hole dimensions are such that they form a waveguide below cutoff at the considered frequency band, so the fields in the cavity are practically not perturbed. The purpose of the holes is to allow the introduction of different material samples into the cavity and therefore to enable relative permittivity measurements.

Here we will only qualitatively assess the relative permittivity and losses of various materials. Recall the cal set for the 2.3 – 2.5 GHz band (Calibration 3). Measure the resonance frequency and the Q-factor of the empty cavity and write the results in Table 7.1. Use the markers and marker functions. What can be qualitatively said regarding the coupling of this cavity to the transmission lines? Repeat the measurement with the given samples placed in the cavity. Order these samples by relative permittivity and loss.

*Note: The Q-factor is defined as  $Q = f_0/\Delta f$ , where  $f_0$  is the resonant frequency and  $\Delta f$  is the half-power bandwidth ( $-3$  dB bandwidth).*

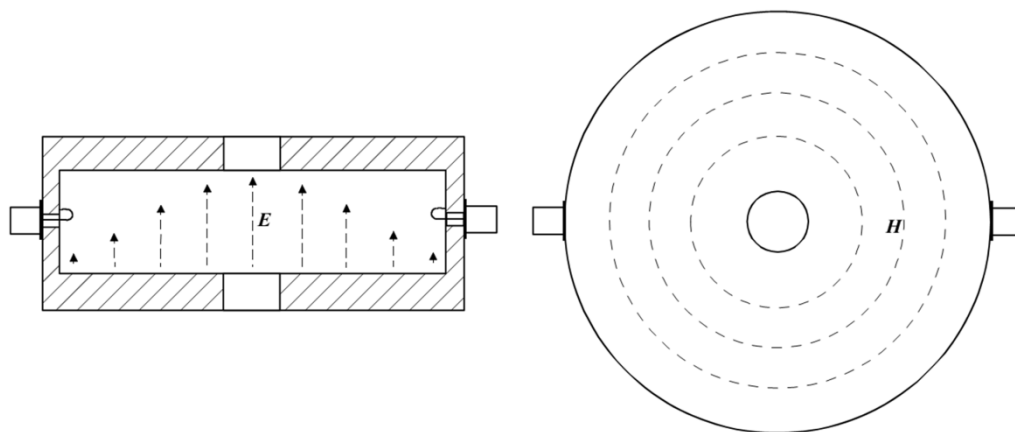


Fig. 7.6 Cavity.

Table 7.1. Cavity measurement results.

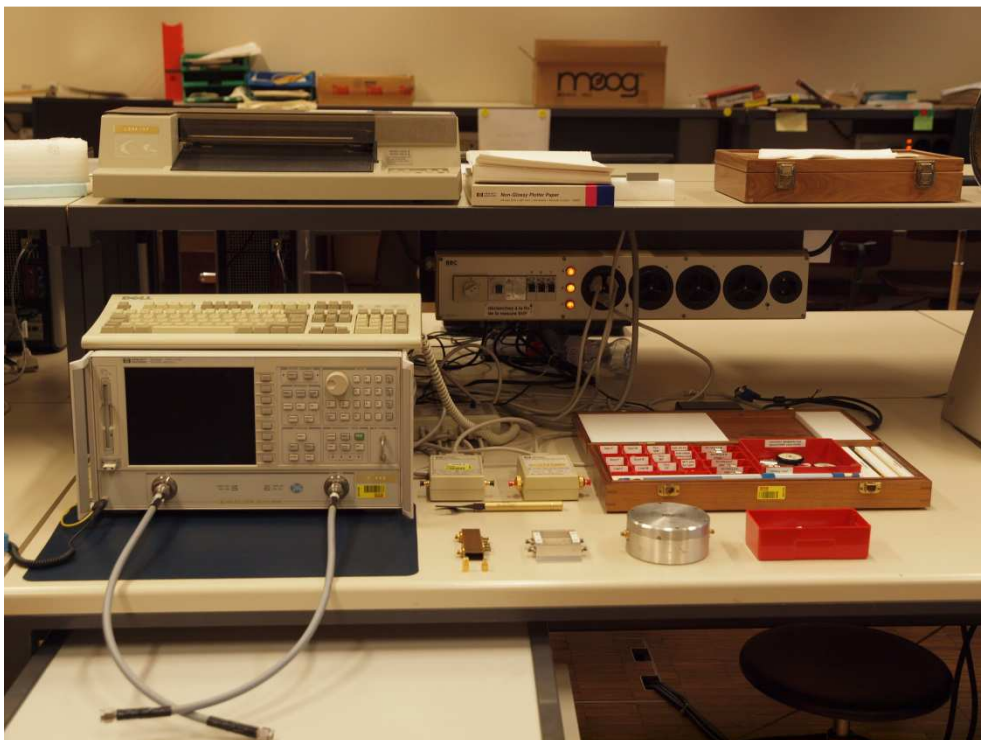
| Sample            | $f_0$ | $Q$ -factor | $\epsilon_r$ -order | loss-order |
|-------------------|-------|-------------|---------------------|------------|
| Empty cavity      |       |             |                     |            |
| Teflon            |       |             |                     |            |
| Polyethylene (PE) |       |             |                     |            |
| Nylon             |       |             |                     |            |
| Plexiglass        |       |             |                     |            |
| Absorber          |       |             |                     |            |
| Water             |       |             |                     |            |



## 4. References

[1] *Network Analyzer Basics*

[http://www.home.agilent.com/agilent/redirector.jsp?action=ref&cname=AGILENT\\_EDITORIAL&ckey=1000001258-1%3Aeps%3Aatcn&lc=ger&cc=CH&nfr=-11143.0.00](http://www.home.agilent.com/agilent/redirector.jsp?action=ref&cname=AGILENT_EDITORIAL&ckey=1000001258-1%3Aeps%3Aatcn&lc=ger&cc=CH&nfr=-11143.0.00)



Photography of the experiment setup for Laboratory session 7.