Application Note

On-Wafer Vector Network Analyzer Calibration and Measurements

The Vector Network Analyzer or VNA has become the workhorse of most network measurements above 1 GHz. Getting the best on-wafer measurement results requires a solid understanding of measurement system components and their interaction. This application note is intended to introduce on-wafer vector measurements and provide references for further study.

VNA Calibration Fundamentals

The representative VNA block diagram (see ***Figure 1)*** shows the key elements of the analyzer. The RF source at the top provides the device-under-test (DUT) stimulus. A forward/reverse switch directs the RF energy to either DUT port. The test set uses directional couplers or bridges to pick off the forward and reverse waves traveling to and from each port, and down-converts these signals to four IF sections. Each IF section filters, amplifies, and digitizes the signals for further digital processing and display.

A VNA measures vector ratios of reflected or transmitted energy to energy incident upon the DUT. As a stimulus-response measurement, a VNA measurement determines the properties of devices rather than the properties of signals. Signals would be measured by instruments such as oscilloscopes or spectrum analyzers.

A significant challenge in stimulus-response measurements is defining exactly where the measurement system ends and the DUT begins. In on-wafer VNA measurements this boundary is known as the “reference plane” of the measurement and will often be located at the probe tips. A typical wafer probing VNA setup is shown in Figures 2 and 3.

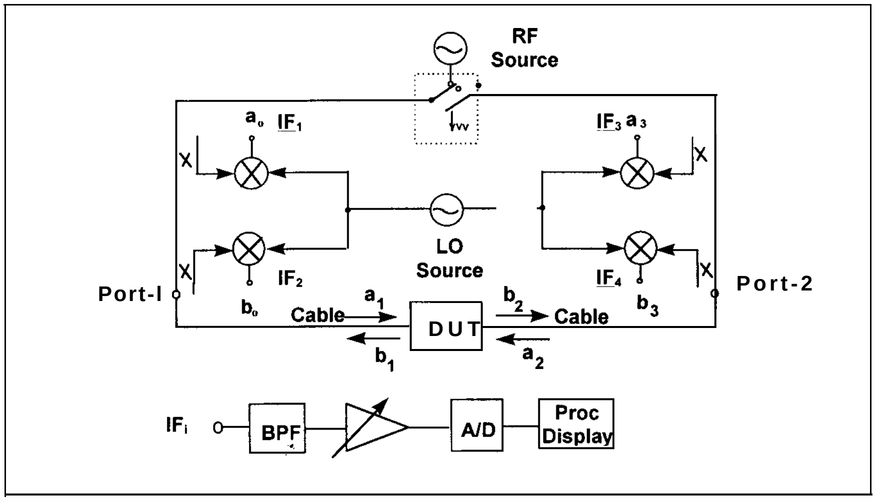

Figure 1. Main hardware blocks in a Vector Network Analyzer (VNA).

Ideally the system will measure the characteristics of whatever is connected to the measurement reference plane. If we ignore any non-idealities of the cables, couplers, mixers, and so forth, then the ratios of wave amplitudes (a’s and b’s) inside of the machine correspond directly to the DUT's S-parameters. For example:

$$b_o/a_o = S_{11} \text{ of the DUT}$$

VNA calibration is the process of measuring devices with known or

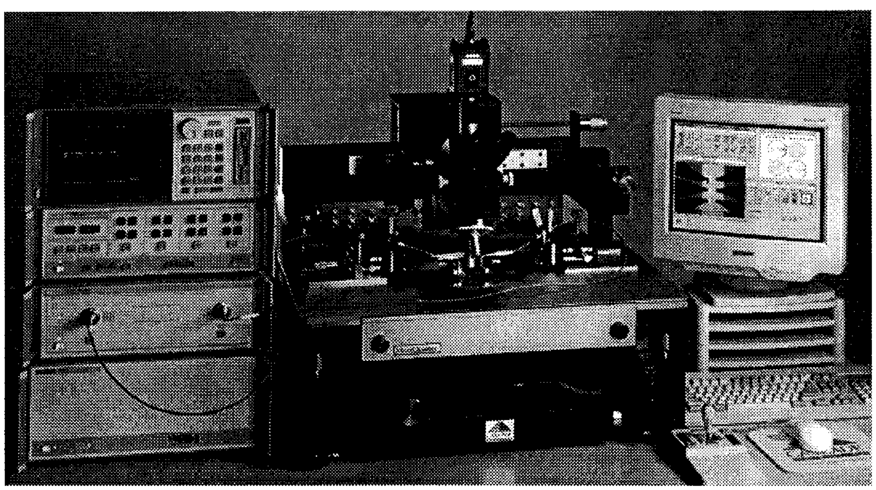

Figure 2. A typical RF device characterization setup is shown above. On the left is a vector network analyzer, in this case an Agilent 8510 system. Cables from the test set ports route over the probe station to a pair of microwave probes which are aligned through the microscope or camera system onto calibration substrates and test devices. The right side of this picture shows the PC that controls the prober and runs the calibration and measurement software.

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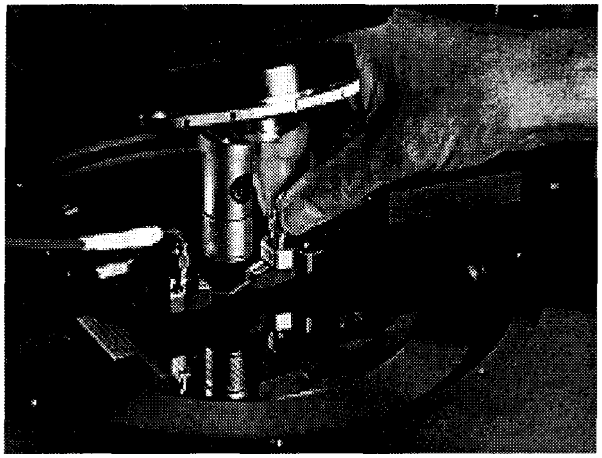


Figure 3. Close-up of microwave probes and cables on positioners providing probe planarity adjustment and cable **restraints.**

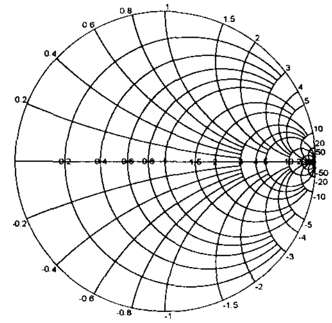


Figure 5. The Smith Chart is a polar graph of reflection coefficient with grid lines showing normalized impedance values.

partly known characteristics and using these measurements to establish the measurement reference planes. Calibration also corrects for the imperfections of the measurement system. These imperfections not only include the non-ideal nature of cables and probes, but also the internal characteristics of the VNA itself

The VNA is calibrated in much the same manner that the "zero" function on your ohmmeter subtracts out the resistance of the test leads. On an ohmmeter, when you activate the "zero" function, it stores a resistance measurement which is then subtracted from all future measurements. The obvious error model is simply a resistance in series with the test port. Corrected VNA measurements are referred to as "deembedded."

A VNA does the same thing as the ohmmeter but uses a more complex error model with several terms for each frequency point. The measurement system is described as an ideal VNA with an error adapter network that models all of the system's non-idealities: directivity of the couplers, imperfect match looking back into the reflectometer (test set ports), imperfect frequency response of the reflectometers and the transmission between ports, and the crosstalk between ports. This error model is shown in Figure 4.

VNA's rely on calibration for accuracy even in measurements with the reference plane defined at the instrument front panel connectors or at the ends of cables. Calibration functions allow the user to store measurements of standards, compute the error models, and automatically apply corrections to DUT measurements.

Where the ohmmeter's calibration simply used a short circuit (connecting the test leads together) to determine the extra resistance term in the error model, a VNA uses multiple calibration standards — typically open circuits, short circuits, loads, and through (thru) connections.

Measuring Impedance

The measured ratios of the a_i and b_i wave amplitudes are called S-parameters. S-parameters are just one type of network representation used for linear, small-signal, a.c. analysis.

A reflection ratio at a device port, with all other ports terminated, is also known as a reflection coefficient. The load impedance, Z_L, is related to the reflection coefficient, Γ, by the bilinear transform pair as follows:

$$Z_L = Z_0 \left[\frac{1+\Gamma}{1-\Gamma} \right] = r + ix$$

$$\Gamma = \frac{V \text{ reflected}}{V \text{ incident}} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

where Z_0= the reference impedance of the measurement system

The Smith chart (see Figure 5) is a polar graph of the reflection coefficient with grid lines showing the normalized impedance values. All passive impedances are represented in a compact unit circle reflection format. Typically the vna automates the display of a wide variety of formats: Smith Chart, polar, and linear and log magnitude formats.

Calibrated VNA Accuracy

As with any corrected measurement, the absolute accuracy of a calibrated VNA measurement is determined by the techniques and completeness of the error model used, the accuracy of the description of the reference devices (calibration standards), and the repeatability of the measurement system.

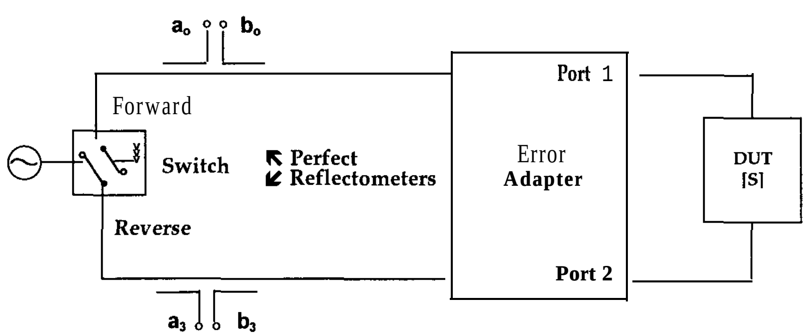


Figure 4. Error model for a typical network analyzer. All errors are modeled by an error adapter in front of an otherwise perfect system.

If performed improperly, calibration can introduce errors. The impedances used in the calibration must be accurately known and entered. Assumption of ideal behavior of standards is a recipe for errors, but worse things can happen. For example, improperly entering a description of a short circuit or open circuit standard will lead to useless results that may not always be obviously wrong. The VNA will believe everything that *you* tell it. Accurate descriptions of the electrical behavior of the various calibration standards must be supplied to the VNA.

Corrected measurements rely on the repeatability of the measurement system. Just as an ohmmeter cannot correct for a changing resistance of its test leads or drift in the ohmmeter circuitry, a VNA cannot correct for random errors such as noise or dynamic range, cable repeatability, or instrument drift. Any change in the measurement due to, for instance, drift of the VNA test set, thermally induced cable length changes, or even the effects of noise due to VNA dynamic range can invalidate the correction. Sensitivity of cable electrical performance (such as phase delay) to environmental changes is a significant element of quality and suitability for VNA use.

VNA error models are based upon the use of S-parameter representations of network properties. S-parameters are signal flow and transmission line based. Only a single mode of propagation at device terminals is assumed. Situations that violate this assumption such as using waveguides that can propagate multiple modes, radiation, or parasitic coupling between networks other than at the device terminals are not properly handled.

If a second mode, radiation, or extra parasitic doesn't change for any and all devices being measured then it will drop out with the calibration. Usually, however, these extra modes have behavior that is DUT dependent and VNA calibration will not account for the effects. A clean, well-designed probing system (including die pad pattern) with good quality transmission-like interconnections will minimize these errors as much as possible (see *Figure 6).*

An extensive discussion of VNA calibration and accuracy is included in Calibration and Accuracy Factors Summit High-Frequency Probe Station Reference Manual. [1]

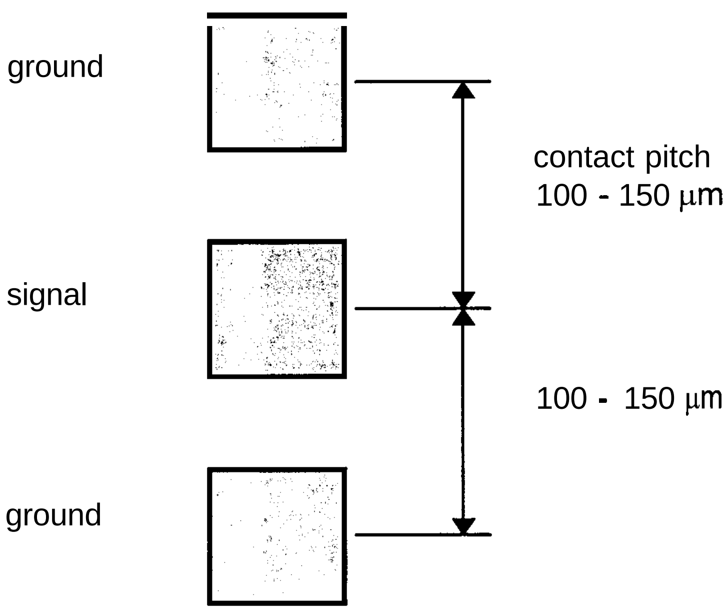


Figure 6. Recommended microwave pad pattern for each measurement port.

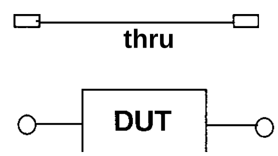
VNA Calibration Options and Standards

The VNA will measure the uncorrected S-parameters if not calibrated, though not very accurately. Uncorrected measurements are rarely used (see *Figure 7).*

- **Convenient**
- **Generally not accurate**
- **No errors removed**

Figure 7. Uncorrected VNA.

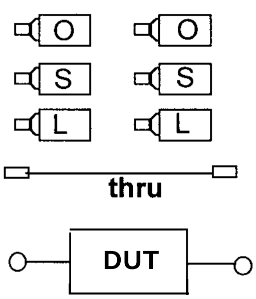
A "response" calibration is simply a vector magnitude and phase normalization of a transmission or reflection measurement, used only at low frequencies (See *Figure 8).*



- **Use when highest accuracy is not require'**
- **Removes frequency response error**

Figure 8. Response calibration.

Typically a full calibration of all the error parameters is used as a reference or to assure the highest accuracy (see *Figure* 9). [2]



- **Highest accuracy for P-port devices**
- **Removes these errors**
  - **directivity**
  - **source match**
  - **load match**
  - **reflection tracking**
  - **transmission tracking**
  - **crosstalk**

Figure 9. Full 2-port calibration.

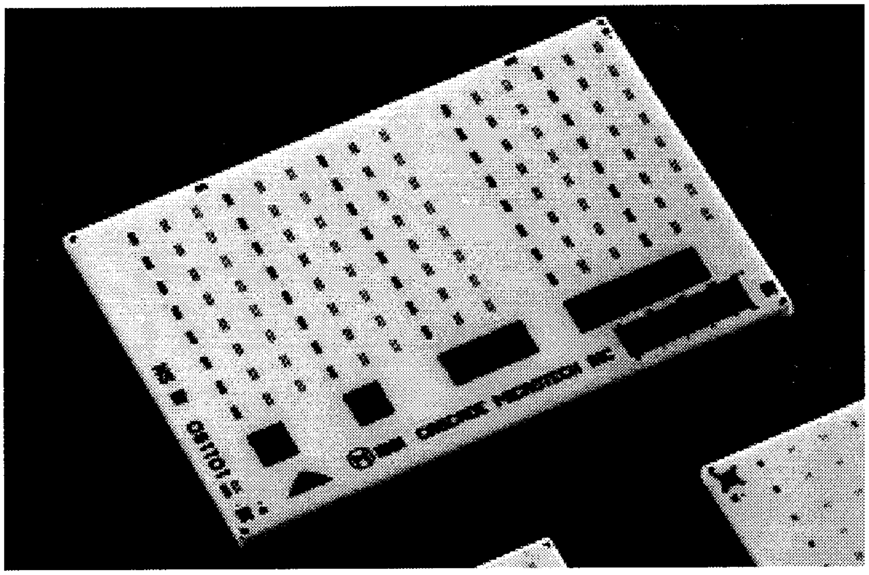


Figure 10. The LRM Impedance Standard Substrate (ISS) has multiple repeated patterns of Short-Load-Thru Standards and alignment marks for setting proper probe separation. A set of transmission lines are also provided for TRL Calibration.

Calibration Standards

On-wafer calibration standards most often are precision thin-film resistors, short-circuit connections, and 50 ohm transmission lines fabricated either on the wafer containing the DUT or on a separate Impedance Standard Substrate (ISS). Cascade Microtech trims high-performance ISS load resistors to within 0.3% of their desired d.c. value (usually 50 ohms). Open circuit standards are normally implemented by raising the probe in air above the wafer by 250 µm or more.

A true 'thru' standard does not exist for on-wafer measurements since probes cannot directly connect to each other and must instead use a very short transmission line as a thru standard. A thru line standard may be referred to either with the label of thru or line. For the Cascade Microtech LRM ISS (see *Figure 10)* the thru lines have 1 ps delay for the version suitable for probes with contact pitch (center-to-center spacing) of 250 µm or less, and 4 ps delay for the wide-pitch version used for probes with more than 250 µm pitch.

It is important to note that the specific electrical behaviors of the standards depend upon the probe pitch used. The calibration data is therefore, supplied with the probe, rather than being a single value for a standard as would be the case for coaxial standards where there is no ambiguity about what connections can be made to it. Calibration data is normally specified for a specific probe spacing used with a particular impedance standard substrate, and is only valid for a particular probe-ISS combination. The contact pattern, e.g., ground-signal-ground or ground-signal, (see *Figure 11)* will also impact calibration data (see *Table* 2).

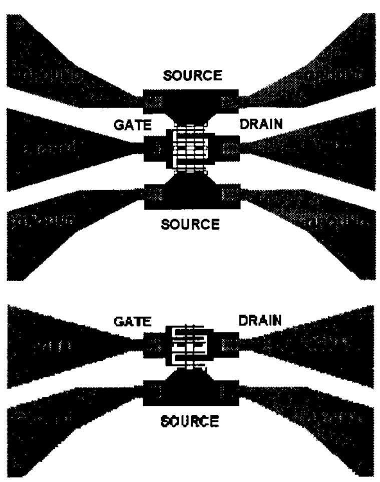


Figure 11. Microwave probe contact patterns. The Ground-Signal-Ground (GSG) pattern has higher performance than the Ground-Signal (GS/SG) configuration.

On-wafer standards, fabricated on the same wafer as the DUT, are sometimes desirable since the probe-to-standard transition can be designed to be very similar to the transition to the DUT. This is helpful at frequencies above 20 GHz since a primitive transition may introduce extra parasitics or modes which, since they are occurring at the probe-tip reference plane, may not be corrected by calibration. In many cases these transition errors may be deembedded using simple lumped element equivalent circuit models.3

The use of off-wafer standards on an Impedance Standard Substrate is very practical and Cascade Microtech has demonstrated calibration results comparable to results obtained by using the special on-wafer standards methods recommended by the United States National Institute of Standards and Technology. In cases where the transition on-wafer is dramatically different than that of the ISS, such as on silicon substrates, the use of a set of dummy pads on-wafer allows the removal of additional pad parasitics. Pad parasitic removal algorithms are discussed in On *the Characterization and Optimization of High-Speed Silicon Bipolar Transistors.4*

A very useful feature to look for on probe stations is an auxiliary chuck or independent vacuum hole pattern specifically for holding small substrates such as an ISS. The ability to have both the test wafer and the calibration standards immediately accessible eliminates frequent swapping of the wafer and the ISS. In Cascade Microtech thermal chuck systems the auxiliary chucks are insulated from the thermal system, allowing better control of the standards. The thin film load resistor has a temperature dependence, making the auxiliary chuck system a must for obtaining the most accurate results.

Transistor Characterization Measurements

In characterizing devices on-wafer, the goal is to obtain the electrical behavior of the intrinsic device. This is the transistor without the parasitics associated with bond pads and interconnections.

Cascade's WinCal software supports pad parasitic removal, when measurements of identical pad configurations without an active device are used to deembed intrinsic device behavior (See ***Figure 12 & 13).***

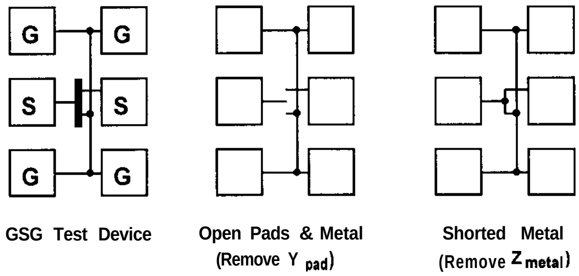


Figure 12. Pad Parasitic Removal structures.

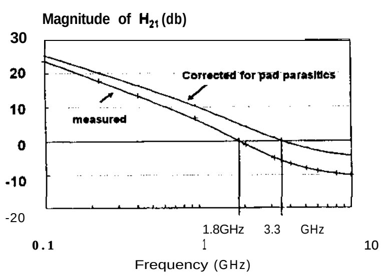


Figure 13. Apparent bandwidth improvement due to removal of pad parasitics.

After a probe-tip calibration, the open-circuit admittance parameters of open-circuited pads are subtracted from device measurements to eliminate shunt capacitances and conductances. Also, series resistance and inductance are eliminated by subtraction of short-circuit impedance parameters obtained from measurements of shorted pads and interconnections.

Apparent device f_T can be significantly increased by eliminating pad parasitics. But be wary of large increases in f_T when residual errors in pad measurements are significant. Also, series inductance from layout inductance and/or probe placement errors can resonate with device output capacitance and distort f_T results (See ***Figure 14).***

Calibration Standards for Pyramid Probe™ Cards

Calibration standards for use with Pyramid Probe Cards differ little from those used in standard microwave probing. In many cases traditional ISS's may be used. The fixed input to output spacing of probe cards may be inconvenient, however. Conventional separate probes can be adjusted to land on pairs of standards simultaneously. For probe card contact separations differing from the distance between standards on ISS's, separate landings for each port are required. Additionally, the thru line may not be the appropriate length to connect the input and output. Transmission line standards on the ISS may be used as the thru if they happen to be the length that matches your probe contact separation. The delay and loss of the thru must be accounted for in your calibration.

The General Purpose Membrane ISS (see ***Figure 15)*** addresses the problem of thru length by providing a number of microstrip and coplanar waveguide (CPW) lines

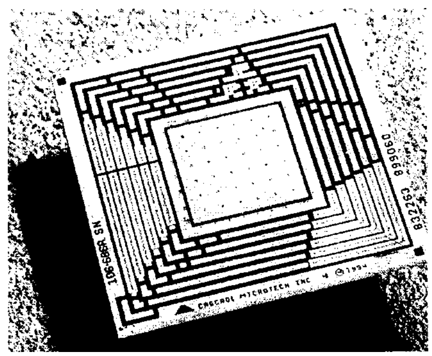


Figure 15. The General Purpose Membrane Impedance Standard Substrate.

with a variety of straight and right angle lengths. If no line fits well enough, the next larger line can be cut to length. Loss and delay data for the straight CPW lines on the GP Membrane ISS are shown in Table 1. Loads trimmed to 1% accuracy are provided in openings in a large field of metal which is also used for the short circuit standard.

The RFC-CAL is a custom membrane with specific length thru connections mounted on a glass slide. It is sometimes useful to use a thru

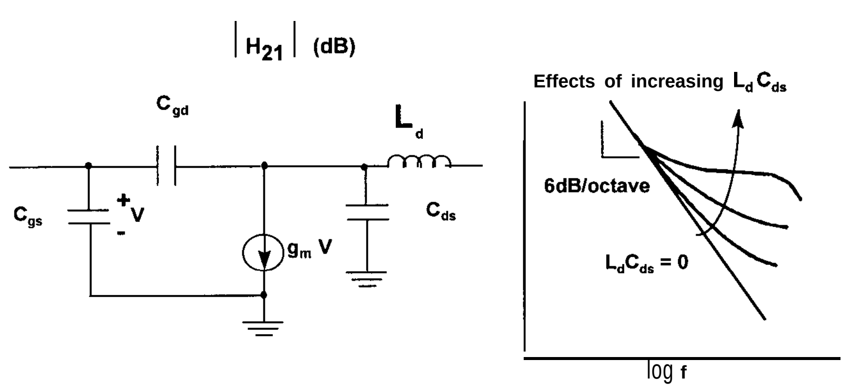


Figure 14. Inductance, L_d, due to layout inductance can resonate with device output capacitance and distort the measured frequency response.

Line #	Delay (ps)	10 GHz Loss (dB)
1	3.8	0.025
2	5.8	0.044
3	11.5	0.093
4	17.1	[illegible]
5	22.8	0.19
6	28.3	0.24
7	34.2	0.28
8	39.7	0.34
9	45.3	0.38
10	52.7	0.44
11	60.4	0.52
12	67.7	0.59

Table 1. Properties of CPW thru lines on the General Purpose Membrane ISS.

structure with an inverted matching network for calibration of impedance matching probes.

A fully custom Impedance Standard Substrate is yet another alternative. This ISS can have patterns that provide each standard type to all of the microwave ports simultaneously. A custom ISS may be particularly valuable when automating calibration. Contact Cascade Microtech for details on these options.

Short-Open-Load-Thru Calibration

By far the most commonly used method, the Short-Open-Load-Thru (SOLT) calibration is available on every commercially available VNA. This calibration is the combination of two one-port Short-Open-Load calibrations with additional measurements of a thru standard to complete the two-port calibration. All of the standards must be fully known and specified.

The SOLT standards are reasonably well modeled with simple lumped elements: open-circuit capacitance, short-circuit inductance, load inductance, and thru delay (and loss). Often the open-circuit capacitance will have a negative value since the probe lifted in air has less tip loading than when it is in contact with a wafer.

All standards must be accurately contacted physically, since the inductance values are very dependent on probe placement on the standard. A 1 mil (25.4 µm) longitudinal change in the overlap of the probe tip over the standard can result in a significant change in the inductance value (see Figure 16).

Typical values of calibration coefficients for individual microwave probes (Cascade Microtech ACP style) are shown in Table 2.

Calibration coefficients must be correctly entered into the VNA to do any good. This would seem to be an easy task with only three coefficients per probe, but improper calkit entry is one of the largest sources of error in on-wafer VNA measurements. VNA front panel data entry of calibration coefficients can be tedious and error prone.

Some VNA's do not allow lumped element models for all standards. The use of an offset transmission line based equivalent circuit is required. The lumped element series inductance represented by the load (term) or short can be effectively modeled by a short section of high impedance transmission line offset. Normally the offset impedance is set to the maximum value allowed by the VNA (e.g., 500 ohms for the HP **8510)** and the corresponding delay is determined using the equation
$T_D = L/Z_o$.

For example, the 4.8 pH short circuit inductance of a 150 pm pitch, ground-signal-ground configuration ACP probe would be entered into an HP 85 10 calkit as a short standard with a 9.6 fs (4.8 pH / 500 Ω) long 500 Ω offset.

Another common source of error is to forget to enter the delay of the thru line standard. A 1 ps thru is normally used with the standard probe pitch ISS versions (PNs 101-190 and 103-726) while a 4 ps thru is used with the wide probe pitch ISS versions (PNs 106-682 and 106-683). When using long thru lines such as for Pyramid Probes it is important to use an accurate delay value and to provide an accurate loss value. The offset loss term (in GΩ/s at 1 GHz) for the HP 85 10 is given by:

$$OffsetLoss\left(\frac{G\Omega}{S}\right)_{1GHz} = \frac{dB_{loss}\big|_{1GHz}\; c\; \sqrt{\varepsilon_r}\, Z_o}{10\,\log_{10}(e)\,\ell}$$

where dB_{loss} = measured insertion loss at 1 GHz, Z_o = thru line impedance (normally 50 Ω), and l = physical length of the offset.

For a standard specified by loss and delay at a particular frequency, the offset loss term calculation simplifies to:

$$OffsetLoss\left(\frac{G\Omega}{s}\right)\Big|_{1GHz} = \frac{230.3 \cdot Z_o \cdot dB_{loss}}{T_{delay} \cdot \sqrt{f}}$$

where dB_{loss} is the measured insertion loss *(dB)* at frequency f (GHz) for a line with offset *delay* = T_{delay} (ps) and offset impedance = Z_0 (usually 50 Ω). For example, table 1 shows that the CPW line #6

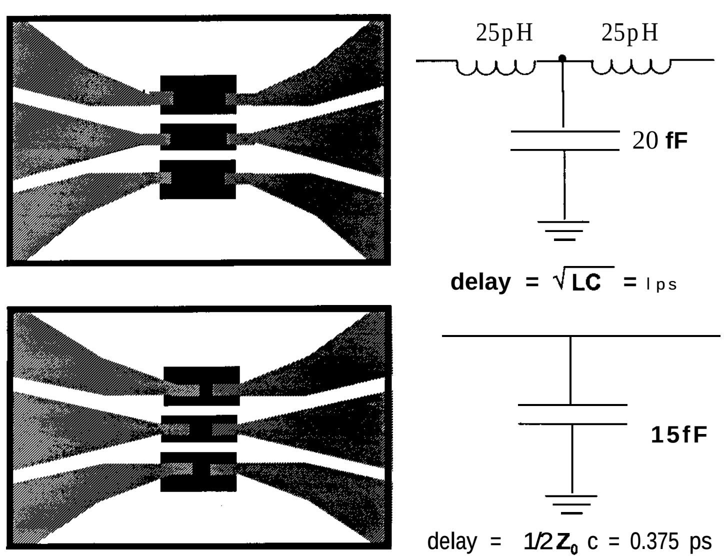


Figure 16. Improper probe placement will impact the electrical behavior of a measured standard. Use of alignment marks to set probe separation and reasonable care in placement will provide good results.

on the general purpose membrane ISS has 0.24 dB loss at 10 GHz and 28.3 ps delay so this equation gives:

$$OffsetLoss\Big|_{1GHz} = \frac{(230.3)\cdot(50)\cdot(0.24)}{(28.3)\cdot\sqrt{10}} = 30.9\,\frac{G\Omega}{s}$$

An offset loss value of **31 GΩ/s** should provide good results for all but the shortest of the CPW lines on the general purpose membrane ISS.

The thru standard loss parameter entry with the requirement for nearly ideal behavior of the thru standard is a major limitation of **the** SOLT calibration method. Any loss behavior that doesn't match the ideal loss model built into the VNA or extra reflections, such as those generated by a right-angle bend when connecting orthogonally oriented probes, will introduce significant error. Similarly, excess length of a thru line over the spacing between RF contacts on a Pyramid Probe will add parasitic shunt stubs from the excess line length. These act as open circuit stubs and will spoil the accuracy of an SOLT calibration.

An alternative to the SOLT calibration is the SOLR[5] (Short-Open-Load-Reciprocal) advanced calibration. This algorithm is similar to the SOLT calibration for one-port corrections, but the redundant information available in the standards set allows the R standard to be any reciprocal two-port. No other knowledge of the standard is required to complete the calibration.

The SOLR algorithm is very powerful when only non-ideal thru standards are available: orthogonal probes, excess thru line length, lossy or mismatched thru line, incompatible port geometries (pitch), etc. The SOLR calibration algorithm is an advanced calibration method and is not directly available on any VNA presently made. SOLR requires special software – such as Cascade Microtech's WinCal – running on a PC communicating with the VNA via IEEE-488 instrument bus commands. Additionally, the VNA must be one that supports true TRL calibration (a four sampler VNA) in order to be able to provide enough information for the SOLR algorithm to be calculated. Calibration of right-angle oriented probes using SOLR is discussed in ***An SOLR Calibration for Accurate Measurement of Orthogonal On- Wafer DUE.6***

A **standard** SOLT calibration can present the dilemma of conflicting information to the VNA. The number of measurements and standard definitions exceeds the number of unknowns in the two-port error model. This mathematically 'over-determined set of equations will not necessarily have a single entirely self-consistent solution. The implications of this lack of self-consistency are subtle, numerous, and unavoidable. One example would be measuring slight differences between S_{12} and S_{21} for a passive reciprocal structure. The SOLR calibration is not over-determined and is inherently self-consistent.

Advanced Calibration Methods

S-parameters require measurements with each port of the measured device stimulated in turn. For a two-port VNA this means that the microwave source power must be switched to each port (as shown in Figure 1). When the switch changes position the error model of each port changes due to the non-ideal nature of the microwave transfer switch, the source output impedance, and the response termination load impedance. The full two-port error model provides for these switching terms by the use of two different error models – one for forward and one for reverse measurements. The error model shown in Figure **17** is consistent with the SOLT calibration method.2

Normally in on-wafer measurements the isolation terms, E_X, are neglected since they are relatively

C-Open (fF)	GSG L-short (pH)	L-Term (pH)	GSG ISS P/N	Probe Pitch (µm)	GS/SG ISS P/N	C-Open (fF)	GS/SG L-short (pH)	L-Term (pH)
-9.3	2.4	-3.5	101-190	100	103-726	-11.0	33.5	36.5
-9.5	3.6	-2.6	101-190	125	103-726	-11.0	41.7	47.2
-9.7	4.8	-1.7	101-190	150	103-726	-11.0	49.8	57.8
-10.1	7.2	0.2	101-190	200	103-726	-11.0	66.2	79.2
-10.5	9.6	2.1	101-190	250	103-726	-11.0	82.5	100.5
-15.7	11.0	-25.0	106-682	250	106-683	-7.0	27.0	0.0
-13.6	15.8	-21.0	106-682	350	106-683	-7.0	28.2	0.0
-12.6	18.2	-19.0	106-682	400	106-683	-7.0	28.8	0.0
-10.5	23.0	-15.0	106-682	500	106-683	-7.0	30.0	0.0
-9.6	28.1	-3.3	106-682	650	106-683	-6.4	42.9	14.1
-9	31.6	4.4	106-682	750	106-683	-6.0	51.6	23.4
-7.5	40.4	23.6	106-682	1000	106-683	-5.0	73.4	46.6
-6	49.1	42.9	106-682	1250	106-683	-4.0	95.1	69.9

Table 2. Air-Coplanar Probe (ACP) calibration coefficients. Coefficients for VNA calibration depend on the style and pitch of the probe, as well as the ISS used. The wide-pitch ISS's (106-682 and 106-683) use a 4 ps long thru line while the standard-pitch ISS's (101-190 and 103-726) have a 1 ps thru line.

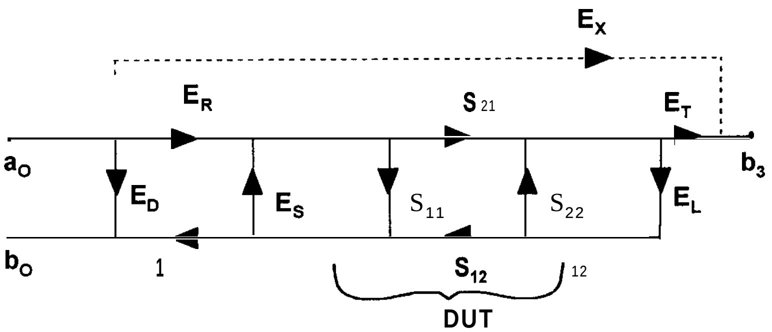


Figure 17. Signal flow graph of the full two-port VNA error model without switch corrections. The forward stimulation case is shown, a similar error model is **used** for reverse stimulation.

small and are not the same for the standards and DUT.

VNA's that have the ability to sample the energy reflected from the switch termination as well as the stimulus, transmissions, and reflections - the four sampler architecture – allow removal of the switching terms from raw measurements. This results in a reduced error model shown in Figure 18 which has error boxes at each port that contain all of the VNA and interconnection errors. A great deal of study has gone into various methods for determining the coefficients of the error boxes from measurements of known and partially known structures.

The most fundamental of these methods, the Thru-Reflect-Line (TRL) calibration algorithm, uses the characteristic impedance of a transmission line as the reference for calibration.7 Line pairs differing only in length are measured along with a reflect standard that is known only to the sign of the reflection coefficient. The line length difference must not be near 180 degrees of phase since a half wavelength transmission line mimics a zero length line and provides no additional information. In practice a line pair will only provide useful results over a 20 to 160 degree phase difference range. Wider bandwidths require multiple line lengths to provide suitable phase differences over a wide frequency range.

The TRL calibration process itself does not determine the characteristic impedance that is the reference for the resulting S-parameters. Additional assumptions and measurements may be used to determine the Z_O and renormalize the S-parameters to 50 ohms (for example). Often this is not done and the frequency dependence and imaginary part of Z_O due to loss are disregarded. At low frequencies, where the per-unit-length inductive reactance is small compared to the ohmic loss, the imaginary part of Z_O can be large. This effect can be present at moderate frequencies (perhaps up to 1 GHz) for relatively high resistance transmission lines such as are found in thin film circuits.

In the TRL calibration (and its variations) the thru line must be fully known to allow the measurement reference plane to be moved to the probe tips from the midpoint of the thru line. In some applications using on-wafer standards, the DUT is effectively embedded at the thru mid-point, eliminating the need for this reference plane change.

The TRL calibration method is not practical for Pyramid Probes and other probe cards since it is not possible to measure multiple line lengths with fixed spacing probes. Even with individual probes, the TRL calibration requires programmable probe positioners for fully automatic calibration. An alternative to the TRL is the Line-Reflect-Match (LRM) calibration. The LRM calibration uses TRL-like mathematics but uses a broadband match standard to set the system impedance. The match essentially acts as an infinitely long, infinitely attenuating transmission line.

The LRM calibration standards are suitable for fixed probe spacing and can be used with probe cards or manual positioners. The standards are a subset of those used for

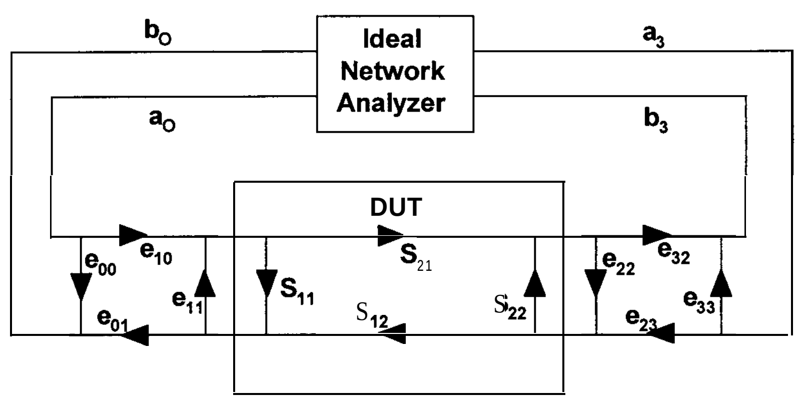


Figure 18. Signal flow graph of the switch corrected two-port VNA eight-term error model. Since S-parameters are ratios, only seven unknowns must be determined to complete the calibration.

SOLT since either the short or open can be used as the reflect standard. In on-wafer measurements the open standard is preferred since it has no probe placement issues to effect repeatability. The conveniently available standards combined with superior performance make the LRM calibration a natural first step to improved calibration accuracy over using SOLT.

The one weakness of the LRM calibration is that the inductance of the load standards becomes part of the reference impedance of the measurements. Methods for automatic determination of the load inductance and correction of measurements are available in Cascade Microtech's WinCal VNA calibration software.8 These more sophisticated versions of the LRM calibration are only suitable for relatively small thru line lengths (a few ps) but when applicable can yield performance comparable to the most advanced TRL calibrations.

LRRM Calibration with Automatic load Inductance Extraction

A variation of the Line-Reflect-Match, the Line-Reflect-Reflect-Match advanced calibration provides calibration accuracy comparable to the NIST multiline TRL algorithm described below without the need for changing probe separation.[9] The LRRM calibration algorithm is available only in Cascade Microtech's WinCal VNA calibration software running on a PC.

The standards used for LRRM are identical to those used for SOLT but without the requirement for careful specification of the short and open standard behavior. In LRRM, only the thru line delay (and loss for longer lines) and d.c. resistance of one load standard must be specified.

The inductance of the load is extracted from the redundancy of information provided by the extra standard measurements. By using only one Match standard any ambiguity in load inductance between ports is eliminated, reducing the sensitivity to probe placement since the actual value is directly extracted.

LRRM provides high-performance calibrations with fixed probe separations, allowing simple, automated calibrations.

A Cascade Microtech Summit probe station using WinCal software allows highly repeatable, fully automated VNA calibrations initiated with a single mouse click. See the Cascade Microtech Technical Brief Technique Verifies *LRRM Calibrations for GaAs measurements.* [10]

NIST MultiCal

Research by the Microwave Metrology Group of the U.S. National Institute of Standards and Technology (NIST) has advanced the quality of rigorous on-wafer VNA measurements. The focus of this work has been the development and application of a multiline TRL calibration algorithm using the full redundancy of the standards. While normal TRL selects line pairs for applicable frequency ranges, the NIST multiline TRL uses a continuously varying optimally weighted average of all of the data. [11,12]

The multiline TRL algorithm is available in NIST's MultiCal software. This HP BASIC program runs on HP 9000 workstations and PCs and is compatible with the HP 8510B, HP 8510C, and HP 8700 and Wiltron 360 series VNAs

MultiCal allows high-performance calibration using on-wafer standards and computes measurement error bounds from calibration comparison. [13]

One-Tier vs. Two Tier Calibrations

In most on-wafer VNA measurement applications a single set of calibration measurements are made to characterize everything at once: the VNA errors, cables, and probes. There are situations where you may want to make this a two-step process. A two-tier calibration is obtained by performing one calibration – the first tier – and following it with a second calibration – the second tier – that uses first tier corrected standards measurements. Two-tier calibrations normally require special software, such as Cascade's WinCal, since these functions are generally not provided in the VNA.

The second tier actually obtains error boxes that represent the change in the system between two calibrations. If a cable calibration is followed by a second tier probe-tip calibration the second tier error box will be the network parameters of the probe (see *Figure 19).*

Separation of the cable cal from the probe details can be useful in complex multiport situations. The error box S-parameters of the various probe contacts are determined and the data mathematically cascaded with the cable calibration error boxes. This technique is used in some microwave production test systems to reduce the number of on-wafer standards needed for multi-port calibration.

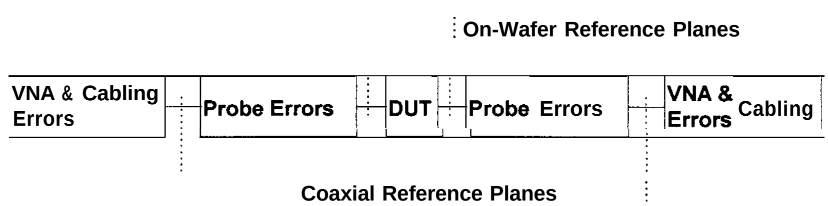


Figure 19. Error boxes for a two-tier calibration. A coaxial first tier is followed by an on-wafer second tier.

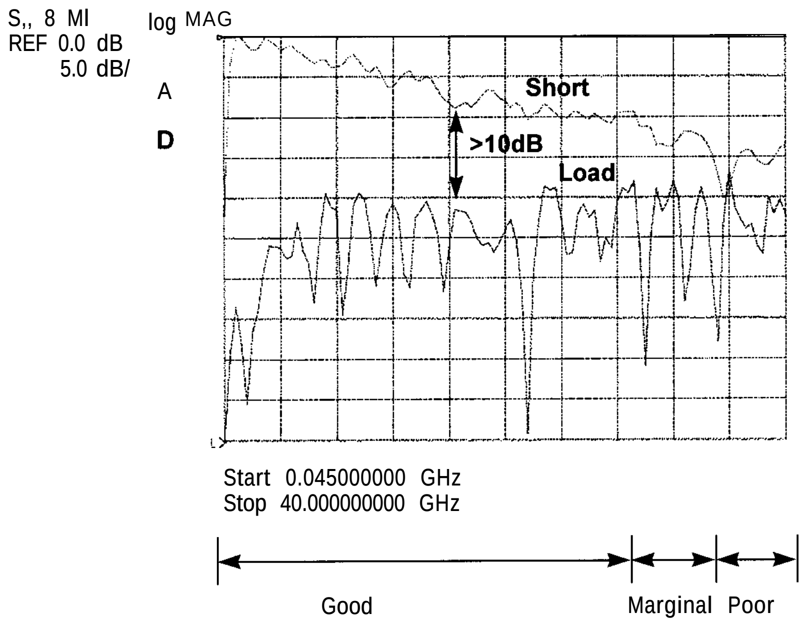


Figure 20. The relative magnitudes of uncorrected measurements of a short and a load provide a good check on proper system function.

Another application of second tier calibrations is for determination of error bounds due to measurement system repeatability. A first-tier probe-tip calibration followed by a second tier calibration at the same reference plane will determine error boxes that represent the change in the system due to drift between the calibrations. This information can be used to calculate bounds on the repeatability errors impacting measurements that were made between the two calibrations, providing a useful measure of one of the components effecting overall measurement accuracy.

Measuring Cal Standards

The process of completing the calibration entails placement of probes on standards and directing the VNA measurement system to acquire data. This process is somewhat error prone since it is not always easy to determine if the standard is properly connected.

While uncalibrated or 'raw' S-parameters from a VNA are often far from accurate they can be used to help verify proper contact with the calibration standards.

The raised probe open measurement does not have any contact issues and can be used as a reference. The measurement of a short standard will show an ideally 180 degree phase rotation of the reflection coefficient. This can be seen as a rotation of the raw data Smith chart constellation or a shift in a phase display occurring when the probe makes contact. In practice second order terms in the error box will also somewhat impact the actual change of observed reflection, but the shift will be very noticeable and provide a good indication confirming visual identification of proper alignment and contact.

The load standard shows a significant reduction in the magnitude of the uncorrected reflection coefficient when contact is made. Contact with a 50 ohm load will tend to reduce the Smith chart display toward the ideal center dot. Particularly at higher frequencies the various reflections from adapters, cable connectors, and probes can degrade the overall return-loss of the load standard. The measured reflections will normally be reduced by more than 10 dB when the load is in contact. Smaller reductions are signs of poor system return loss that may require correction (see *Figure 20).*

The thru line measurement will exhibit the matching characteristics of the load and will also show an increase in the raw S_{21} transmission measurement. A few experiments will provide a good idea of what to expect from your fixturing and VNA measurement system.

Calibration Verification

Verification of proper calkit entry and calibration can be demonstrated by measuring a long open circuit and/or long transmission line. The reflection coefficient of the long

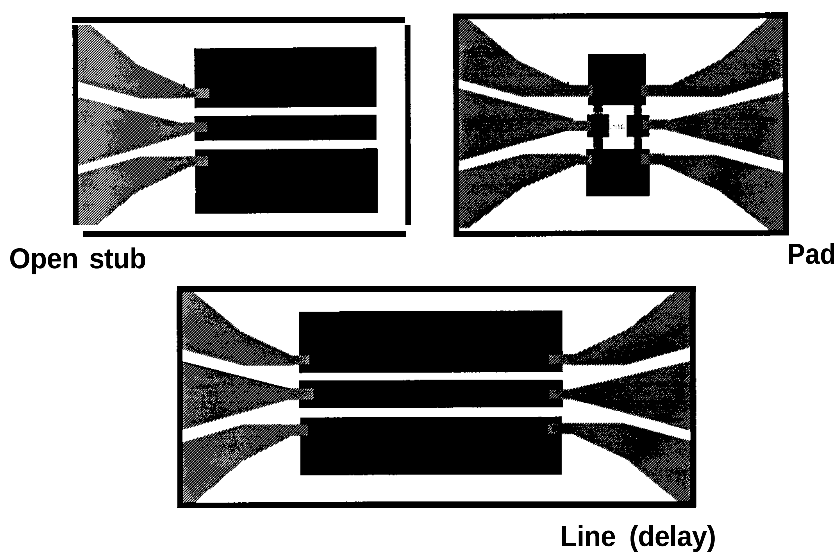


Figure 21. Typical on-wafer verification elements. In many cases measurement of such structures will catch the most common errors and problems.

open circuit should exhibit a smooth monotonic inward spiral on the Smith chart. Look for linear phase in the transmission response of the long transmission line verification standard. High Q-factor inductors or capacitors can similarly be used for calibration verification. It is a good practice to perform one or more of these verification methods after completing every calibration. Some common verification standards are shown in Figure 2 1.

Verification is particularly important with the SOLT calibration to ensure both proper calkit entry and successful probe calibration standard measurements. Do not remeasure a calibration standard as a verification, since the only thing that will be revealed is the repeatability of the measurement. If the system is repeatable then the remeasurement will simply show you what you entered into the calkit for that standard. A VNA cannot recognize the errors caused by using incorrect impedance standards. A load resistor of the wrong value will not be recognized: it will be accepted as 50 ohms. The VNA will even accept interchanged open and short standards without complaint. Either mistake can result in significant measurement error.

Measurement of calibration standards for the advanced calibrations where standards don't have to be specified is useful for verification. Examining the open that is used for the reflect standard in a TRL or LRM calibration can identify problems. After calibration, the open may not have perfectly zero return loss. The probe in air will actually have slightly less loss then the probe in contact with the wafer, so in addition to some negative capacitance a small amount of return gain from the calibrated open may normally be observed. The specific strength of this effect is very dependent on the probe design and will vary for different probe types and thru losses.

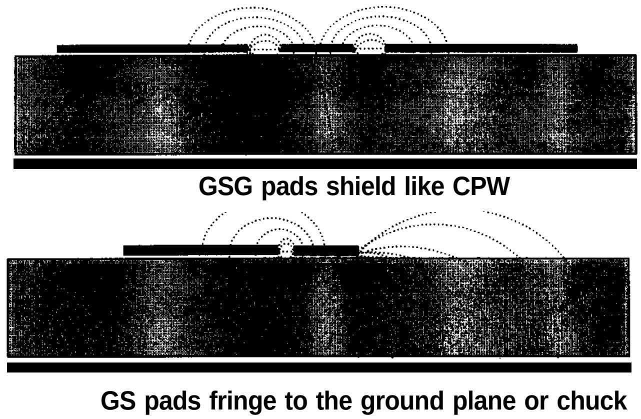


Figure 22. GS pads fringe to the ground plane or chuck.

The thru line standard is a useful verification element for an SOLR calibration. Again the verification should reflect expected behavior so this is only useful when the behavior is predictable. The SOLR can calibrate successfully even with a highly reactive and complicated frequency response of the reciprocal thru which won't be predictable. However, a good line standard will exhibit attenuation with square-root of frequency dependence consistent with thin-film transmission lines. Excess line length beyond the probe contacts will act like capacitive stubs resulting in increased attenuation at higher frequencies. Linear transmission phase would be expected unless the standard has dispersive characteristics.

A golden standard device – a device that has been characterized using a (hopefully) known good test system – is another way to validate a test system. It is difficult to validate a calibration and measurement method this way however. Slight differences in calibration reference planes may appear as significant error. Differences in circuit bias or power supplies can also appear as errors in the microwave measurement. A golden standard can, however, be an effective and simple test for qualifying a new system that uses identical equipment and methods as a reference measurement system.

GSG vs GS Pads

After probe positioning and gross cal calibration errors, the most significant inaccuracy in microwave probing is associated with parasitic coupling at the probe tip (see Figure 22).

A ground-signal-ground interface terminates field lines effectively, but ground-signal pads allow the open side fields to terminate on the wafer ground plane or prober chuck. The degree of this coupling is dependent on substrate thickness and pad spacing.

An undesirable mode of propagation where all top side conductors form a microstrip with the bottom of the wafer can occur in these structures. The best way to deal with this problem is usually to minimize the excitation of that mode.

The GSG pad configuration excites the undesired microstrip mode less than the GS configuration. A reasonable rule is to avoid GS pads for good results above about 10 GHz.

GS Probing Parasitics

Figure 23 depicts a GS probe tip, two connection pads, and a DUT, along with the main reactive parasitics of the connection. The ground is the back side of the wafer, the wafer chuck, or a high-conductivity substrate such as Silicon.

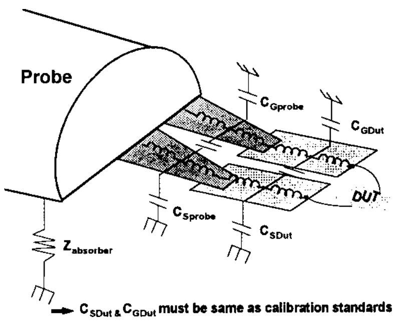


Figure 23. GS probing parasitics.

The desired transmission line uses the inductances in series with the DUT and the corresponding bridging capacitors. The resistor represents polyiron material used on Cascade Microtech single line probes that acts to absorb energy in the undesired mode. This attenuates energy propagating up the ground which could resonate with the probe holder.

Proper selection and use of a microwave probe will allow the parasitic C_{SProbe} and C_{GProbe} to be small and repeatable. However, differing pad sizes or conductor geometries on test structures can cause C_{GDut} or C_{SDut} to be different from one structure to another, or from the calibration standards.

Only when these values are equal for calibration standards and measurement devices will these parasitics be removed by VNA calibration. But changes in metal configuration will often occur. For measurements above 10 GHz, the GS configuration is inadequate and the superior shielding of GSG is preferred.

Device Bias Considerations

Power supplies may be supplied through the VNA bias ports which combine the DC and RF signals together at the measurement ports using bias tees. If the performance of the VNA internal bias tee is inadequate, or your VNA does not provide one, then an external bias tee may be preferred.

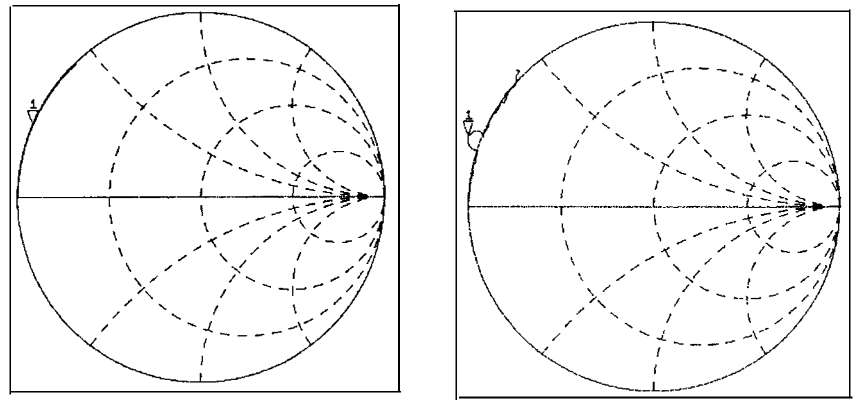


Figure 24. Calibrated measurement of short circuit standard before and after distressing a cable. A change has occurred in the cable electrical behavior resulting in a 20 GHz resonance.

A bias tee is a three-port network with the properties of a diplexer; that is, a wide bandwidth port is coupled to the bias port via a low-pass filter and to the RF port through a high-pass filter. Important selection parameters of a bias tee are: cross-over frequency, bandwidth, current and power rating, resistance and loss, and connector type.

The series and shunt resistance of the bias tee will be significant when measuring individual transistors or other devices where a precise bias point is desired. For moderate to large currents the series voltage drop will make a change from the expected bias voltage. Expected device currents will vary from actual due to the current path provided by shunt resistance. This resistance is high, but not high by the standards of parametric measurements with currents possibly ranging from 1 fA to 100 mA. Probes, cables, and probe stations designed specifically for dc parametric measurements are generally preferred for these cases.

For microwave integrated circuits the bias and power lines will often use separate pads from the RF connections. For these circuits, either a multi-contact probe, hybrid RF and needle probe system, or a Pyramid Probe Card is needed. Low impedance is the primary desirable characteristic in a power supply and is a major feature of the Pyramid Probe Card with its bypass capacitors very close to the contacts and excellent grounding.

Needles, either used in a hybrid probe card or as additional probes on separate positioners, have high inductance since they are not closely coupled to a ground return. Inductance on supplies can cause power supply ‘bounce’ in digital circuits and instability or gain flatness problems in analog circuits. Adjacent needles may be inductively coupled or even by virtue of sharing a common ground return path may create signal paths between various portions of a circuit by way of power connections.

Cable Sensitivity

Correcting the network analyzer measurement through a lossy cable is similar to the correction we subconsciously use to see an image through a dirty window. We correct for the attenuation due to dirt on the window as well as reflections from the window’s surfaces. It is important that the cables be highly repeatable as well as reasonably low loss, so that there is enough dynamic range after looking through and correcting for the lossy cable.

Calibrated measurements of a short circuit standard before and after the cable has been significantly flexed, shown in Figure 24, demon-

Symptom	Likely Problem	Trv
Measurements do not repeat at any freq	Cables or adapters are loose or faulty	Calibrate in coax with and without cables and adapters
	Analyzer fault	Calibrate in coax directly at test set port
	Probe Contact fault	Verify probe contact visually or at dc
	Probe head fault	Calibrate in coax at probe connector; if good, replace probe head
	Oscillating DUT	Use different bias condition to verify; change low-frequency DUT terminations
Measurement noisy at all freqs	Insufficient averaging on HP8510	Increase averaging to at least 4 in ramp mode, or 128 in step mode
	Poor ramp sweep repeatability	Use step mode
Measurement noisy at certain freqs	Sweeper band switching	Increase averaging, use step mode. Change sweep rate
	Loose connection	Tighten connectors
	Faulty probe resonating	Check open stub on ISS - should be smooth inward spiral
Measurement noisy at high freqs only	Poor return loss at high freqs	Measure ISS load with corrections off - should be at least 10 dB below the open or short-trace back to test set using coaxial load and short
DUT measurements noisy at low freqs only, or Transistor S_{21} compresses at low freqs (passive elements ok)	DUT is being biased by rectified RF, or RF is compressing DUT gm	Reduce RF power level, add device input port attenuation, use power slope
Passive element reflection coefficient outside Smith chart	Incorrect cal coefficients	Adjust cal coefficients
	Poor probe placement on standards	Use alignment marks to improve placement **accuracy**

Table 3. Troubleshooting guide.

strates **the importance of measurement repeatability. The resonance at about 20 GHz would significantly distort further DUT measurements.**

When troubleshooting the responses of a VNA, it is useful to keep in mind that impedances that vary rapidly with frequency cannot be due to errors near the DUT. When wafer probing there is insufficient electrical length on the wafer or in the probes to cause resonances or impedances that change rapidly with frequency.

Troubleshooting

Table 3 may be helpful in troubleshooting VNA measurement problems (some details apply only to Agilent 8510 systems).

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13. **For more information contact Dylan Williams, NIST 813.06, 325 Broadway, Boulder, CO 80303.**