VNA CALSET PORT AUGMENTATION FOR IMPEDANCE MATCHING PROBE CALIBRATION

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ABSTRACT

A method for calibrating an on-wafer VNA measurement system with unequal port impedances determined by impedance matching probes is presented. The method starts with an existing stored calibration set for measurement reference planes at the ends of the coaxial cables. A new calibration set with a probe-tip reference plane is determined through a calibration set augmentation procedure using measured two-port normalized S-parameters of each probe.

INTRODUCTION

On-wafer measurement of devices and circuits that are not impedance-matched to the test equipment is sometimes necessary. Power devices for wireless applications often are designed to work with low voltage power supplies and will have correspondingly low output impedance. These devices need to be characterized in an environment with port impedances that closely mimic the eventual application to get accurate characterization of parameters such as efficiency.

The use of coaxial impedance matching probes for device characterization was discussed previously by Basu [1]. The use of the impedance matching probe as a pre-matching element allowed generation of a higher reflection coefficient at the probe-tip. Normally losses in the cable and probe between the variable tuner and the DUT limit the magnitude of reflection coefficient that can be generated. For example, a tuner with the ability to generate 0.9 reflection can only present 0.8 to the DUT through 1 dB of loss.

Functional test of circuit blocks may also benefit from impedance matching fixturing. Power amplifiers implemented in GaAs sometimes use off-chip matching networks to meet cost and performance goals. The matching network can then be implemented in a less expensive technology such as a thin-film circuit on an Alumina substrate.

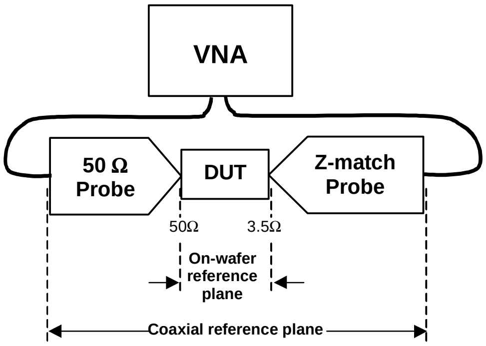


Figure 1. Block diagram of the two-tier calibration 'augmentation' used for impedance matching probe Vector Network Analyzer calibration.

Such a situation was recently reported. Tonks [2] discussed the use of an impedance matching membrane style probe card. The Pyramid Probe^{TM} card provided a load impedance of approximately 2.5 ohms by the use of a quarter-wavelength impedance matching section.

Calibration of measurement systems incorporating impedance matching fixturing has been primitive and only indirectly addressed. In [1] the error in a Short-Open-Load-Thru (SOLT) calibration due to the impedance mismatch was accounted for apart from the calibration. Manual correction of the S_{12} and S_{21} transmission terms was required after the VNA corrected measurements to remove the effects of the port impedance ratio.

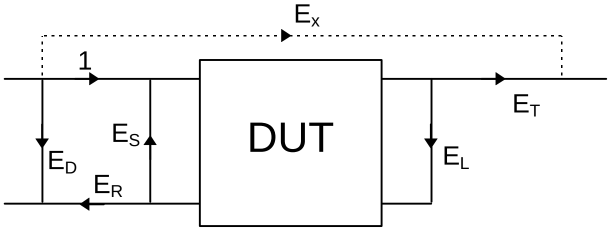
The probe card used in [2] required a long custom Thru standard for response calibration. An estimate of the loss of the Thru was used as a manual correction to the measurement.

The need exists for a method to provide VNA calibration with on-wafer reference planes that incorporate the impedance matching port definitions.

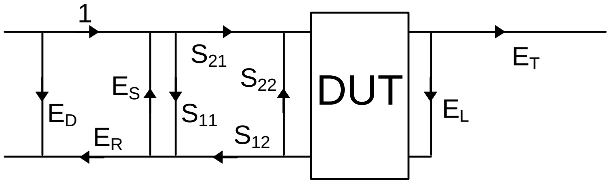
CALSET PORT AUGMENTATION

The calibration method proposed in this paper starts with an existing two-port calibration at coaxial reference planes. This would normally be performed at the ends of the cables where they connect to the probes. The two-port S-parameters for a probe are then combined with the coaxial calibration resulting in a new calset that has incorporated the probe parameters in the calset error model. Performing this process for both probes results in a calset with probe-tip reference planes, see Fig. 1.

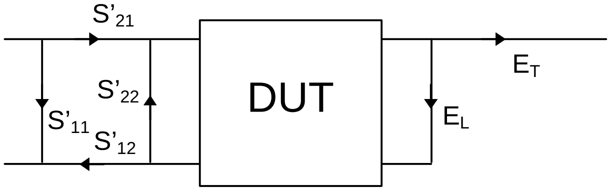
The basic forward error model for applying corrections is as follows [e.g., 3]:



With the addition of a two-port network at port 1 and omission of the crosstalk terms (normally not used in on-wafer calibrations) we then have:



We need to reduce this to the form of the first figure. An intermediate step gives:



where the S' are the cascaded error terms given by:

$$S'_{11} \quad E_D \quad \frac{E_R S_{11}}{1 \quad E_S S_{11}} \qquad S'_{21} \quad \frac{S_{21}}{1 \quad E_S S_{11}}$$

$$S'_{12} \quad \frac{E_R S_{12}}{1 \quad E_S S_{11}} \qquad S'_{22} \quad S_{22} \quad \frac{S_{12} S_{21} E_S}{1 \quad E_S S_{11}}$$

The reduction to the original error form gives:

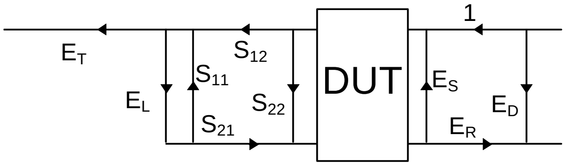
$$E'_D \quad E_D \quad \frac{E_R S_{11}}{1 \quad E_S S_{11}} \qquad E'_S \quad S_{22} \quad \frac{S_{12} S_{21} E_S}{1 \quad E_S S_{11}}$$

$$E'_R \quad \frac{E_R S_{12} S_{21}}{1 \quad E_S S_{11} \quad {}^{2}} \qquad E'_T \quad \frac{E_T S_{21}}{1 \quad E_S S_{11}}$$

$$E'_L \quad E_L \qquad E'_X \quad E_X$$

for the forward terms.

The reverse terms are similarly impacted by a two-port added to port 1:



and the section left of the DUT reduces to two terms

$$E'_L \quad S_{22} \quad \frac{S_{12} S_{21} E_L}{1 \quad E_L S_{11}} \qquad E'_T \quad \frac{S_{12} E_T}{1 \quad E_L S_{11}}$$

In all cases the convention on the subscripts of the S-parameters is that the S_{11} side of the augmenting two-port is at the probe connector (away from the DUT) and the S_{22} side is at the probe tip (toward the DUT). This holds true for augmentation of either port 1 or 2. The resulting equations are summarized in Table 1.

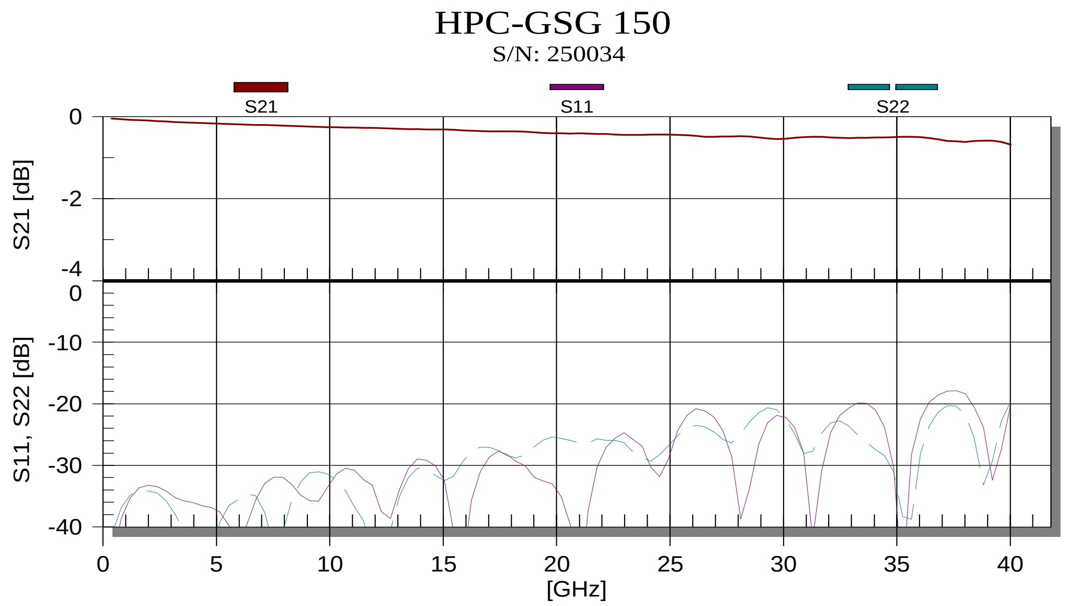
MEASUREMENT EXAMPLE

The S-parameters of the probe may be determined several ways. The Cascade Microtech WinCal Software [4] Probe Test function was used for this work and typical probe parameters are shown in Fig. 2. Probe Test uses an existing cable calibration to measure a probe touching Short, Open, and Load standards with known parasitics. The probe S-parameters are determined using an algorithm similar to the S-O-L one-port VNA calibration.

The requirement of known parasitics, while troublesome for wide-bandwidth metrology grade measurements, is not a significant error source in this example where the frequency is relatively low. Reasonable estimates of the parasitics are provided in a table of calibration coefficients included with the AirCoPlanar (ACP) coaxial probes. For more exacting applications a precision calibration method that is not dependent on known parasitics may be used to characterize the effective behavior of the standards – at least to the limits of standard measurement repeatability associated with probe placement accuracy.

Probe on Port 1	**Probe on Port 2**
$E'_{DF} \quad E_{DF} \quad \frac{E_{RF}S_{11}}{1 \quad E_{SF}S_{11}}$	$E'_{DR} \quad E_{DR} \quad \frac{E_{RR}S_{11}}{1 \quad E_{SR}S_{11}}$
$E'_{SF} \quad S_{22} \quad \frac{S_{12}S_{21}E_{SF}}{1 \quad E_{SF}S_{11}}$	$E'_{SR} \quad S_{22} \quad \frac{S_{12}S_{21}E_{SR}}{1 \quad E_{SR}S_{11}}$
$E'_{LF} \quad E_{LF}$	$E'_{LR} \quad E_{LR}$
$E'_{RF} \quad \frac{E_{RF}S_{12}S_{21}}{1 \quad E_{SF}S_{11}\,{}^{2}}$	$E'_{RR} \quad \frac{E_{RR}S_{12}S_{21}}{1 \quad E_{SR}S_{11}\,{}^{2}}$
$E'_{TF} \quad \frac{E_{TF}S_{21}}{1 \quad E_{SF}S_{11}}$	$E'_{TR} \quad \frac{E_{TR}S_{21}}{1 \quad E_{SR}S_{11}}$
$E'_{XF} \quad E_{XF}$	$E'_{XR} \quad E_{XR}$
$E'_{LR} \quad S_{22} \quad \frac{S_{12}S_{21}E_{LR}}{1 \quad E_{LR}S_{11}}$	$E'_{LF} \quad S_{22} \quad \frac{S_{12}S_{21}E_{LF}}{1 \quad E_{LF}S_{11}}$
$E'_{TR} \quad \frac{S_{12}E_{TR}}{1 \quad E_{LR}S_{11}}$	$E'_{TF} \quad \frac{S_{12}E_{TF}}{1 \quad E_{LF}S_{11}}$

Table 1. Summary of the equations needed to augment an existing calset with a probe on one port. The S-parameters for the probe use the convention that the subscript '1' indicates the coaxial connector side (S_{11}) of the probe and '2' indicates the probe tip side (S_{22}). This convention holds true regardless of the port to be augmented. Augmentation of both ports is accomplished by using the augmented calset for one probe as the starting point for calculation of the changes due to the second probe.



02-26-1999 13:19:47
Load Impedance=50.0+j0.0 Ohm   System Impedance=50.0+j0.0 Ohm
C-open = -9.7 fF   L-short = 4.8 pH   L-term = -1.70 pH

Figure 2. WinCal Probe Test measurements of standard 50Ω probe S-parameters.

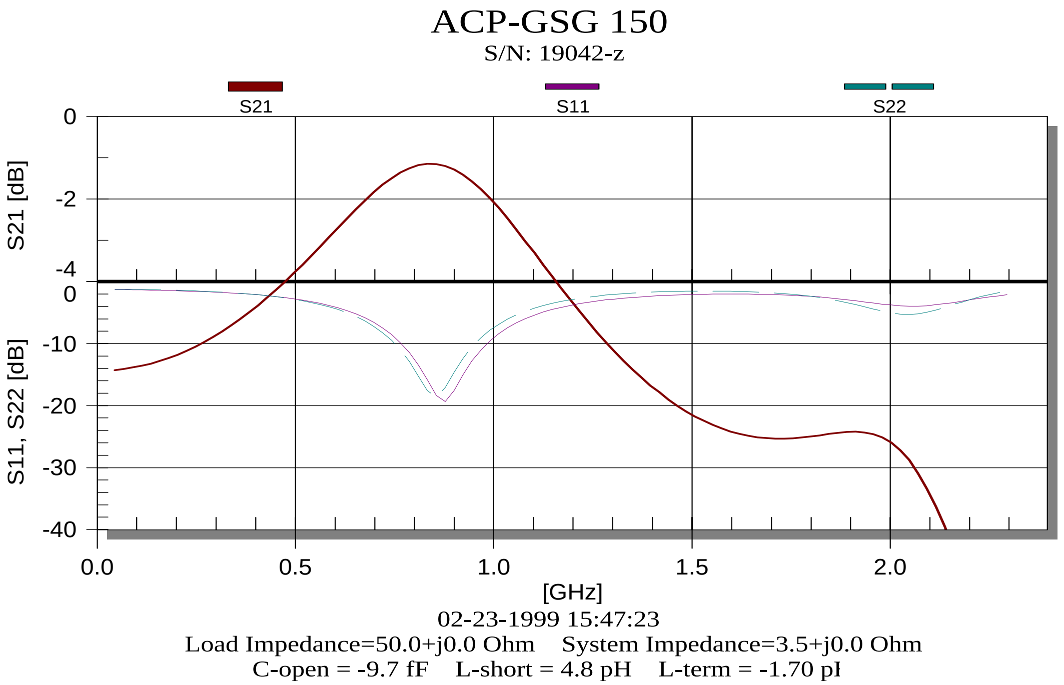


Figure 3. WinCal Probe Test determined S-parameters for an ACP20Z-GSG-150 50Ω to 3.5 Ω impedance matching probe. This probe has approximately 10% bandwidth centered at 850 MHz.

Probe Test supports the use of differing load resistance and port impedance. In Fig. 3, the S-parameters of an experimental impedance matching probe with 3.5 ohm port impedance are determined from measurements of a 50 ohm load with normal short and open standards. This probe has (by design) approximately 10% bandwidth centered at 850 MHz. The S-parameters are *normalized scattering parameters* and include the effects of differing port impedances.

The augmentation process was performed using a program called “VNAtools” [5]. VNAtools was written in Microsoft Visual Basic with complex number arithmetic functions created in a C++ Dynamic Link Library (DLL). VNAtools interacts with WinCal using OLE Automation for all file I/O and VNA communication including loading and saving of CalSet arrays. WinCal’s automation capability significantly reduces the complexity of VNAtools.

RESULTS AND CONCLUSIONS

Measurement data for a primitive verification structure are shown in Figs. 4 and 5. The electrically short Thru acts essentially as a direction connection of the two ports which for this case of differing port impedances represents a mismatch. Indeed port 1 observes a 3.5 ohm termination relative to a 50 ohm normalization of the S-parameter while port 2 sees 50 ohms normalized to 3.5 ohms.

The response of the transmission terms is also consistent with theoretical expectations for normalized scattering parameters [e.g., 6] calculated for direction connection of a 50 ohm port and a 3.5 ohm port. The forward and reverse transmission terms are expected to be equal for the reciprocal and passive Thru connection.

It is immediately apparent that the calibration succeeds over a much wider bandwidth than the probe impedance match. While this allows correct small signal measurement, the desired physical termination impedance is not what was targeted. The benefits associated with termination equivalent to the application environment only apply within the probe passband.

The port augmentation second tier calibration method presented here should be a practical and useful technique when using impedance matching fixtures or for situations where a well defined Thru standard is not available, impractical, or undesirable.

ACKNOWLEDGEMENT

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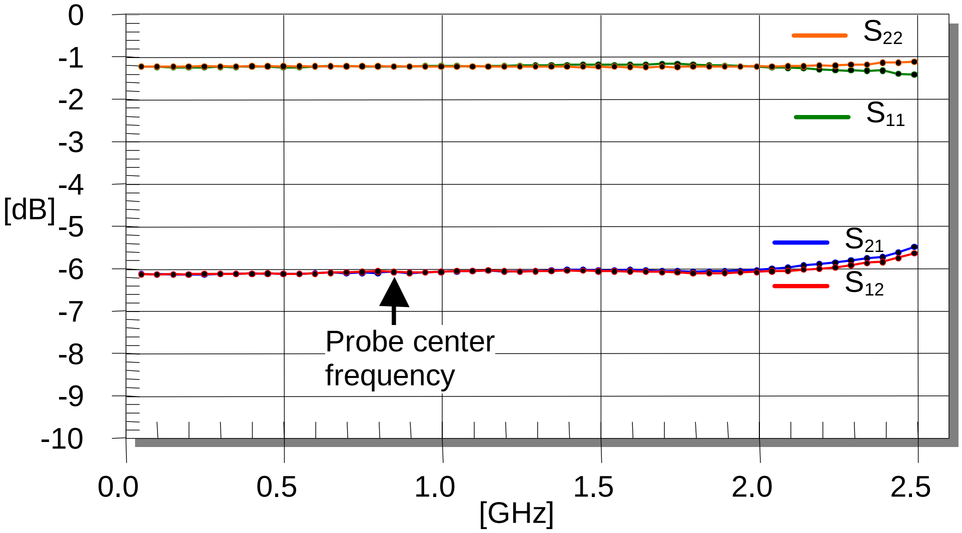

Figure 4. Measured normalized scattering parameters for a direct connection (1 ps Thru) between 50Ω port 1 and 3.5Ω port 2. The calibration succeeded over a frequency range much wider than the impedance matching probe bandwidth (10% centered at 0.85 GHz). The theoretically predicted normalized scattering parameters for this direct connection would be S_{11}=S_{22}= -1.22 dB, S_{12}=S_{21}= -6.12 dB.

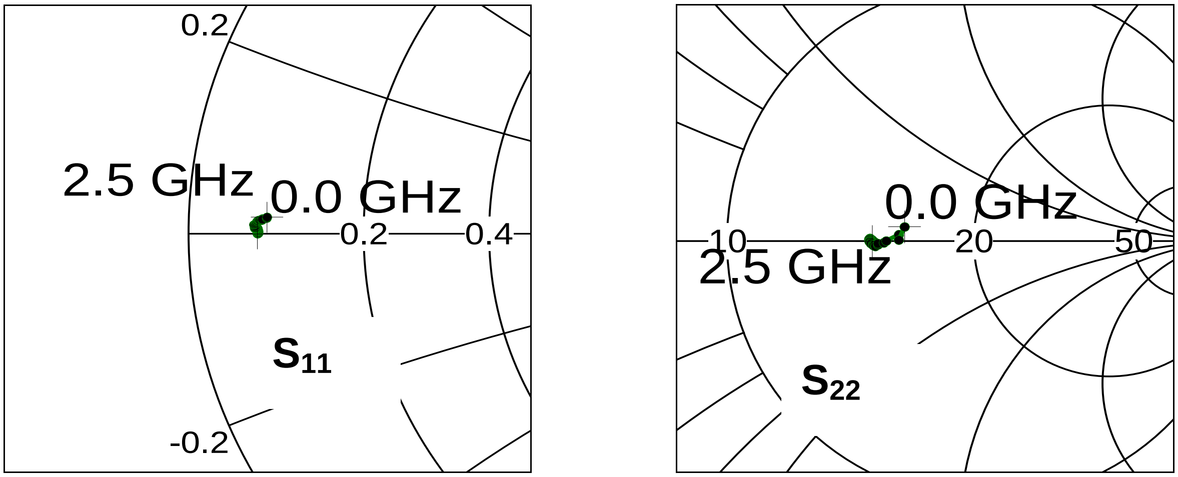

Figure 5. Expanded Smith Chart views of the measured normalized scattering parameters for the direct connection (1 ps Thru) between 50Ω port 1 and 3.5Ω port 2. The S_{11}=0.07 value on the port 1 50 ohm normalized Smith Chart corresponds to measurement of the 3.5 ohm port 2 load. Similarly the S_{22}=~14.5 on the port 2 3.5 ohm normalized Smith Chart corresponds to measurement of the 50 ohm port 1 impedance.