DATA CORRELATION DURING THE TRANSITION FROM LAB TO FAB

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Motivation

- To develop an accurate, repeatable, and easy to implement method for 2-port s-parameter characterization of DUT probe cards. The accuracy of the probe card s-parameters are critical because they will be de-embedded from full path DUT measurement data acquired during wafer-level measurements. The resulting fully de-embedded DUT measurement data is then correlated with “Gold Standard” measurement data established on a characterization test bench. Once correlation requirements are satisfied, the hardware and software test solution is released to the RFMD production test group.
Agenda

De-embedding Methods
- Direct Probe
- 2-Tier Calibration
- Test Fixture Modeling

Data Correlation
- Some Definitions
- Development Process Flow
- Things To Consider

Data De-embedding
- Application Example
- Equations
- Production Data Example
De-embedding Methods Discussed:

- Direct Probe
- Test Fixture Modeling
- 2-Tier Calibration
Direct Probe Method

- This method uses a G-S or G-S-G wafer probe, (e.g. Cascade Microtech ACP or GGB PicoProbe), to directly contact the membrane probe RF signal contact and a ground contact.

![Diagram of Direct Probe Method]

- Perform a full 2-Port SOLT coaxial calibration to cable ends (ref plane).
- Set up PNA to de-embed the wafer probe .S2P data from full path measurement data.
- Connect PNA Port 1 to wafer probe, Port 2 to DUT probe card SMA.
- Measure the RF path S-Parameters and save data to an .S2P file.
Direct Probe Method

Advantages:
• Direct s-parameter measurement of the RF path.

Disadvantages:
• Risk of damage to membrane core bumps by the wafer probe tips
• S-Parameters of G-S/G-S-G wafer probe must be well known
• Potential signal distortion due to unreliable contact
• Time consuming to set up for each RF path
• Multiple wafer probes on hand to match various probe core pitch sizes
2-Tier Calibration Method

This method uses a Macro application found on the Agilent PNA to create an S2P file which models the DUT probe card. The macro calculates four s-parameters from two 1-port calibrations, one on side A of the probe card and the other on side B of the probe card. The resulting S2P file is then used to de-embed the probe card from the full DUT measurement path data.

Cascade Microtech’s “WinCal” has a 2\textsuperscript{nd} Tier Calibration method which is similar to Agilent’s “AdaptorChar” macro. Measurement results using both methods are compared.

*Reference Paper: “Two Port Calibration of test fixtures with OSL method” by Chen, Wang, Liu, and Zhu. This method assumes S21S12 reciprocity of the fixture which is the true with a passive network. (*Note: Paper supplied by Daniel Bock from Cascade Microtech.*)
2-Tier Calibration Method

Equipment

106-686A ISS

Agilent 5230 PNA

eCal module

Wafer Prober

DUT Probe Card
2-Tier Calibration Method

1st - Tier Calibration Step

- Perform a 1-Port SOL coaxial calibration to cable end (ref plane).
- Save calibration as a Tier1 CalSet.
- Connect PNA Port 1 to DUT probe card SMA.
2-Tier Calibration Method

2\textsuperscript{nd} - Tier Calibration Step

Perform a 1-Port SOL wafer level calibration to Pyramid Probe bump using the 106-686A ISS for the RF path of interest.
2-Tier Calibration Method

2nd - Tier Calibration Step (cont.)

Save calibration as a Tier2 CalSet.
2-Tier Calibration Method

Run “AdaptorChar” macro
RFMD Test Fixture Direct vs 2-Tier

Direct Probe Method

2-Tier Method

~800um pitch to closest ground on Pyramid Probe Core. Cal Coefficients = “0” for L-short, C-open, L-Term.
Algorithm Comparison
AdaptorChar vs. WinCal

- S11
- S12
- S21
- S22

Adaptor Char
WinCal
2-Tier Calibration Method

Advantages

• Risk of membrane probe tip damage is minimized, (ISS)
• 2-Tier Method implementation is less complicated than Direct Probe Method
• Less time consuming
• De-embedded data is more accurate since no port extension is used in the VNA calibration

Disadvantages

• Visual alignment to cal standards make this method not suitable for Pogo Pin contactors

*Note: The 2-Tier Calibration Method has replaced the Direct Probe Method for Characterizing DUT Probe Cards which use Pyramid Probe Cores.
De-embedding Methods

Direct Probe

2-Tier Calibration

Test Fixture Modeling
Test Fixture Modeling Method

- This method utilizes a golden standard device and ADS circuit optimization template to tune the Probe Card circuit parameters to match those of a known “Golden Device”
Test Fixture Modeling Method

1. Measure the S-parameter of the DUT + Test Fixture
2. Extract the s-parameters of the test fixture
3. Run the optimization algorithm in ADS
4. Generate the “Golden DUT”
5. “Golden DUT+ Probe card Model” = “Golden DUT + Test Fixture Actual”
6. Measure the S-parameter of the DUT + Test Fixture
Test Fixture Modeling Method

- $S_{11}$ for the Fixture Model + Golden DUT is equal to the response Golden DUT + Test Fixture
- Based on this premise the optimal goal are defined
Test Fixture Modeling Method

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Test Fixture Modeling Method

- The test fixture is modeled using three transmission lines in cascade.
- The parameters that define each transmission line in the model are:
  - $\varepsilon_r$ (Dielectric constant)
  - $\tan\delta$ (Loss tangent)
  - Length
  - $Z_0$ (Characteristic Impedance)
Why two States are Needed?

- Two known variables and three unknown variables, Ideally we should need a system of three independent equations to solve this problem
- With the ADS optimization routine, only two states (equations) are needed to find the four unknowns

\[ S_{11_{DUT}} = \frac{S_{11_{TF}} - \Delta S \times S_{11_M}}{1 - S_{22_{TF}} \times S_{11_M}} \]

where, \( \Delta S = S_{11_{TF}}S_{22_{TF}} - S_{21_{TF}}S_{12_{TF}} \)
Test Fixture Modeling Method

ON-STATE

OFF-STATE

Test Fixture extracted data
Test Fixture Modeling Method

- **Advantages**
  - Less time consuming
  - De-embedded data is more accurate since no port extension is used in the VNA calibration
  - Alignment and contact problems are eliminated, since an automatic prober is used
  - Applies to both Pyramid and Pogo-Pin probe contactors

- **Disadvantages**
  - Gold Device must be well “Known”
  - Requires the DUT to be measured in two State (i.e., On, OFF)
Data Correlation

- Correlation measures the ability of a measurement system to reproduce the measurement (and, therefore, acceptance) values obtained on an originating, or “Gold”, tester
Data Correlation

• A Gold Tester is the measurement system used to determine and assign specifications
• A Control Unit is a DUT measured by a Gold Tester
Data Correlation

- Offset is the difference between the average values of a Control Unit measured in a Correlating Tester and the control unit measured values in a Gold Tester.

- Repeatability is the consistency of a single measurement system to measure the same part multiple times; it is related to the standard deviation of the measured values.
## Data Correlation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recommended Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of Determination $R^2$</td>
<td>$R^2 &gt; 95%$ <strong>Accept</strong>  $87% &lt; R^2 &lt; 95%$ <strong>Marginal Accept</strong></td>
</tr>
<tr>
<td>Offset</td>
<td>$&lt; 5%$ at USL and LSL <strong>Accept</strong>  $5% &lt; \text{Offset} &lt; 8%$ <strong>Marginal Accept</strong></td>
</tr>
<tr>
<td>Linearity</td>
<td>The hypothesis test that slope between the Gold and Production system is equal to one</td>
</tr>
<tr>
<td>Repeatability</td>
<td>$&lt; 10%$ <strong>Accept</strong>, $10% &lt; R &lt; 30%$ <strong>Marginal Accept</strong></td>
</tr>
<tr>
<td>Error Independence</td>
<td>hypothesis test that error is independent of measured value</td>
</tr>
</tbody>
</table>
Data Correlation

Some Definitions

Development Process Flow

Things To Consider
Data Correlation

Some Definitions

Development Process Flow

Things To Consider
Threats to Achieving Acceptable Correlation

- Measurement repeatability (process-or machine-related)
- Clustering of values of the correlation sample
- Insufficient range of values represented by the sample used in the study
- Poor calibration
- Lack of standards available for the calibration process
- Insufficient resolution
- Algorithm differences between participating testers
- Noise floor differences between participating testers
- Tooling differences between participating testers
- Damage to correlation units during the study
- Mislabeled correlation sample
Data De-embedding

Application: FET Switch

- An RF switch includes multiple series and shunt branches and a controller that would provide the necessary bias voltages to the switch devices for a given control bit setting.

- In an equivalent circuit model, ON devices can be considered as resistors, OFF devices as capacitors.
A Figure of Merit, (FOM), commonly used for benchmarking FET Switches is $R_{on}*C_{off}$. Low $R_{on}*C_{off}$ is critical to ensure a switch with low insertion loss (low $R_{on}$) as well as better isolation (low $C_{off}$)

Good RF Switch design should include very low insertion loss in the ON path and high isolation in the OFF path, (along with broad bandwidth, high linearity, and fast switching speed)

$R_{on}$ and $C_{off}$ are calculated from $S_{11}$ (Input Complex Reflection Coefficient), of the DUT. So accurate measurement of $S_{11}$ at the DUT is critical. Also accurate measurement of the RF Probe Card S-Parameters, which are de-embedded from the total DUT measurement path, is critical.
Data De-embedding

Equation to de-embed the probe card from the full RF measurement path data for a 1-Port Shunt Switch

\[
S_{11_{DUT}} = \frac{S_{11_{TF}} - \Delta S}{1 - S_{22_{TF}} S_{11_{M}}} \ast S_{11_{M}}
\]

where, \( \Delta S = S_{11_{TF}} S_{22_{TF}} - S_{21_{TF}} S_{12_{TF}} \)
Data De-embedding

Equations to de-embed the probe card from the full RF measurement path data for a 2-Port Series Switch

\[
\begin{align*}
\mathbf{T}_{\text{MEASURED}} &= \mathbf{T}_A \mathbf{T}_{\text{DUT}} \mathbf{T}_B \\
\mathbf{T}_{\text{DUT}} &= \mathbf{T}_A^{-1} \mathbf{T}_{\text{MEASURED}} \mathbf{T}_B^{-1}
\end{align*}
\]
Data De-embedding

**R\text{on} - C\text{off} Calculation**

\[
\omega = 2\pi f \\
\omega = \text{Freq\text{(MHz)}} \\
Z_{\text{Load}} = 50 \left( \frac{1 + S_{11}}{1 - S_{11}} \right) \\
C_{\text{off}} (fF) = \text{Im} \left( \frac{1}{Z_{\text{Load}}\omega} \right) \times 10^{15} \\
R_{\text{on}} (\Omega) = \text{Re} (Z_{\text{Load}}) \\
FOM = R_{\text{on}} \times C_{\text{off}}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>SOI</th>
<th>pHEMT</th>
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</thead>
<tbody>
<tr>
<td>Insertion Loss (2GHz)</td>
<td>dB</td>
<td>0.34</td>
<td>0.24</td>
</tr>
<tr>
<td>Isolation (2GHz)</td>
<td>dB</td>
<td>20.2</td>
<td>15.0</td>
</tr>
<tr>
<td>Ron</td>
<td>Ohms</td>
<td>2.7</td>
<td>1.9</td>
</tr>
<tr>
<td>Coff</td>
<td>fF</td>
<td>92</td>
<td>147</td>
</tr>
<tr>
<td>Ron*Coff</td>
<td>fs</td>
<td>250</td>
<td>280</td>
</tr>
</tbody>
</table>
USL and LSL are established through correlation of EVB and pre-production release multi-wafer measurement data.

FOM (avg. of passing DUTs) \( \sim 290 \)
Conclusion

- Three probe card de-embedding methods were presented as potential candidates for use in a production environment along with the advantages and disadvantages of each: Direct Probe, 2-Tier Calibration, Test Fixture Modeling.
- 2-Tier Calibration is the best de-embedding method for applications which use Pyramid Probe Cores. The 2-Tier method is not suitable for probe cards with PogoPin contactors due to the need for visual alignment to the ISS.
- Test Fixture Modeling is currently the best de-embedding method for applications which use PogoPin Contactors.
- The correlation process is used to validate production probe data to 'trusted' Lab data.
- A proven and correlated production probe solution can be used to accurately extract critical DUT parameters in production test such as S-Parameters, $R_{on}$, $C_{off}$, and FOM.