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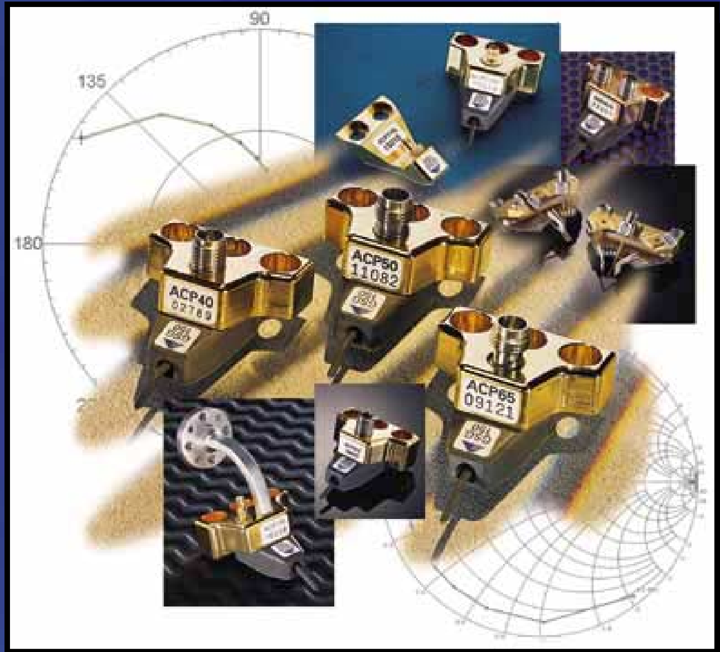
Advanced RF Calibration Techniques



presented by

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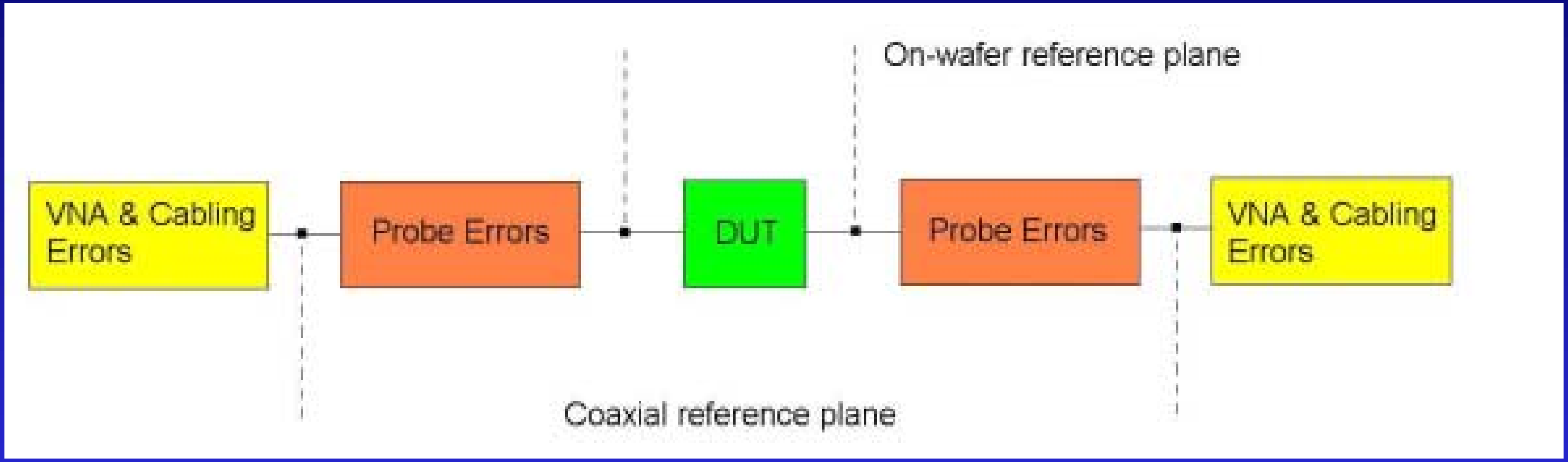
Where is the reference plane?



- In order to know exactly what we are measuring all errors up to the probe tip must be removed
  - This includes internal VNA errors after the sampler, the cables and probes
- Normally a coaxial calibration will remove all errors to the end of the coax cable - For on-wafer measurements we also need to correct for the losses in the probes
  - Thus calibration standards are required to be available at the probe tip

Links

App Notes –

On-wafer VNA

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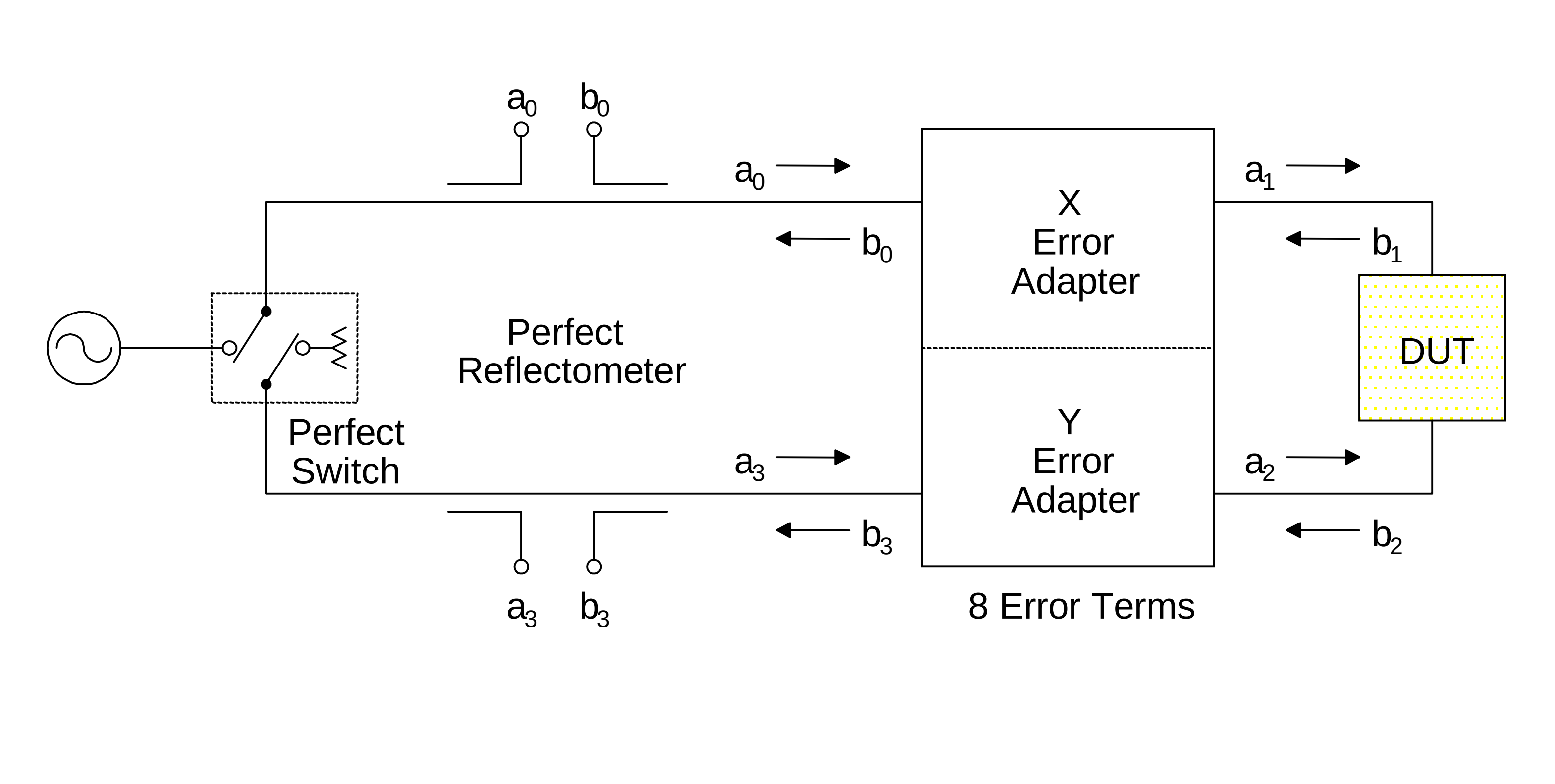
What is the basics of the Vector Network Analyser?



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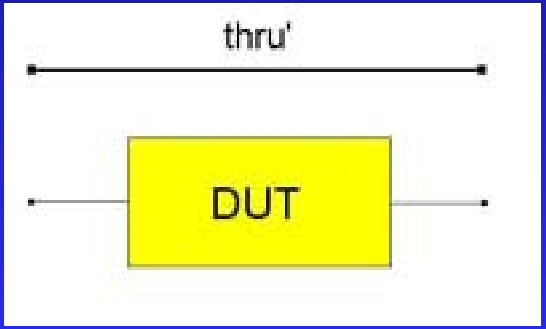
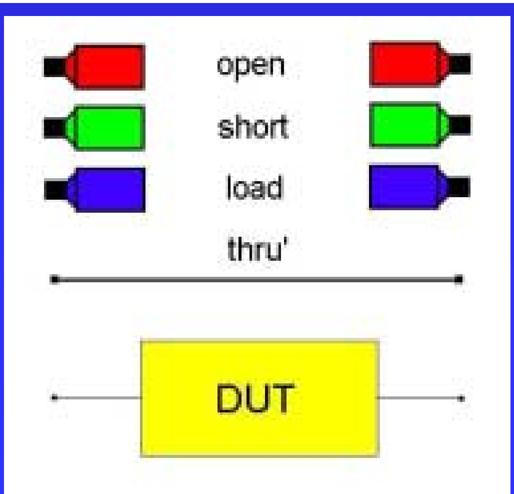
What are the calibration options and standards?

- Un-corrected measurements
  - Poor accuracy, but fast?
  - Rarely used
  - Easy (no calibration required)
- Response calibration
  - Low accuracy
  - Used only when speed is more important than accuracy
  - Only require one standard
- Full 2-port calibration
  - Highest accuracy
  - Removes following errors
    - Directivity
    - Source/load match
    - Reflection/transmission tracking
    - Cross-talk
  - Requires up to 7 standards





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Which Full 2-port calibration techniques can I use?

- Thru-Reflect-Match (LRM)
- Thru-Reflect-Reflect-Match (LRRM)
- Thru-Reflect-Line (TRL or LRL)
- Short-Open-Load-Thru (SOLT)
- Short-Open-Load-Reciprocal (SOLR)

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SOLR

LRRM Verify

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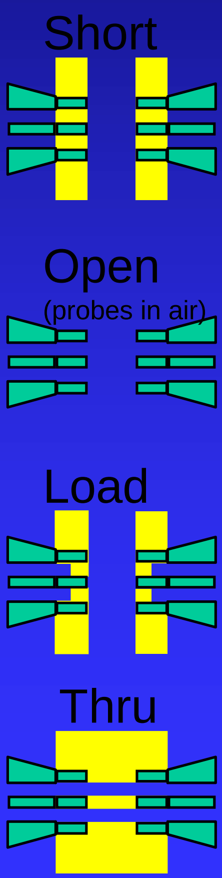
Why should I use SOLT calibration?



- Short-Open-Load-Thru Calibration
  - Most Commonly Used Cal
    - all standards must be perfectly known (cal kit)
    - open has capacitance (often negative)
    - short and load have inductance
    - not inherently self-consistent
    - uses off-wafer standards
    - available on virtually every vector network analyser
    - performs reasonably well if accurate models of calibration standards can be determined
    - sensitive to probe placement

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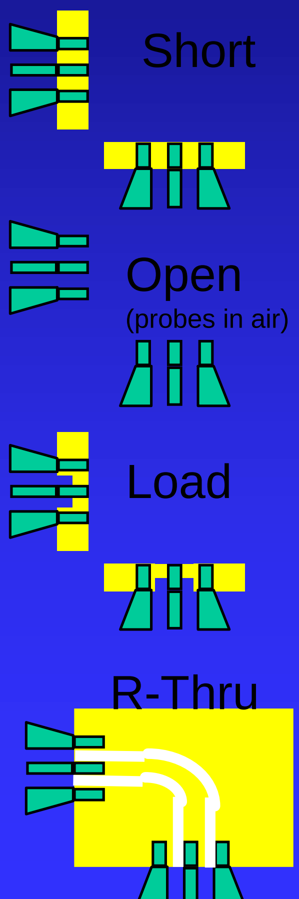
Why should I use SOLR calibration?



- Short-Open-Load-Reciprocal Calibration
  - Like SOLT but with general Thru standard
    - reciprocal thru $S_{12} = S_{21}$
    - tolerant to high loss or highly reactive insertion standard
  - convenient for use with probe cards
    - fixed probe spacing would otherwise require custom standards
  - not available on vector network analysers
    - requires Cascade Microtech software (WinCal)
  - still needs accurate models of calibration standards

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SOLR

Why use an orthogonal calibration?

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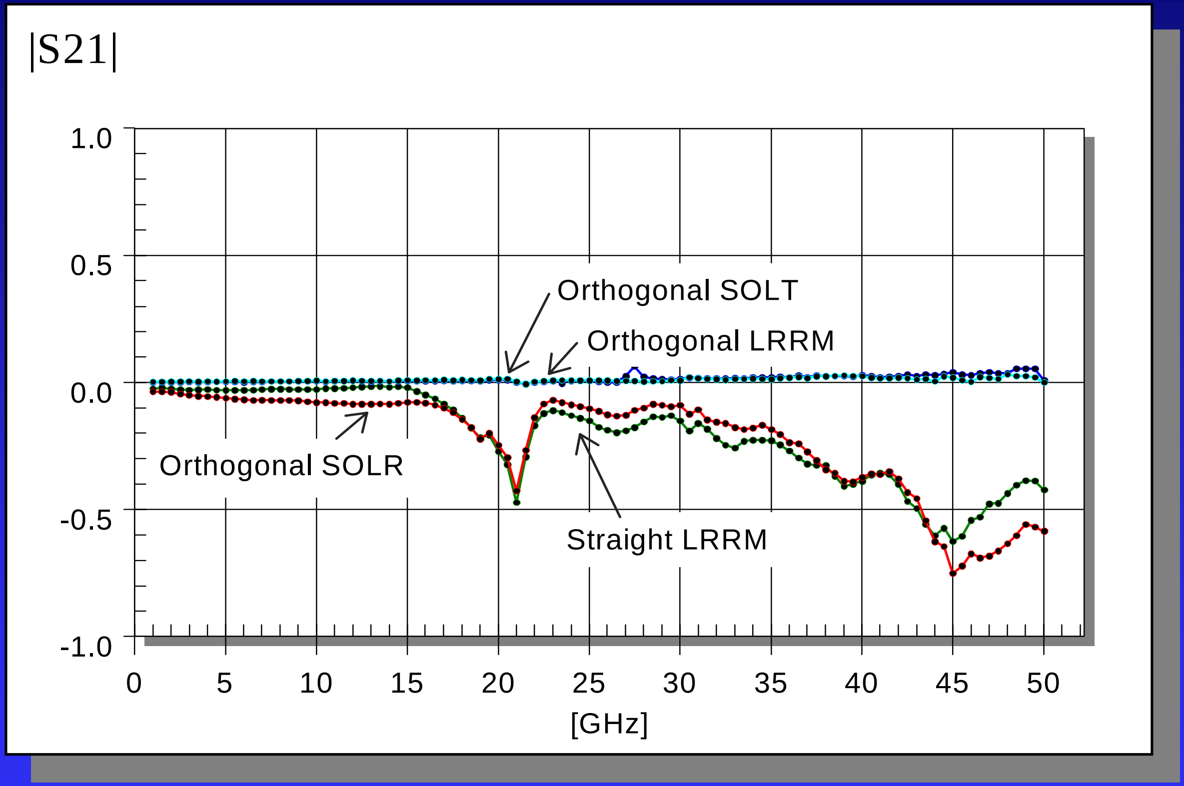

- Insertion loss measurements made of an orthogonal CPW thru' line using straight LRRM and orthogonal LRRM, SOLT and SOLR calibrations

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SOLR

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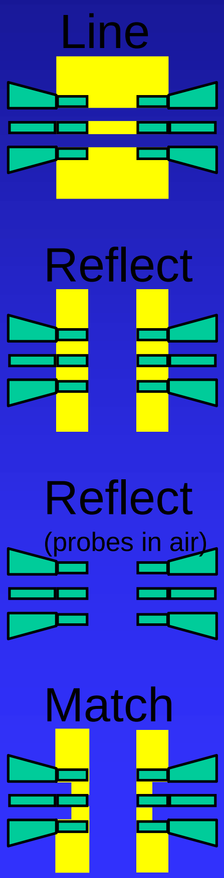
Why should I use LRRM calibration?

- Cascade Microtech Calibration Research
  - Line-Reflect-Reflect-Match Calibration
    - available in WinCal
    - only requires match standard on one port
    - like TRL only Match acts as infinitely high loss line
    - broadband calibration
    - one transmission line standard allows fixed probe spacing calibration
    - Thru (line) delay, Match resistance must be known
    - measurements referenced to laser trimmed resistor
    - uses off-wafer standards
      - Impedance Standard Substrate
    - same standards as SOLT only no need for cal kit



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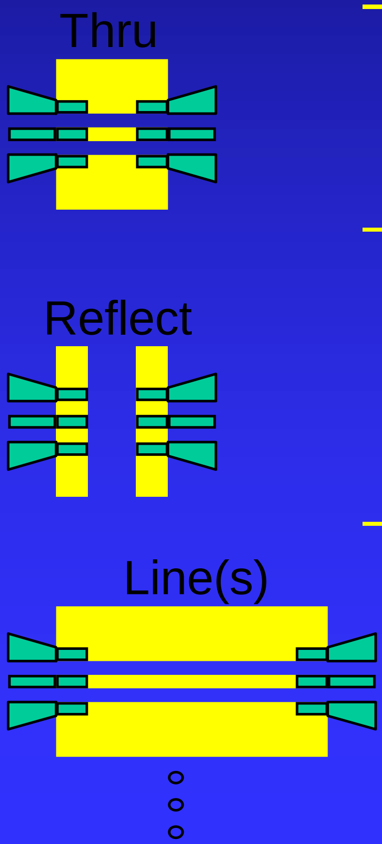
Why should I use TRL calibration?



- Research by the U.S. National Institute of Standards and Technology
  - Multi-line TRL (Thru-Reflect-Line)
    - optimal weighted average of standard measurements
  - uses multiple transmission lines as standards
    - measurements referenced to line impedance
    - limited frequency range (e.g. 3 lines for 2-18 GHz)
  - requires multiple probe spacing
    - not suitable for fixed spacing probes
    - standards need to be on-wafer (with DUT)
    - fully automatic cal achievable with motorized positioners

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Which calibration is best for my application?

	Z_0 Reference	Inherently Consistent	Probe Card Support	Absolute Accuracy
SOLT	Trimmed Resistor	No	Fair	Fair
NIST TRL	Transmission Lines	Yes	Poor	Best
TRL	Transmission Lines	Yes	Poor	Poor-Fair
LRRM	Trimmed Resistor	Yes	Fair	Very Good
LRM	Trimmed Resistor	Yes	Fair	Fair
SOLR	Trimmed Resistor	Yes	Best	Good

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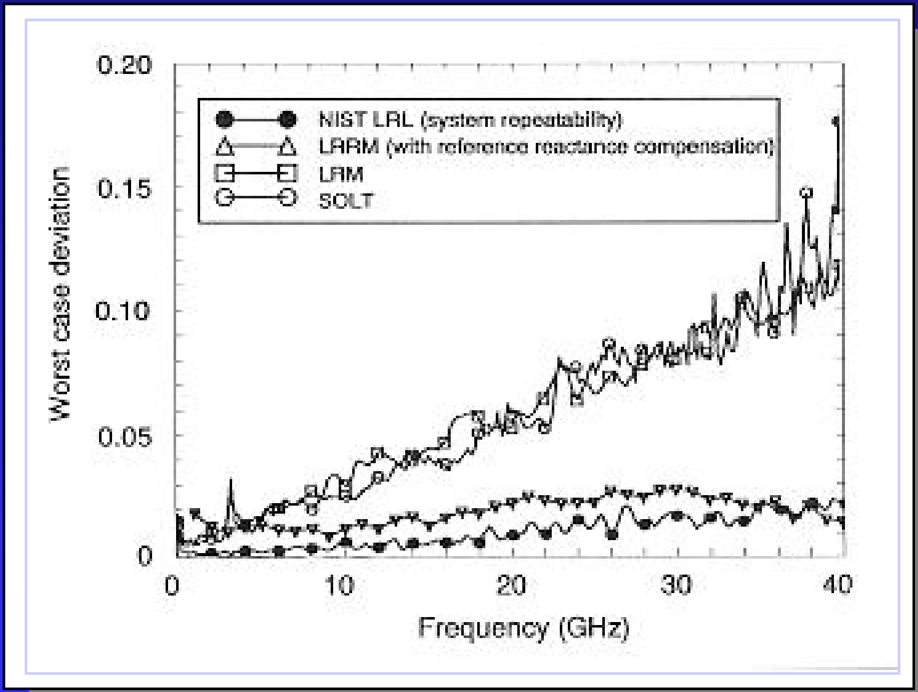
What is the most accurate calibration technique?

- NIST Calibration and Verification Software
- Verification standards are GaAs CPW lines
- 45MHz to 40GHz
- LRRM compares with system drift limit
- SOLT /LRM
  - growing error w/freq
  - possible cal kit error
  - possible ref plane error



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110GHz Comp

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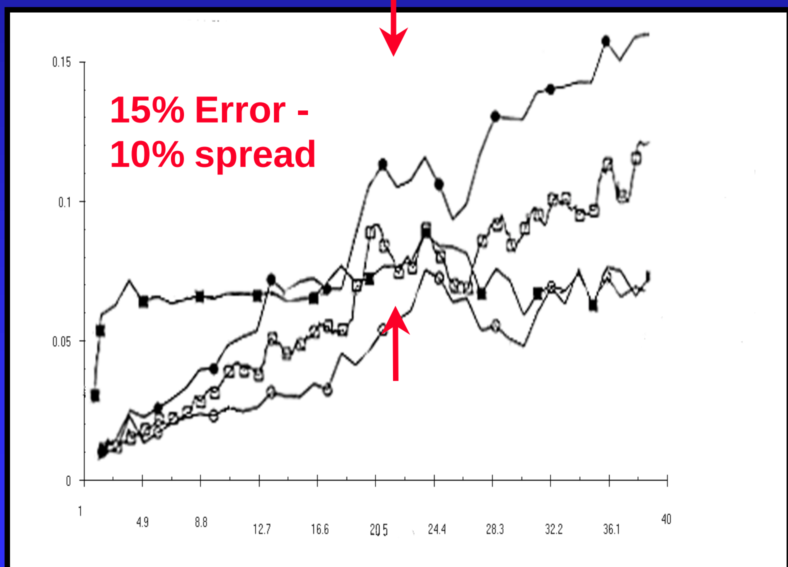
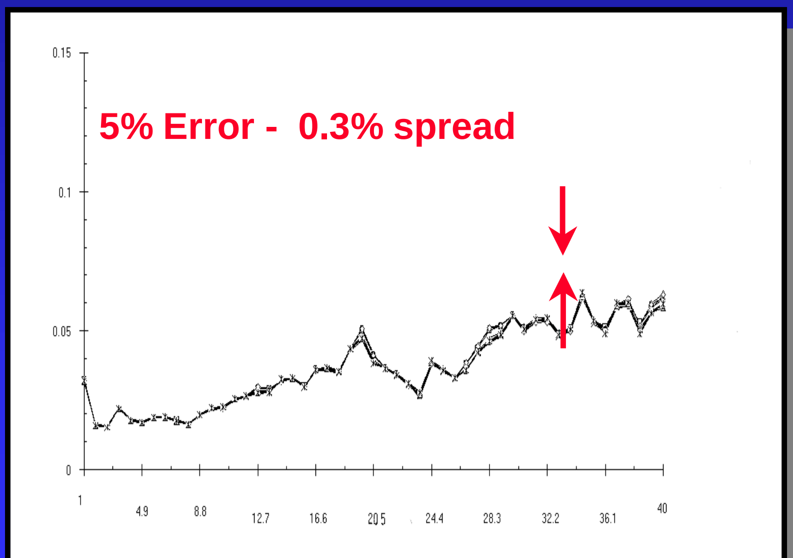
How does a manual calibration compare to an automatic calibration?

Worst Case Accuracy to 40GHz

Four Manual Calibrations



Ten Semi-Auto Calibrations



Semi-auto Prober is faster and far more repeatable!

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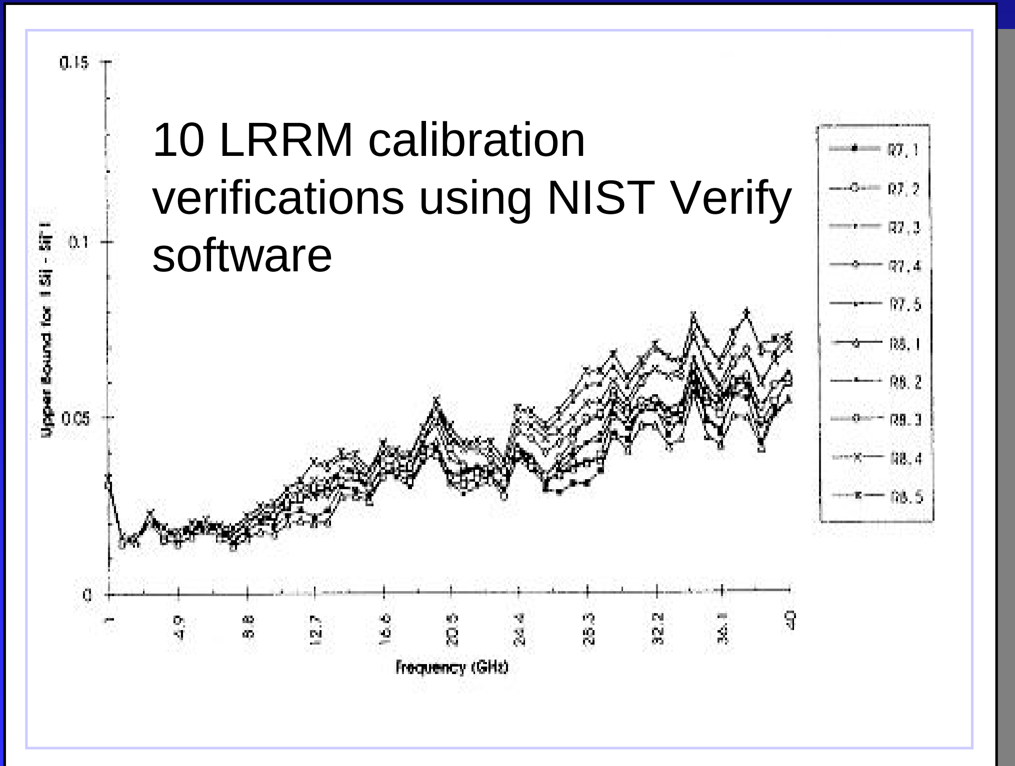
How repeatable are the calibration standards?

Worst case deviation



Frequency (GHz)

- Impedance Standard Substrate Standards are very repeatable

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What are the Problems with Over Temperature Microwave Measurements?

- Frost build-up at low temperatures
  - A small enclosed measurement environment purged to < - 55 degC
- System drift of probes and cables over temperature
  - Calibrate with probes and cables soaked at temperature
- Unknown load standard on ISS
  - A thermally isolated auxiliary chuck is required to mount the ISS
- Wafer expansion/contraction
  - Probe station compensation capability for die to die stepping

Links

App Notes –

HF Over temp

HF Over temp2

Thermal Meas

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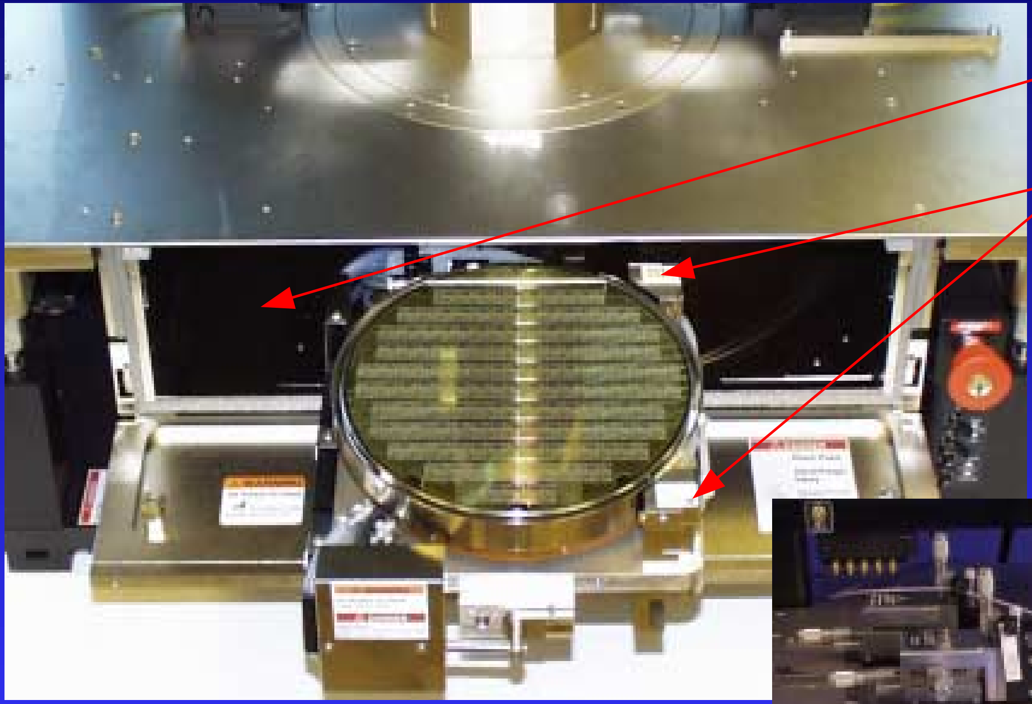
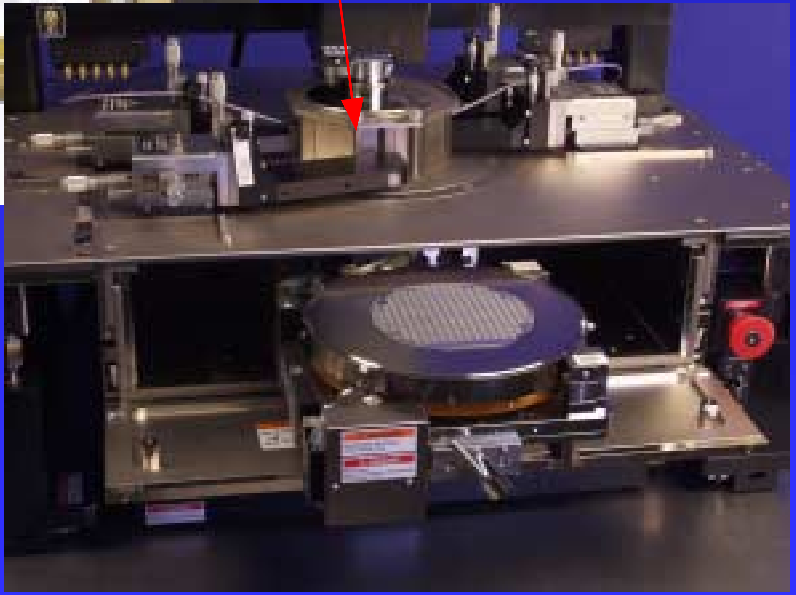
What Can I do to avoid these problems



- Dry, Frost Free environment
- Auxiliary Chucks
- Top-Hat



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HF Over temp

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Thermal Meas

Data sheets –

S300

Summit RF

Summit 9101

RF-1

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Over Temperature Probing Techniques

- Calibrate with probes, DUT and ISS at ambient
  - Good initial calibration accuracy
  - Phase error at temperature due to probe and cables expansion (not recommended)
- Calibrate with probes, DUT and ISS at temperature
  - Poor calibration due to unknown load standard
  - Little system drift (not recommended)
- Calibrate with probes and DUT at temperature, and ISS at ambient (Recommended)
  - Good initial calibration accuracy
  - Little phase error due to probes and cable expansion

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HF Over temp

HF Over temp2

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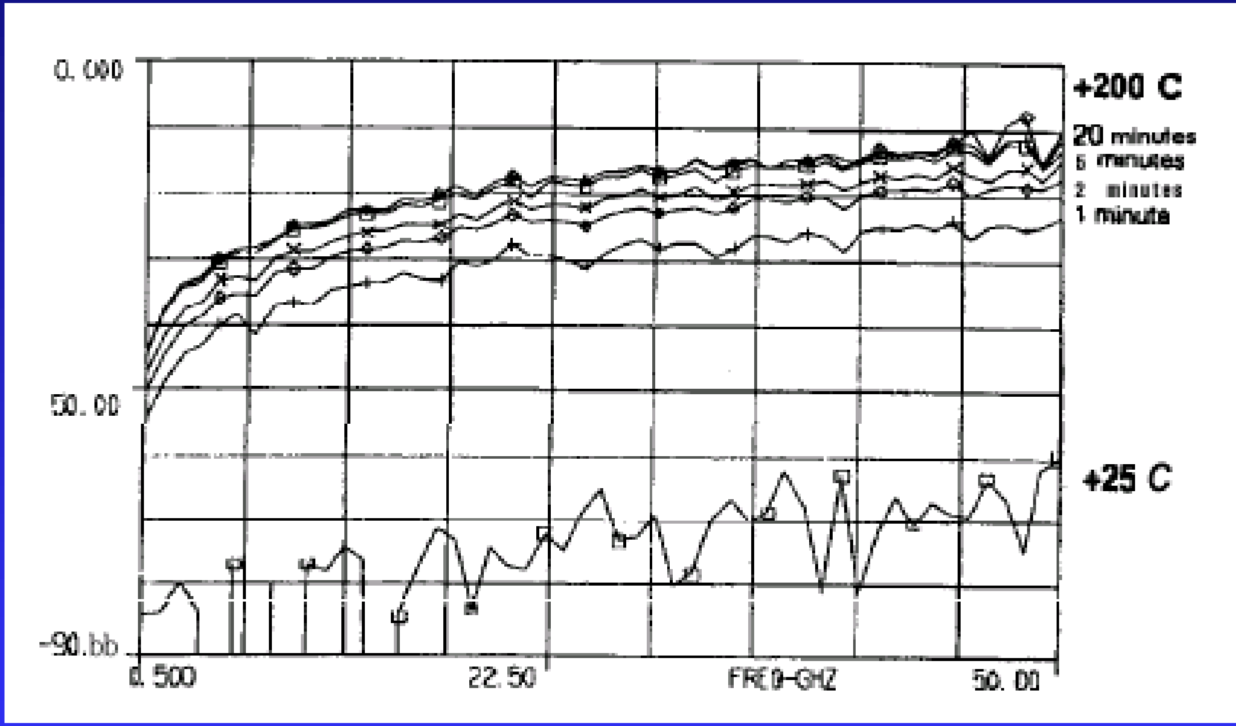
Calibration Stability at 200°C for a 25°C Calibration



Calibration stability unacceptable

- Probe still changing after 15 mins
- Calibration stability exhibits greater degradation with increasing frequency

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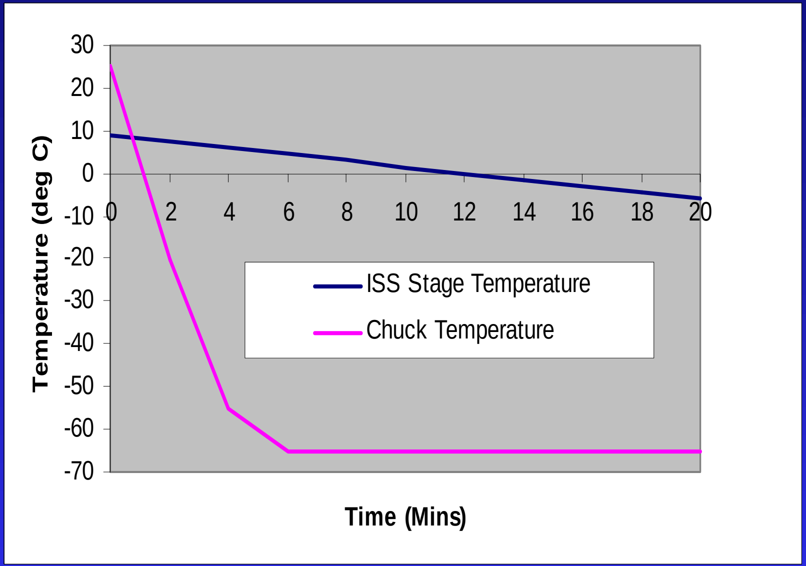
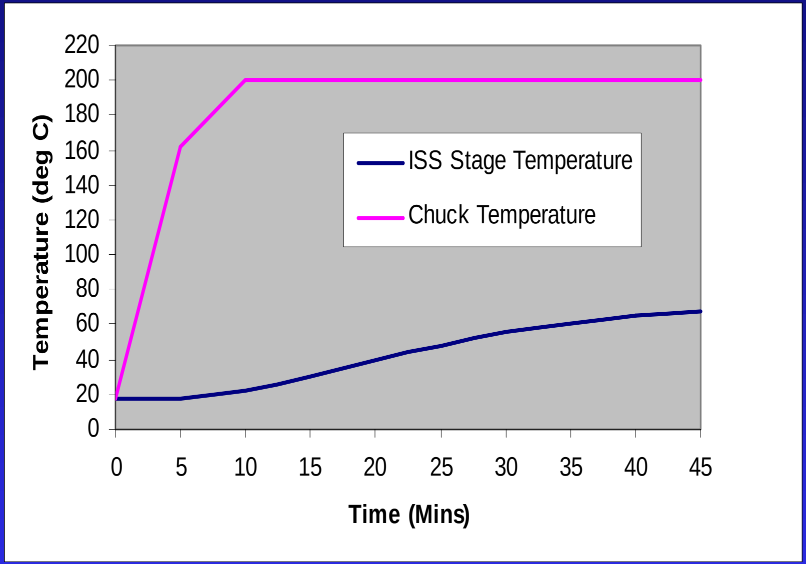
Auxiliary Chuck Temperature





ISS Temperature stays between -10°C and 60°C over the whole thermal chuck range - Reducing error from 50 ohm load standard

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HF Over temp2

Thermal Meas

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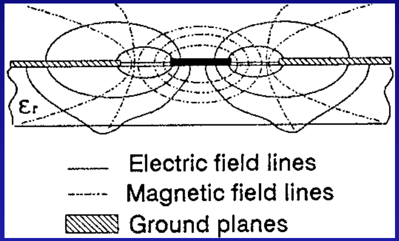
Think About Testability Before Design

- RF Performance
  - Pad configuration (GS Vs GSG)
  - Probe pitch
- Ability to Physically Probe
  - Pad size
  - Pad height
  - Distance between probes
  - Number of contacts per side
- Calibration
  - Paths
  - Best calibration methods



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Layout Rules

WPH900 Rules

On-wafer VNA

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Probe Stations

ACP Probes

Eye-Pass Probe

HPC Probe

Probe Guide

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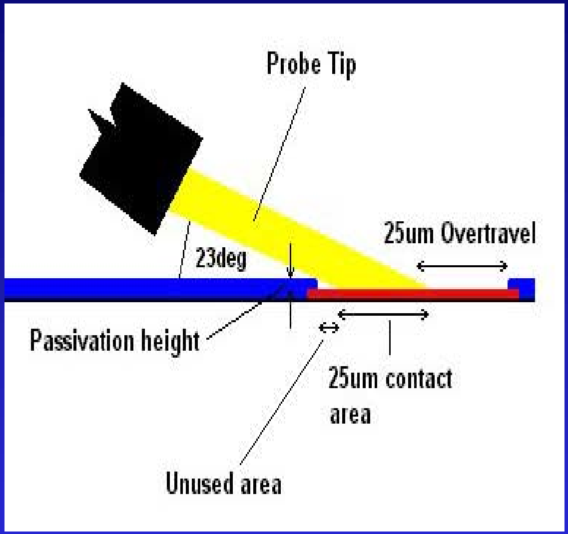
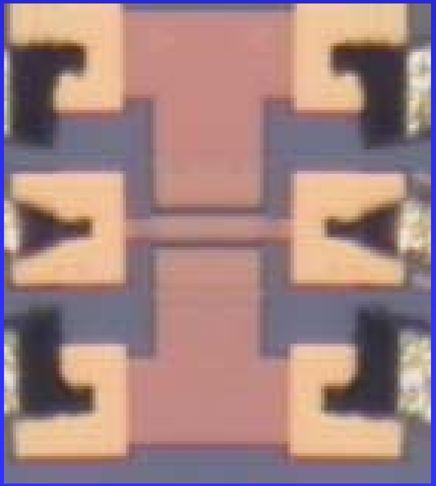
What pad sizes should I use?

- Recommended minimum pad is 80um x 80um for ACP Probes when performing automated measurements
- Smaller pad dimensions can be used for manual probing
- HPC Probe Allows 40um x 70um manual probing
- Passivation height must be considered
- Pad height variation must not exceed 25um





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Probe Stations

ACP Probes

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HPC Probe

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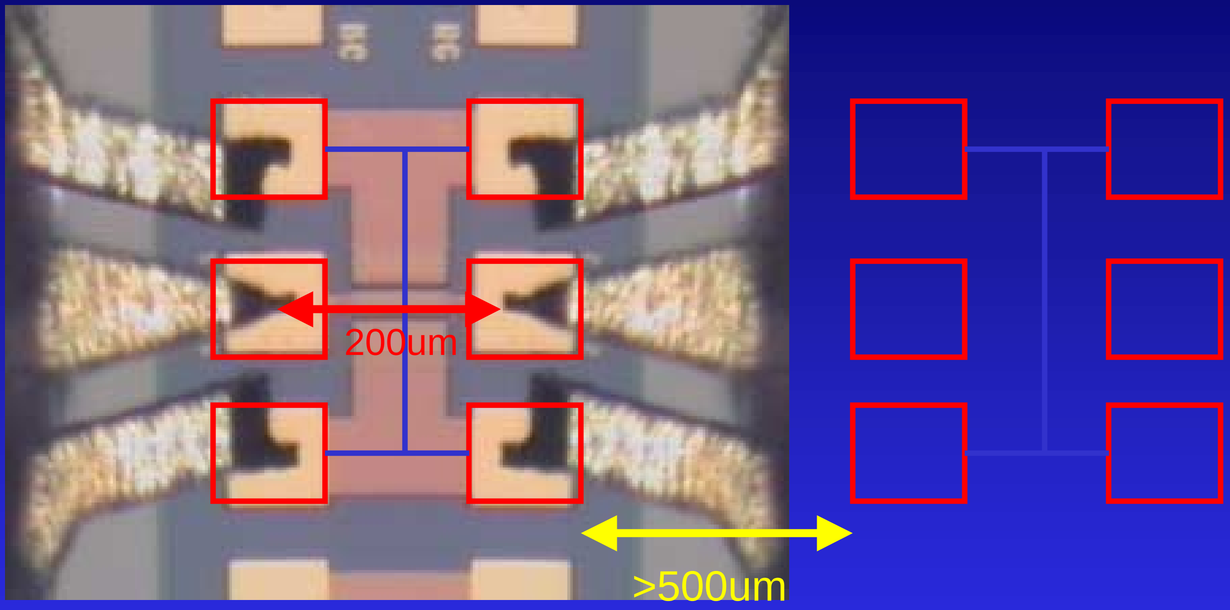
What about probe positioning?



- RF probes should have more than 200um separation to avoid cross-talk
- All pads must be on top surface
- All grounds should be connected together
- Adjacent devices should be >500um away for mm-wave measurements

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What do I need to consider regarding calibration?

- For corrected two-port S-parameter or response calibration a thru' standard is always required.
  - If individually mounted RF probes are used, they should preferably be adjacent
  - If the RF ports are orthogonal or 'horse shoe' SOLR calibration method must be used
  - If a fixed RF probe card is used SOLR and a custom ISS is preferred

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Layout Rules

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SOLR

Data sheets –

ISS Family

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What are the problems with probing Silicon wafers with Aluminium pads?

- Aluminium Oxide on Aluminium pads
  - A layer of Al Oxide will grow on the pad surface when left in air
    - This leads to possible contact resistances and variable contact resistance with time
- Conductive substrate increases parasitic reactance
  - Pad and interconnect capacitance and inductances become more significant during device measurement
    - De-embedding of pads and interconnects is required
- Limitations of Pad Parasitic Removal methods
  - The larger the pads and smaller the device, makes de-embedding more difficult to achieve

Links

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W vs BeCu

On-wafer VNA

Quick Guide –

Tungsten Probe

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ACP Probes

Probe Guide

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How do I overcome the contact resistance problem?

- Must penetrate Oxide on Aluminium pads
  - Standard BeCu tips are usable
    - but multiple touchdown are required to remove the oxide layer from the pad
  - Tungsten tips are superior
    - but the tungsten tip will also oxidise in air
    - Probing Al pads works well with W probes since both metals are very hard and rugged and perform a self-cleaning action when contact is made
      - Lower contact resistance
      - Better stability over time and temperature
      - Improved measurement repeatability

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What is De-embedding?

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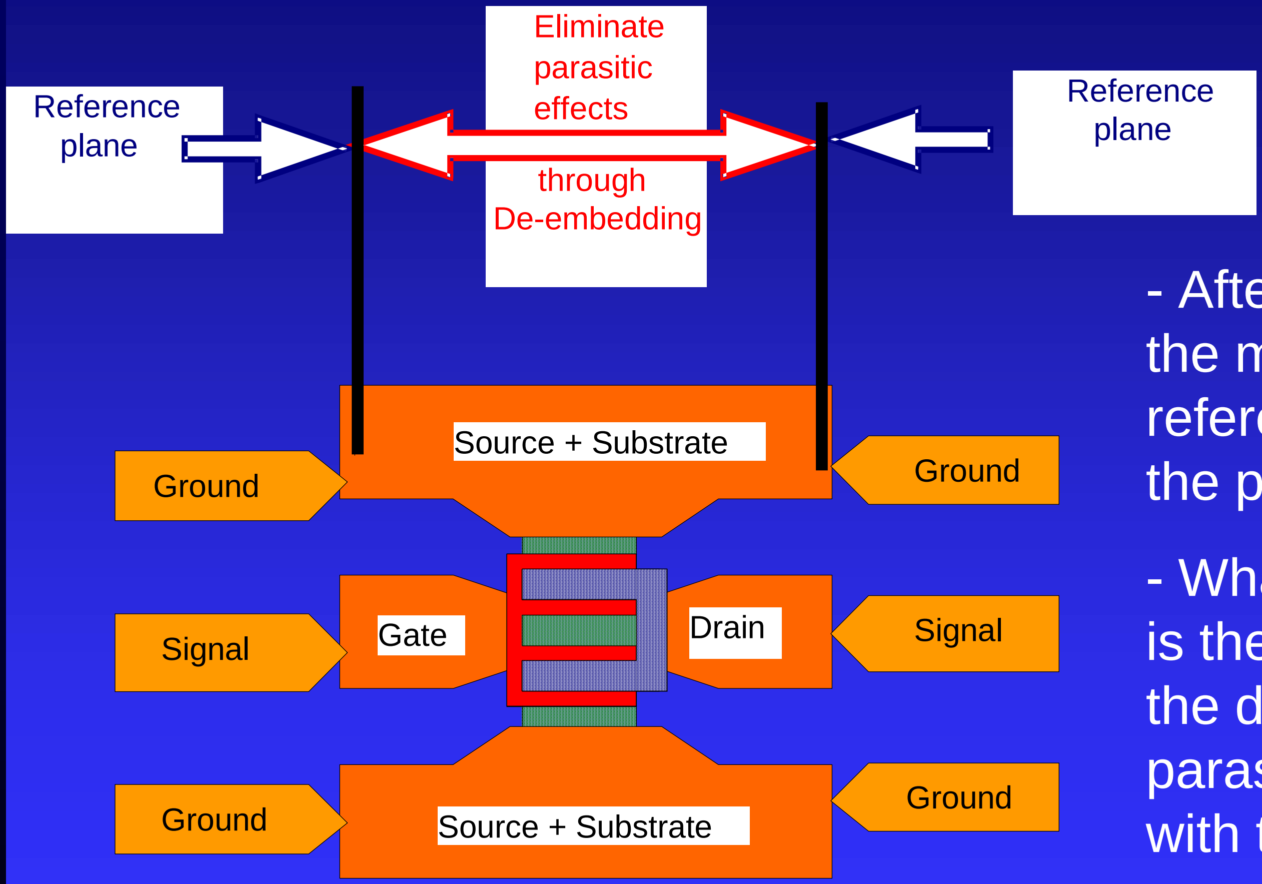

- After calibration, the measurement reference plane is at the probe tip

- What is measured is the response of the device and the parasitics associated with the pads

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Data sheets –

WinCal

De-embedding and Verification Test Structures

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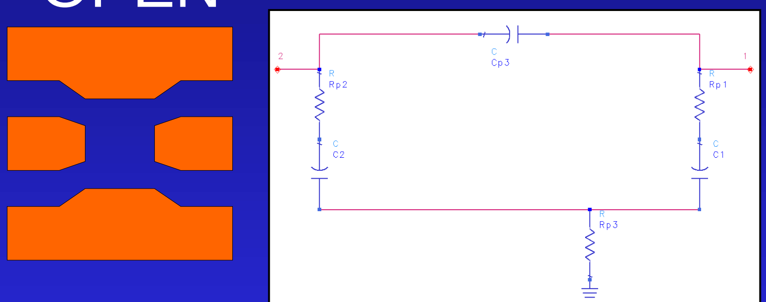
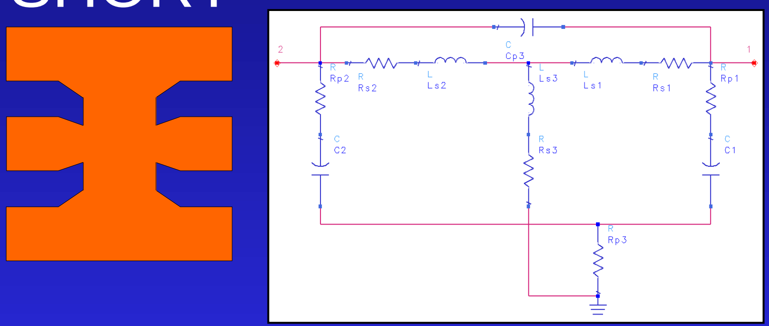
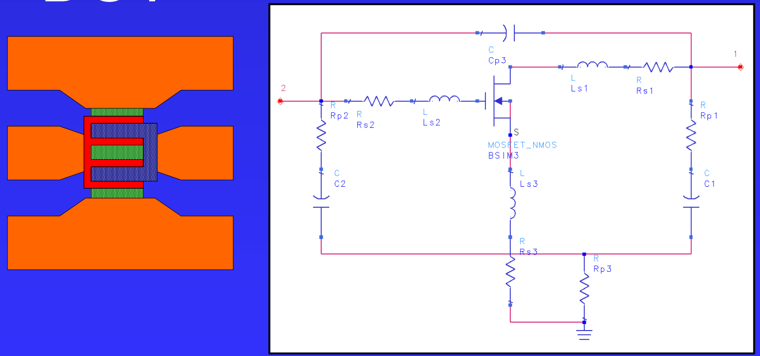
OPEN



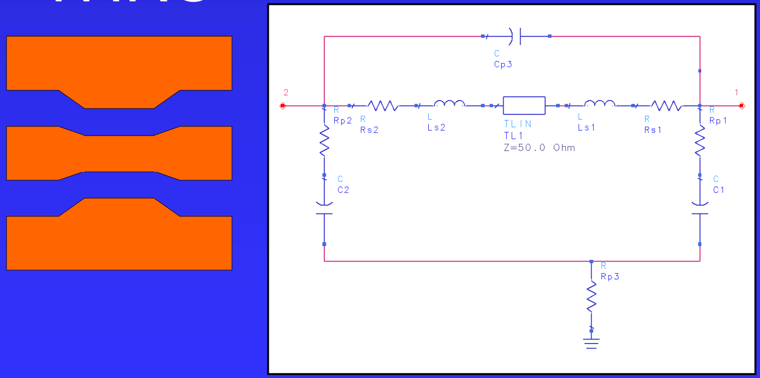
SHORT



DUT



THRU



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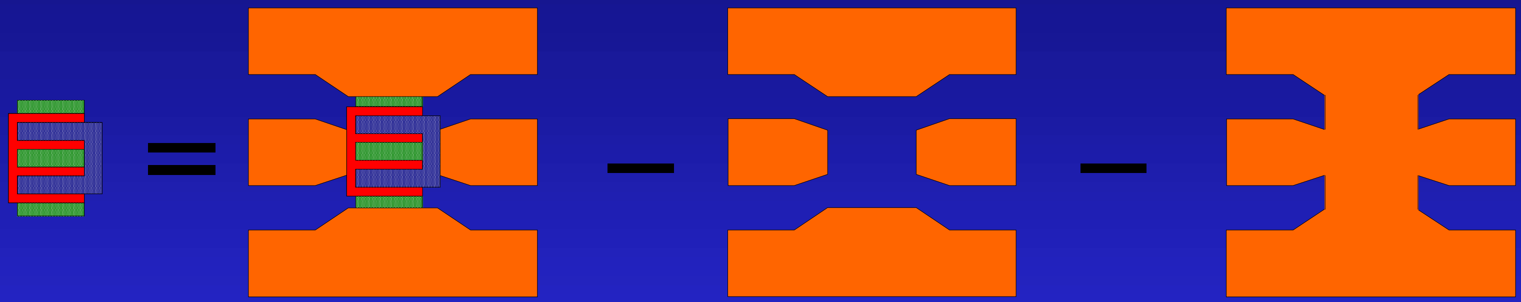
De-embedding from OPEN and SHORT



The parasitics of the OPEN consist only of parallel elements to the DUT

More importance for high impedance devices

The parasitics of the SHORT consist only of series elements to the DUT

More importance for high impedance devices

Use of Z and Y correction also helps eliminate residual cal errors

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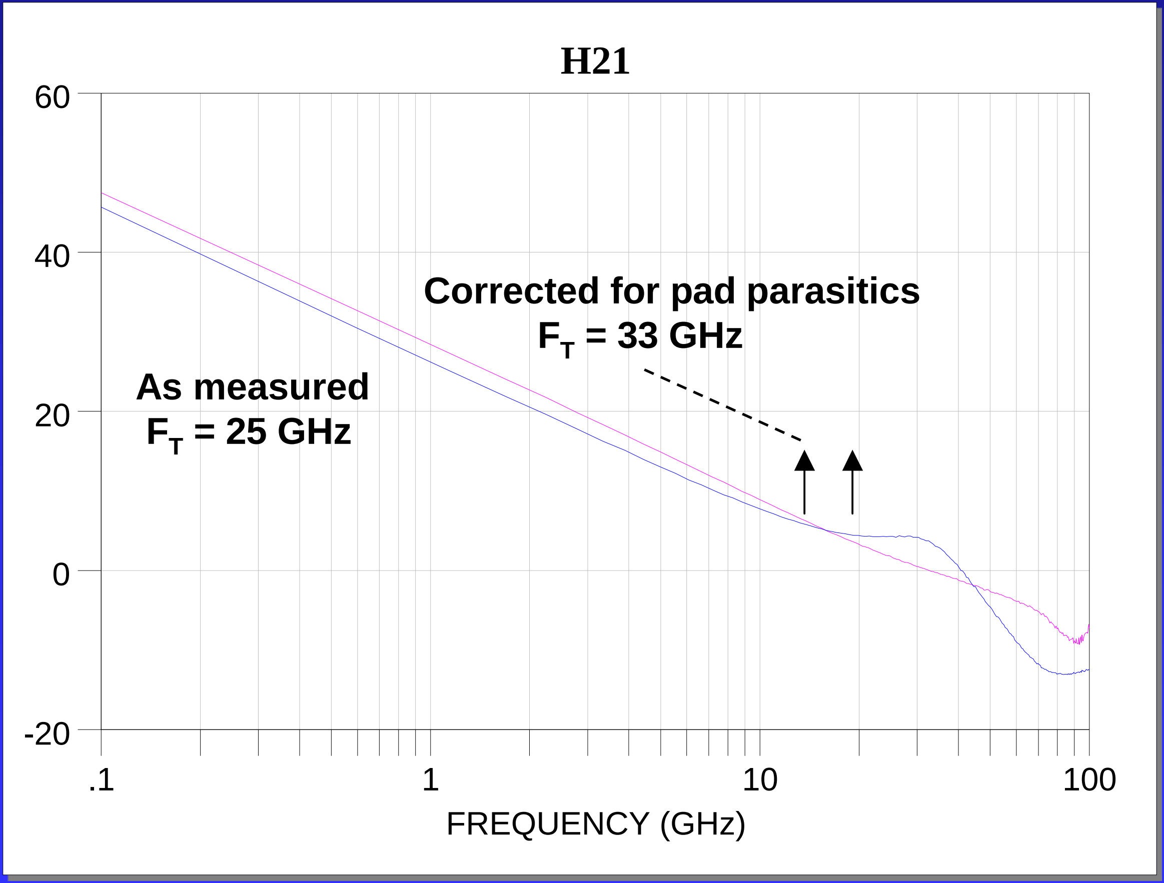
PPR Corrected H_{21} Measurement 0.25 µm CMOS Transistor



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Discussion, links and further information

- Any questions?
- Please note that the CD handout has many application notes, data sheets and information on all areas covered today
- Contact Cascade Microtech for further discussion

www.cascademicrotech.com