2013

JANUARY 28-31, 2013
SANTA CLARA CONVENTION CENTER

Impact of Probe Coupling on the Accuracy of Differential VNA Measurements

Session Code: 13-WP5

2013

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UDM Tech

2013

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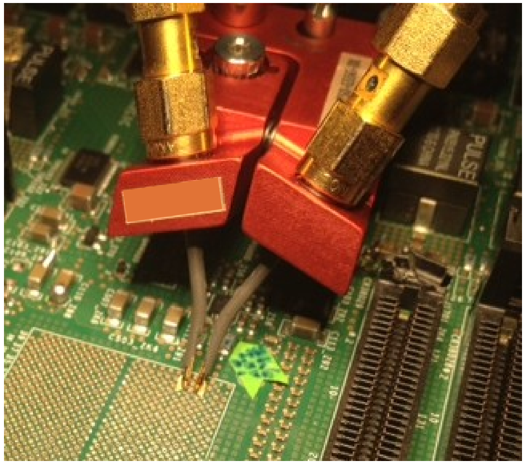
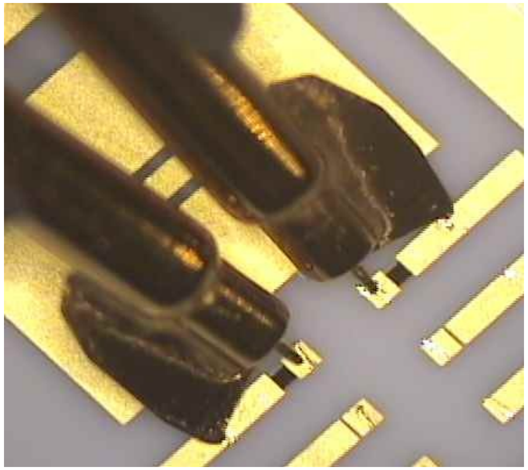
Session Code: 13-WP5

UBM Tech

Motivation

- Is VNA counting for coupling at the probe tips?
- How the measured S-parameters are being affected by probe coupling?
- The spacing between the probe tips may need to be readjusted between the measurements. What would be the effect of it on the measurement results?





Agenda

- VNA and measurement accuracy
- Coupling between differential probes
- Verifying the observed coupling with 3-D field solver simulation
- Can we count for coupling during calibration?
- Modeling the calibration residual and probe coupling
- Studying the effect of probe coupling on the measured S-parameters

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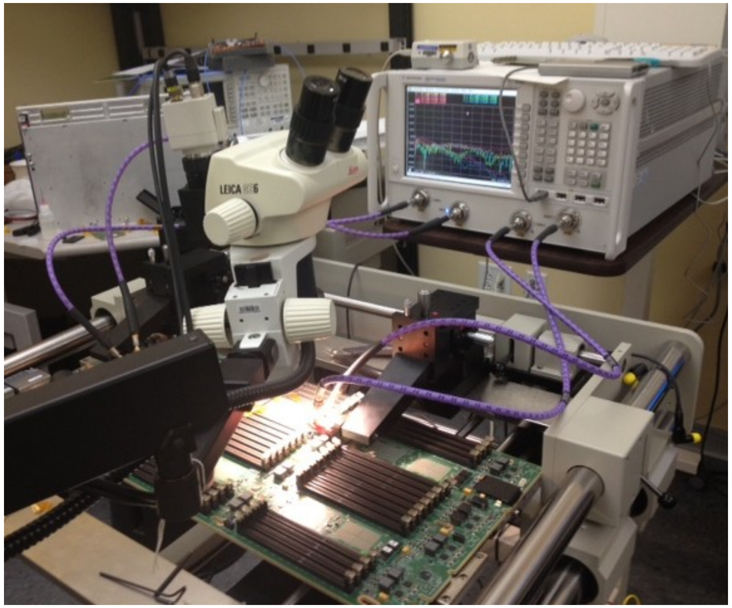
Vector Network Analyzer

- Signal integrity analysis along with accurate high-frequency measurements are essential parts of modern electronic design process.

- The Vector Network Analyzer (VNA) offers an extremely stable, precise, and versatile measurement platform for the design validation, analysis and troubleshooting of package and PCB high speed interconnects.

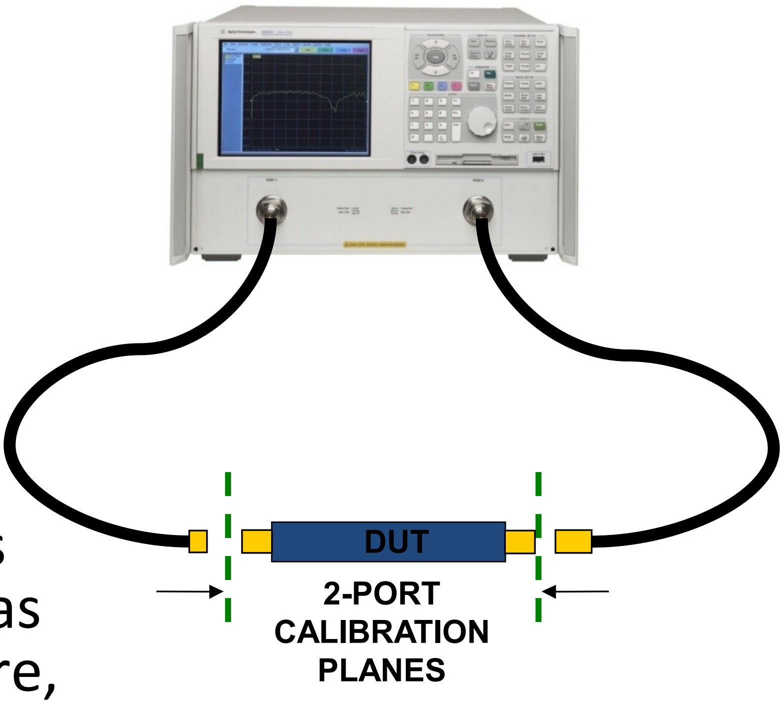


Measurement Errors

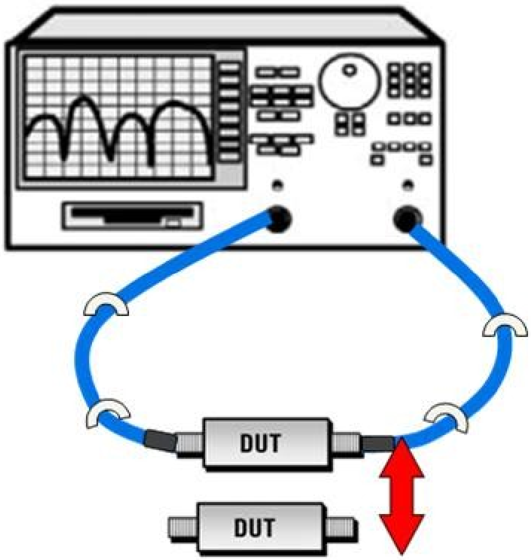
1. Systematic: repeatable errors due to imperfections in components, connectors, test fixtures, etc.

2. Random: vary unpredictability with time and cannot be removed.

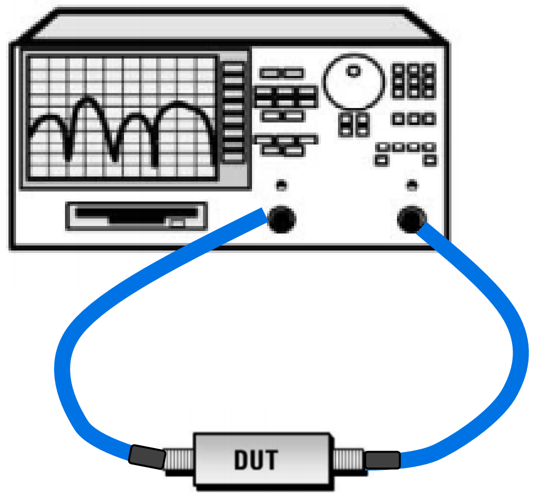
3. Drift: caused by changes in systems characteristics after a calibration has been performed due to temperature, humidity and other environmental variables.



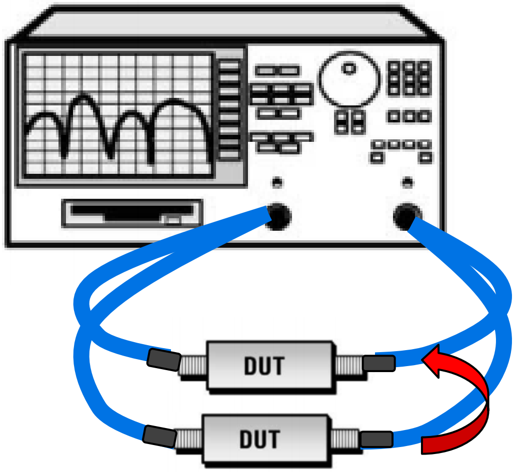
Reducing Random Errors



Connecting and Disconnecting

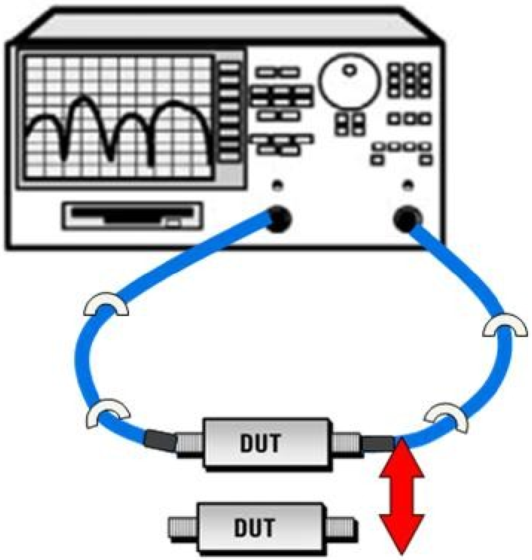


Drift



Cable Movement

Reducing Random Errors



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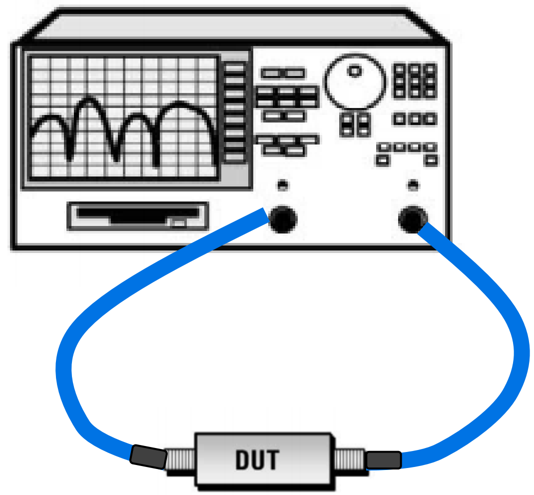
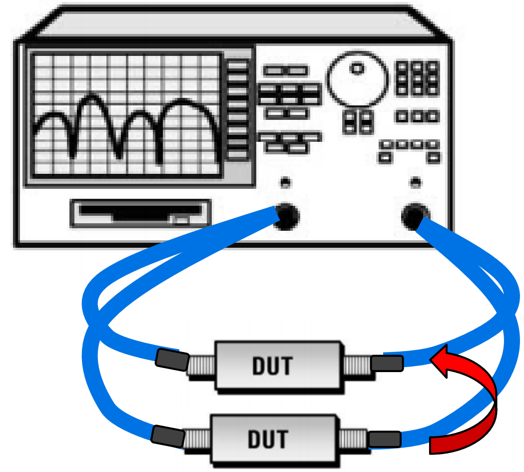
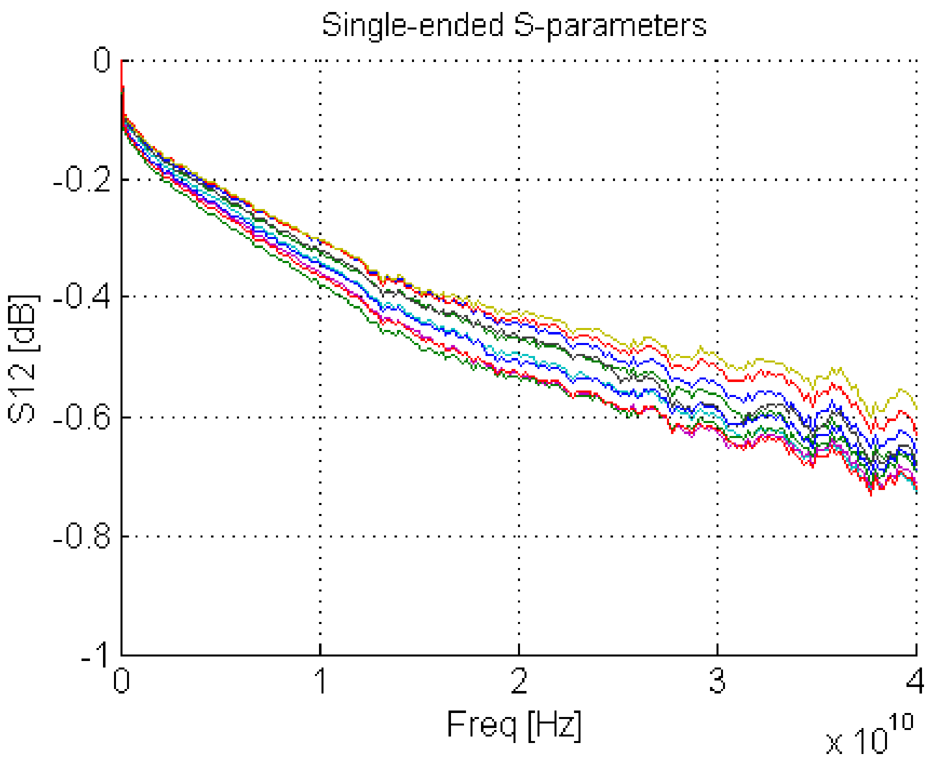


Drift



Cable Movement

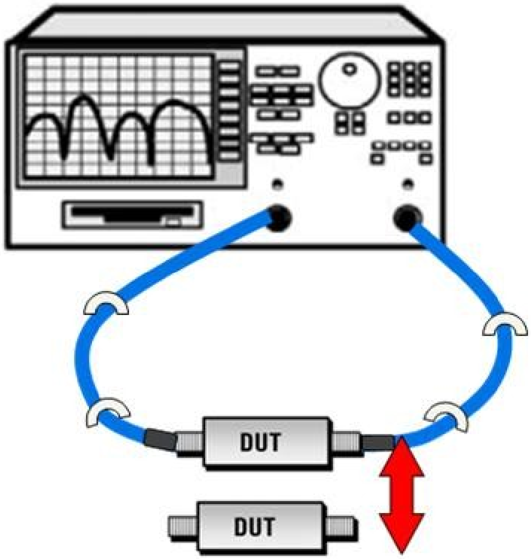
Connecting and Disconnecting



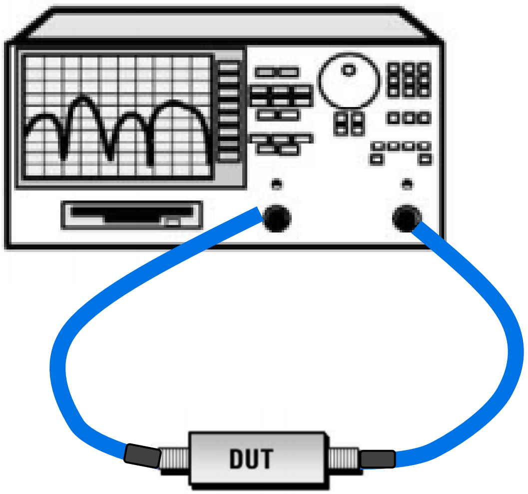
$$STD = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N}}$$

Maximum STD :± 0.036 dB

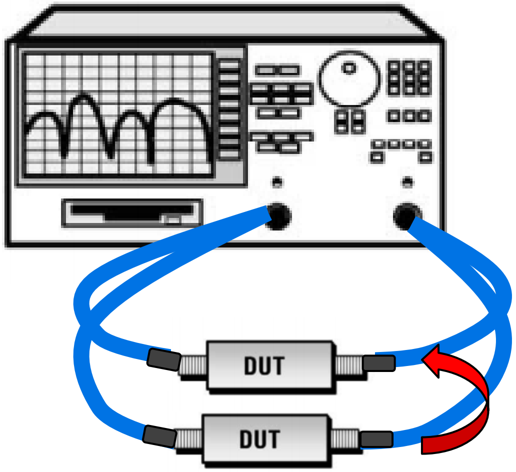
Reducing Random Errors



Connecting and Disconnecting

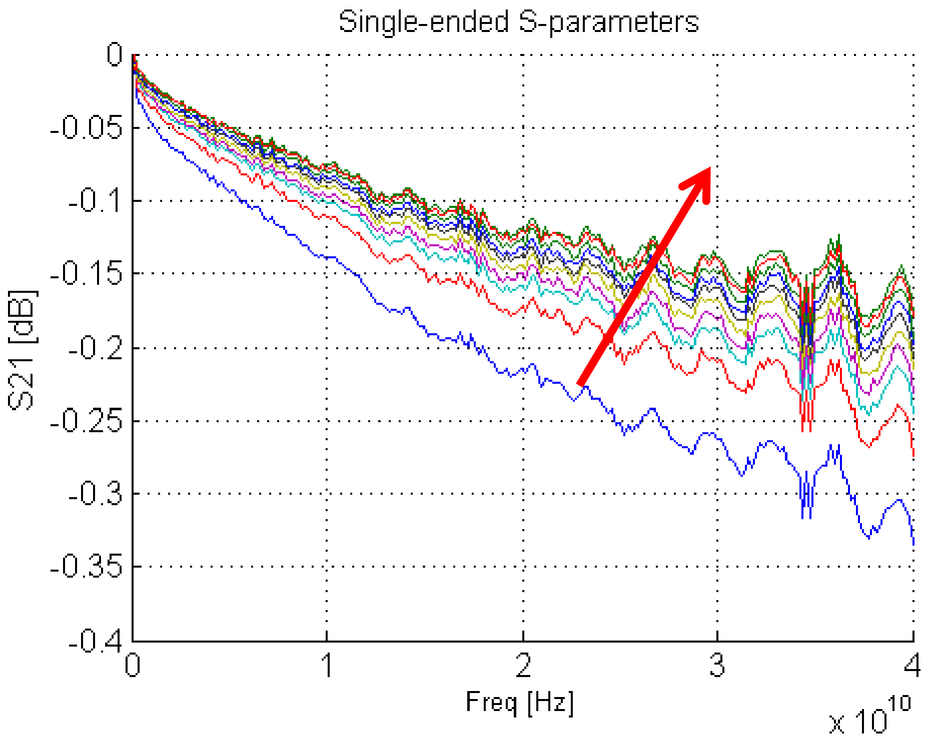


Drift



Cable Movement

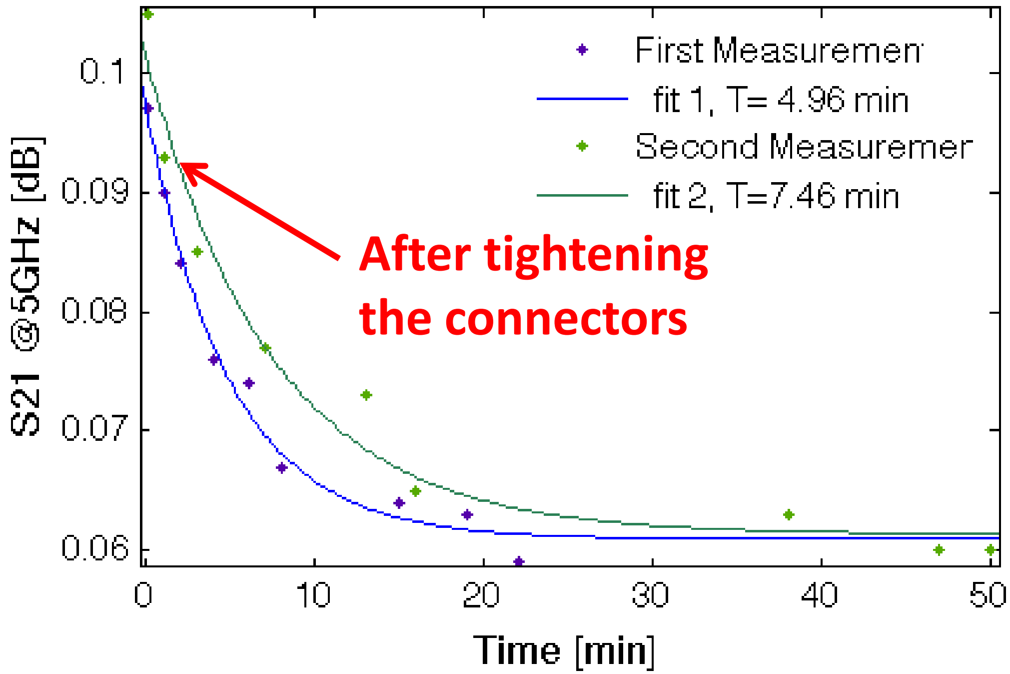
Drift



- Is this error because of the instrument? Noise/temperature?
- Why it's decaying during time?
- Why it's different for different cables?

Drift @5 GHz

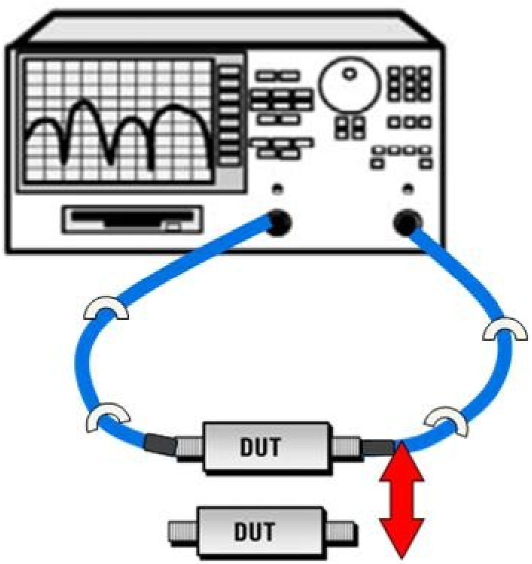
ΔS21=0.045 dB



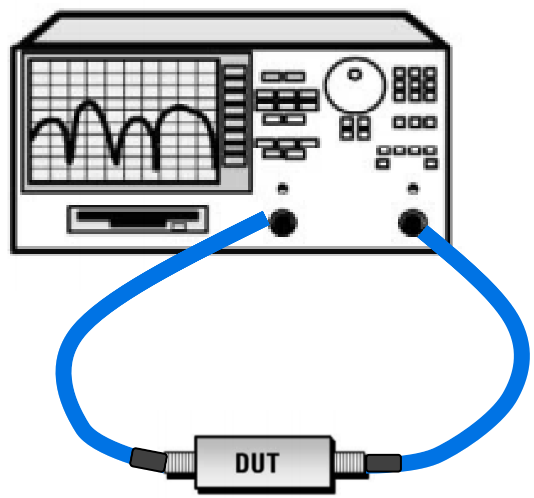
The observed drift can be because of: twisting the cables or dielectric inside the connectors

It is important to allow enough time for the cable and connectors to stabilize before making measurement.

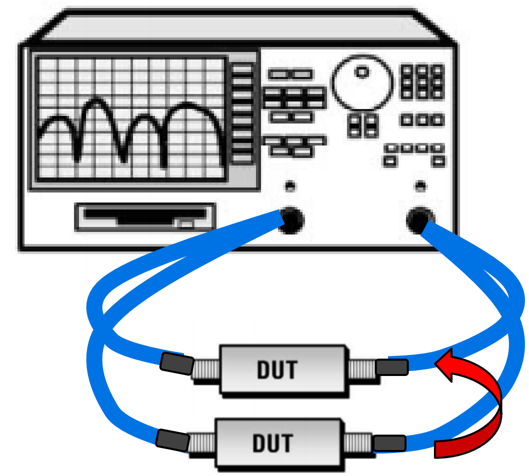
Reducing Random Errors



Connecting and Disconnecting

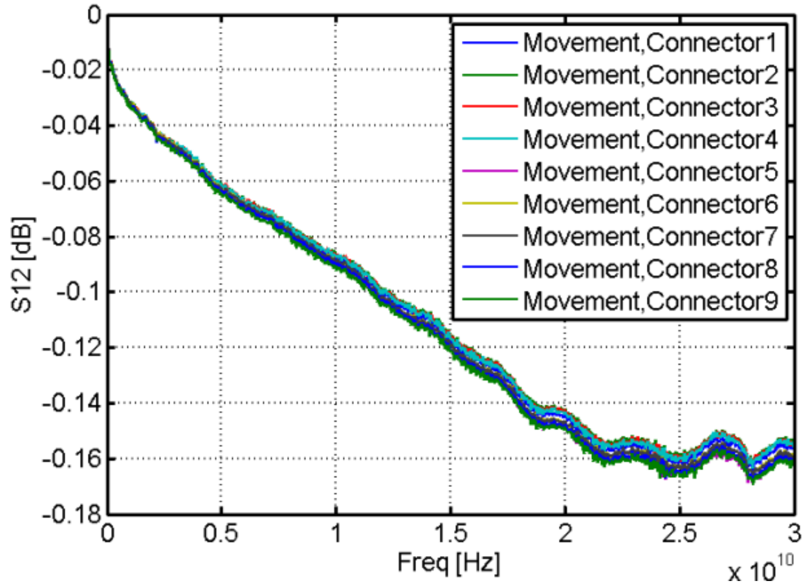


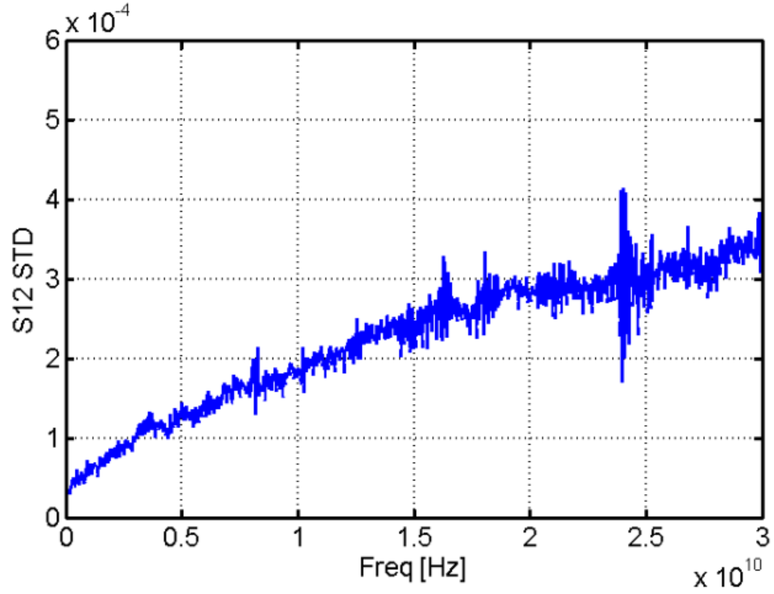
Drift



Cable Movement

Cable Movement





Cable movement error was minimized by using high quality cables.

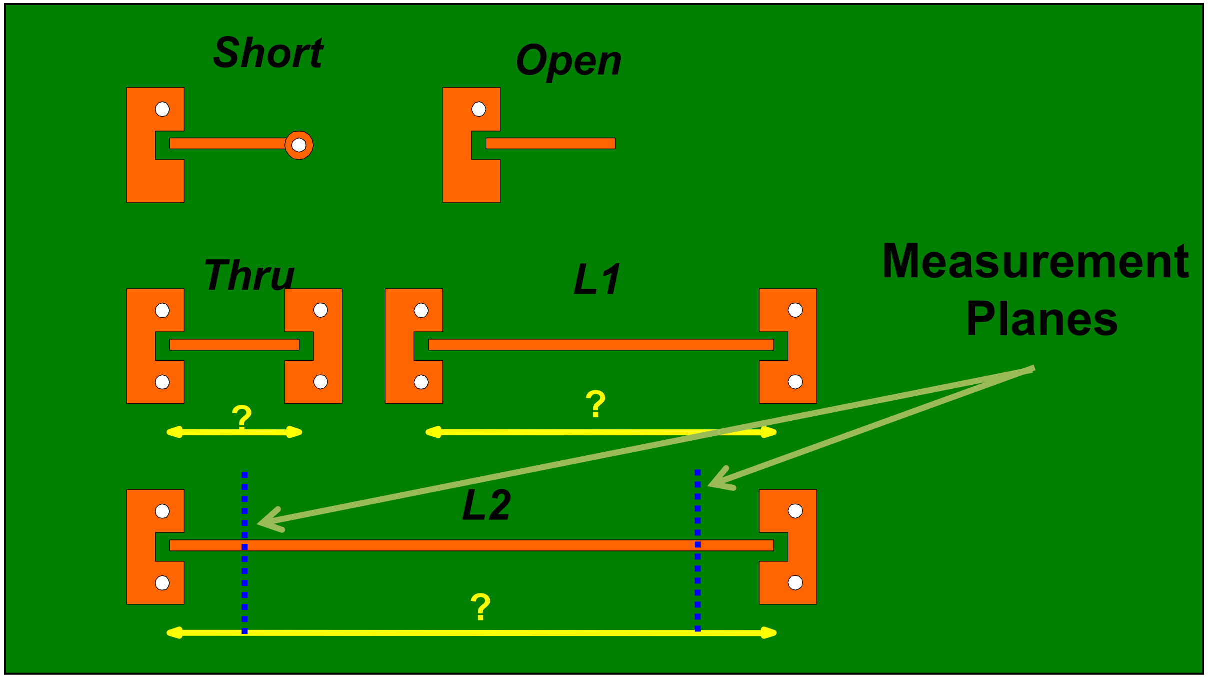
VNA Calibration

- Proper calibration is critical!!!
- The measurement system can be calibrated by measuring accurate, known standards.
- There are two basic calibration methods
  - ❖ Short, Open, Load and Thru (SOLT)
    - ✓Calibrated to known standard(Ex: 50Ω)
  - ❖Thru, Reflect, Line(TRL)
    - ✓Calibrated to line Z_0

TRL Calibration Structures

TRL PCB Structures

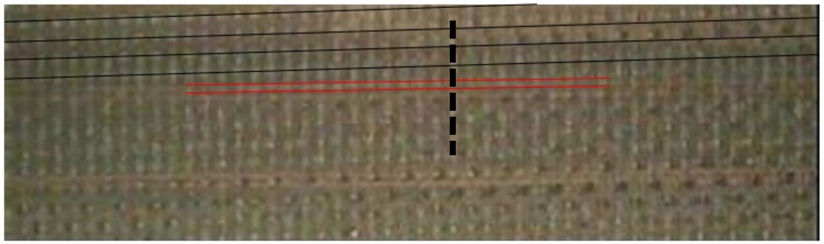
- Normalized Z_0 to line (Required to know impedance and approximate electrical length of line standards
- De-embedd's launch structure parasitics



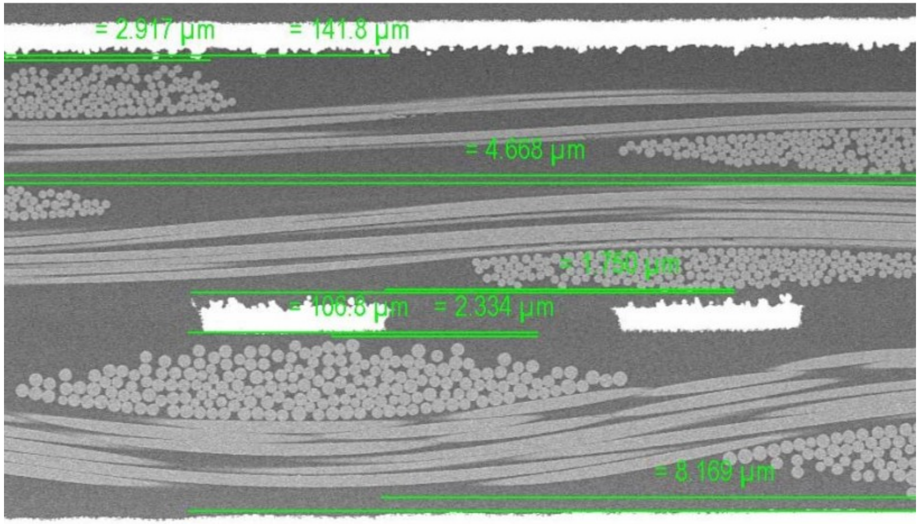
Howard Heck, "Advanced Transmission Lines; 2 Port Networks & S-Parameters," OGI EE564.

Why We Don't Use TRL Method?

TOP VIEW



Cross Section



This weaving effect may create a non-uniform dielectric constant;
The dielectric of glass is much higher than that of epoxy.

J.Miller and et al., "Additional Trace Losses due to Glass-Weave Periodic Loading," DesignCon 2010

Why We Don't Use TRL Method?

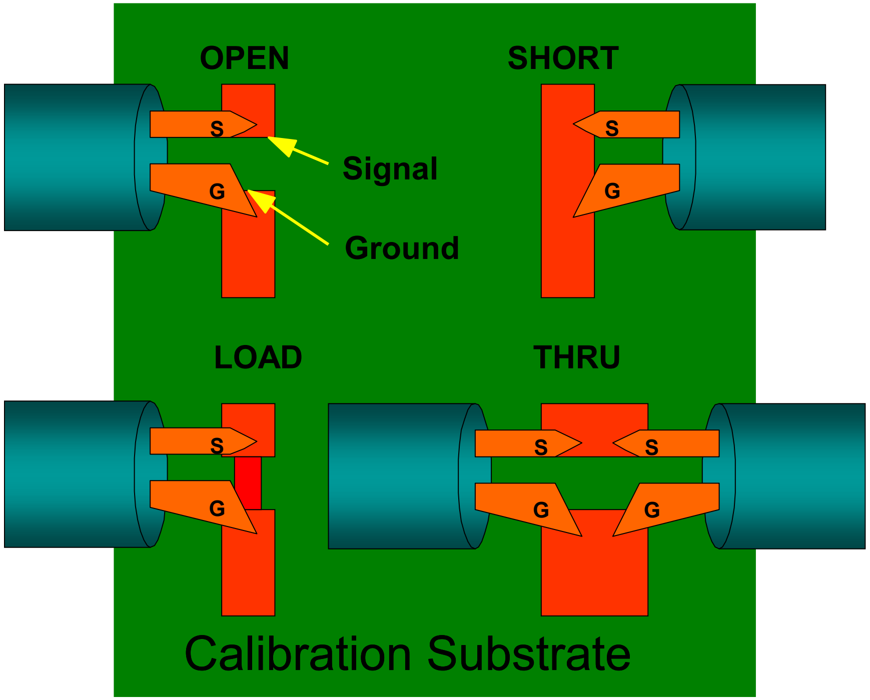
1. Due to:
   - Glass weaves and inhomogeneous dielectric
   - Dimensional variation within a PCB Board

   It's difficult to have identical characteristic impedance.
2. Calibration fixtures need to be designed and fabricated from the same material.
3. Some PCB real estate should be used for placing the

"Determining PCB Trace Impedance by TDR: Challenges and Possible Solutions" By Istvan Novak

SOLT Calibration Method

Calibration with Picoprobes



Courtesy to Howard Heck

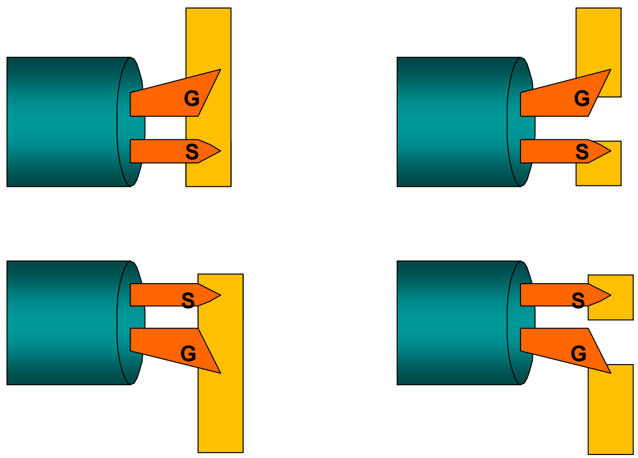
SOLT

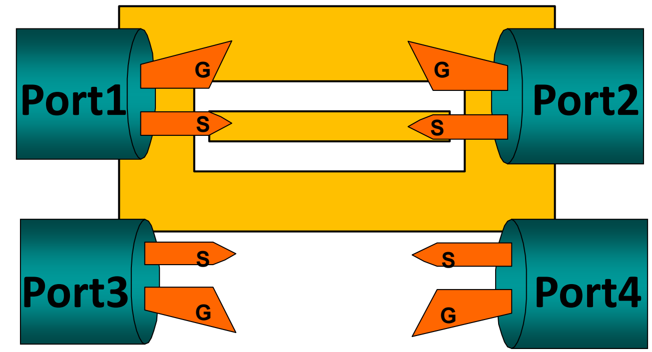
- Uses short, open, load, known-and unknown thru standards.
- Uses the 12-term error model

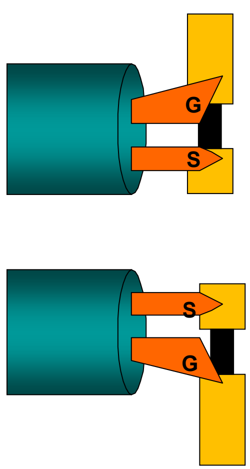
12-term Error Model

- The four-port SOLT calibration utilizes a ***12-term*** error model.
- The 12-term error model ***cannot*** mathematically correct for coupling at ***the reference planes.***
- ***16-term*** error models include leakage at the test ports and reference planes, but such calibrations mostly require specific or custom calibration substrates and have not been implemented in most VNAs

Probe Coupling Effect







During short, open and Thru measurement, the second probe will be floating.

- Is the calibration affected by energy leakage to the neighbor probe during calibrating each port?
- If so, is probe spacing during calibration important?
- Should we keep the spacing the same between calibration and measurement?

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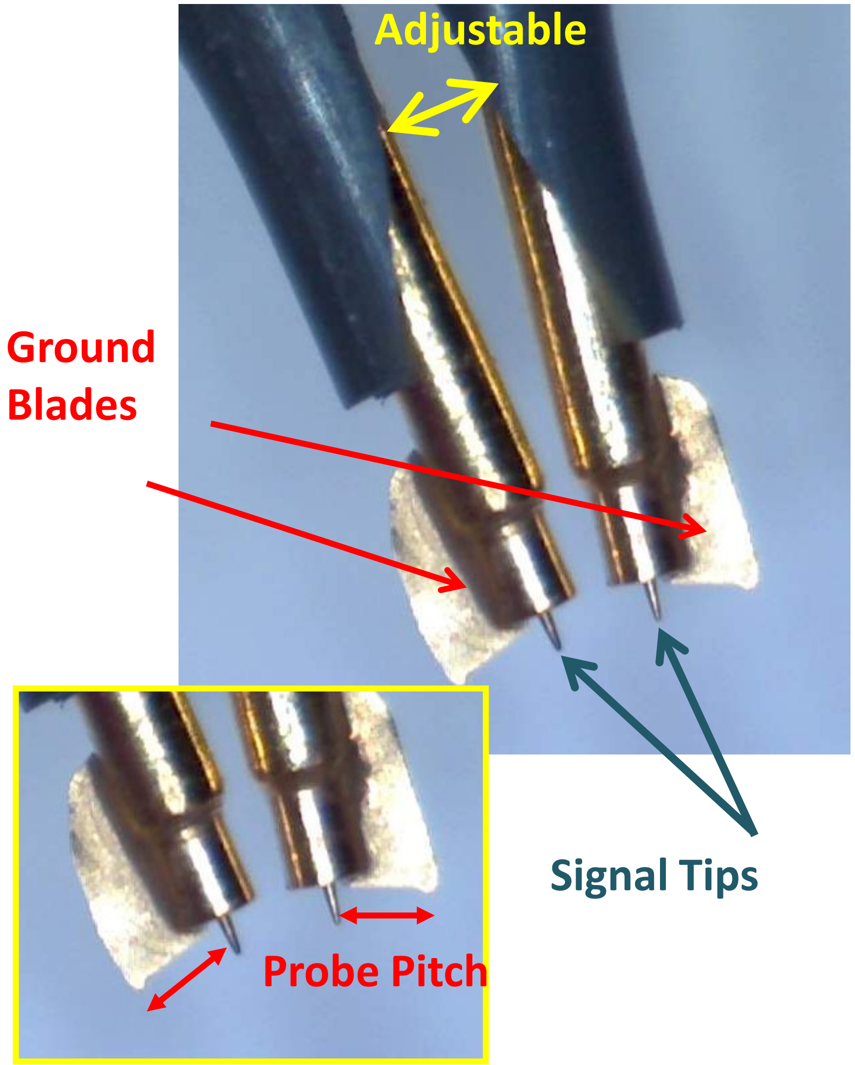
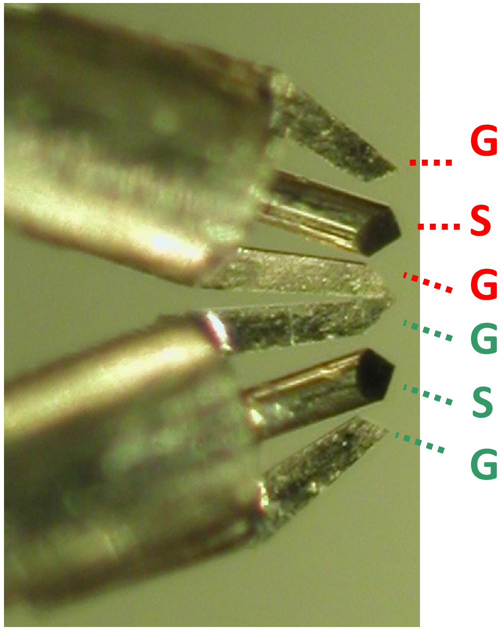
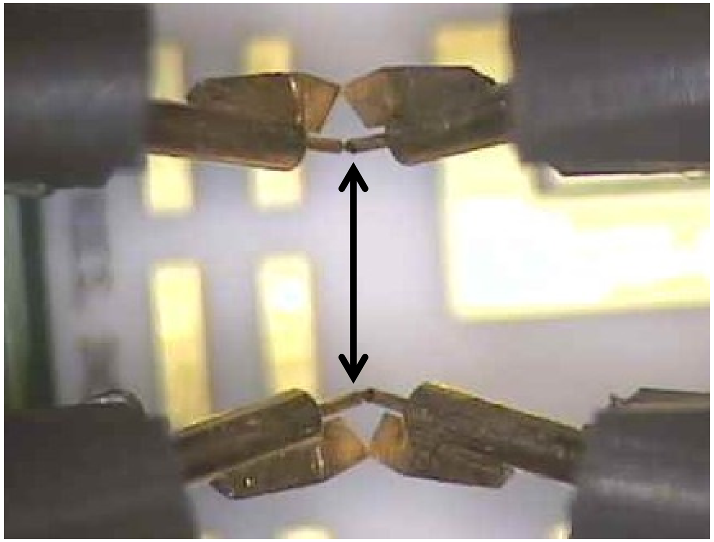
Differential Probe-to-Probe Coupling

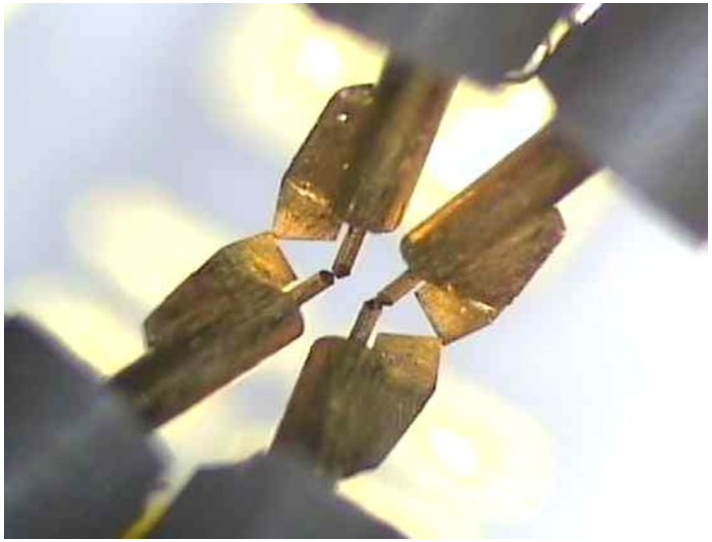




- Middle ground blades reduces the coupling between probes.
- However in most of PCB boards we have GSSG configuration

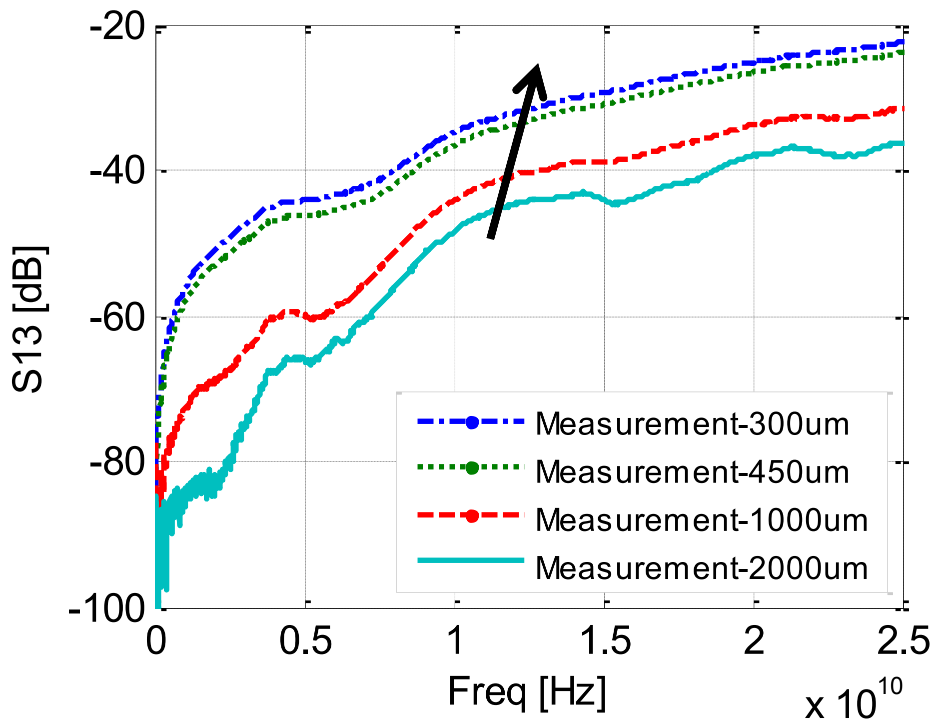
Studying the Coupling Between GSSG Pico-probes

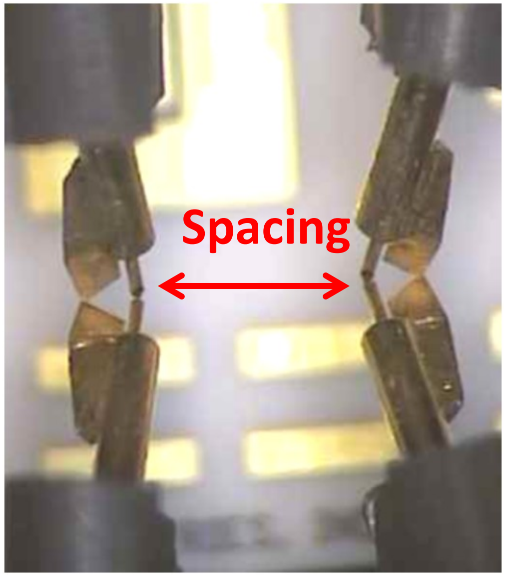




Calibrating probes with different spacing; Touching probes in air and performing a thru measurement at different spacings

Probe-to-probe Coupling as a Function of Spacing





Near-end crosstalk varies up to 15 dB by changing the spacing between probe tips.

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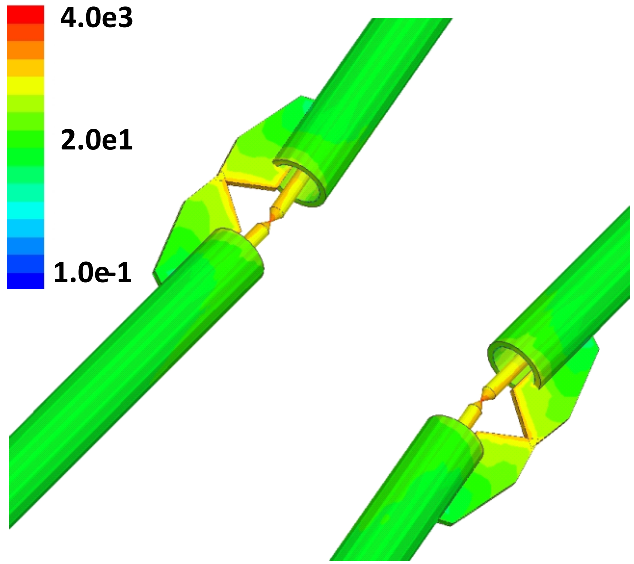
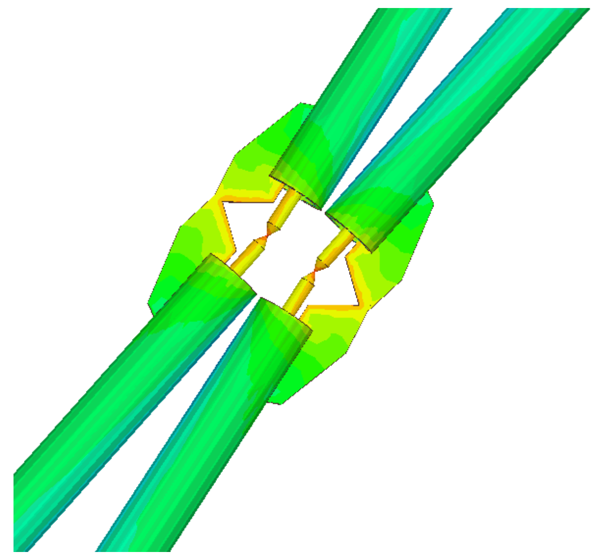
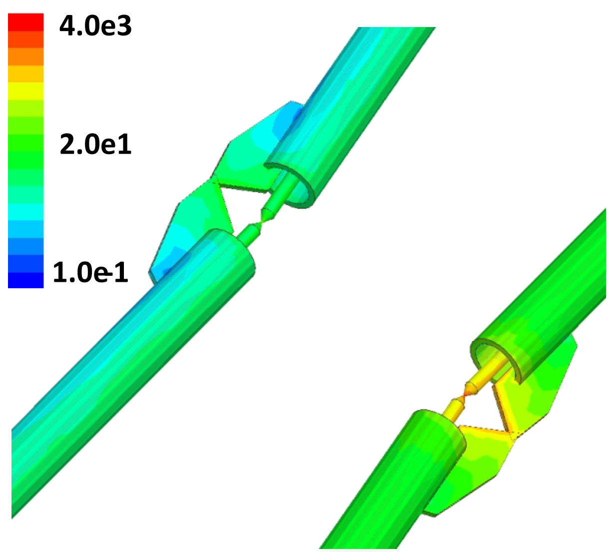
3D Simulation of 500 µm-Pitch Differential Pico-probes

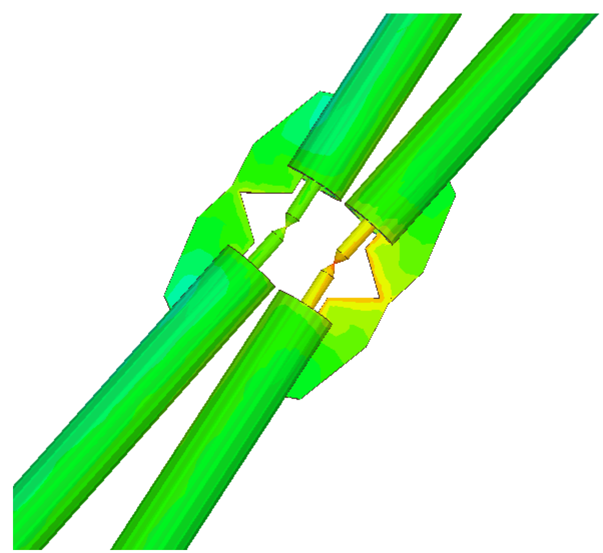
Probe Spacing: 2000 µm



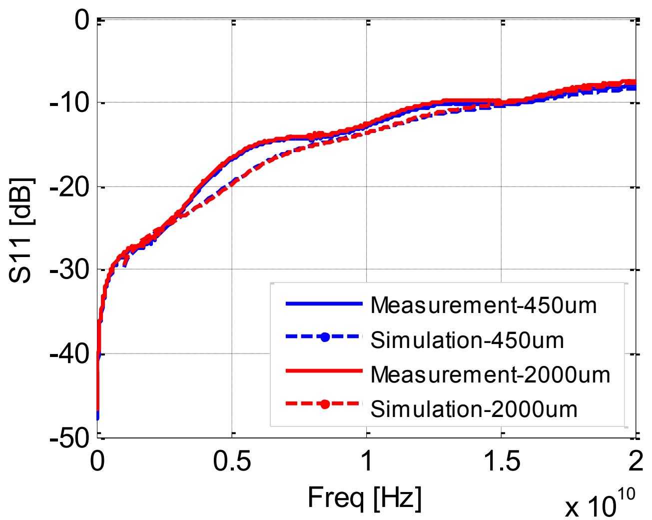


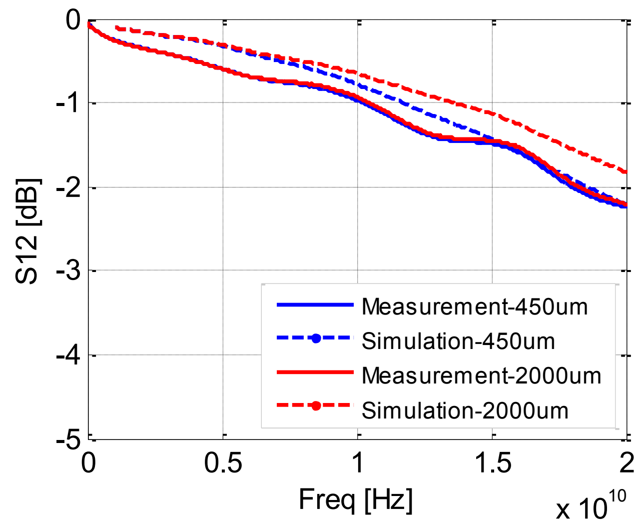
Probe Spacing: 450 µm

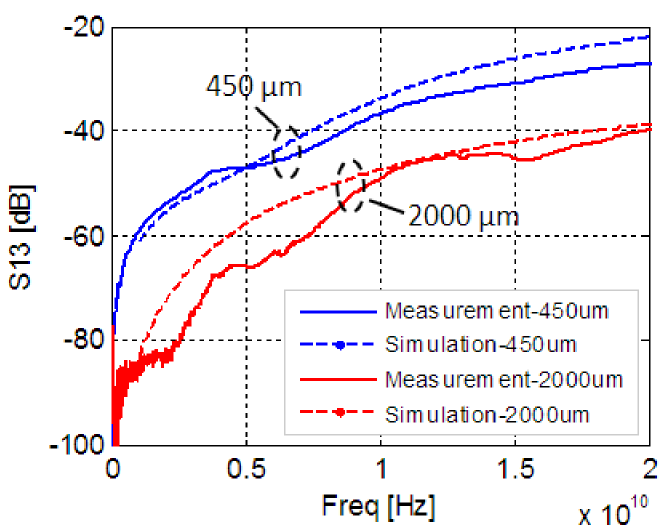


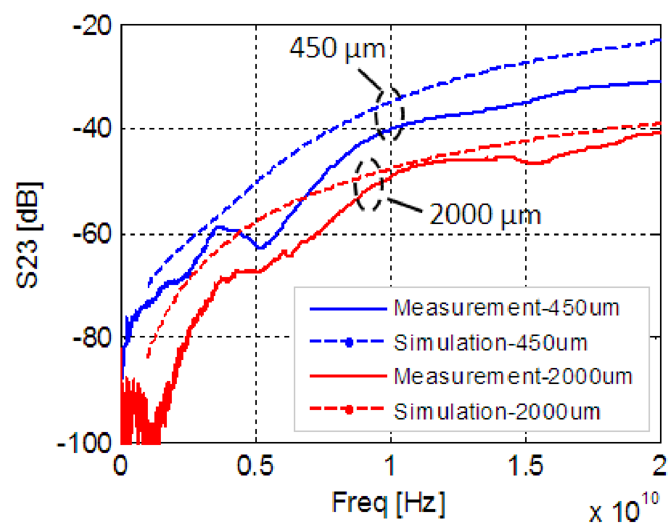


3D Simulation of 500 µm-Pitch Differential Pico-probes

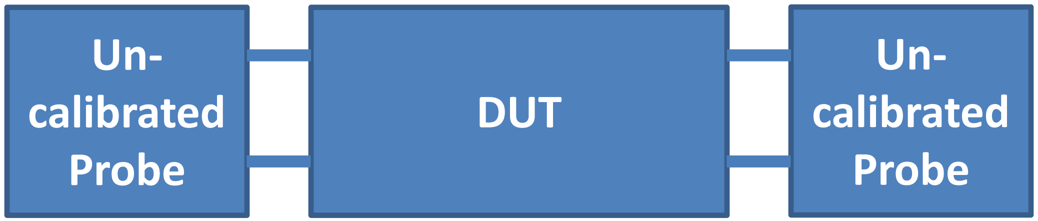








Summary



- A 3D field solver was used to perform full-wave field simulations
- A good correlation between the measurement and the generated model were achieved.
- The measurement can be done with un-calibrated probes and the effect of probes can be de-embedded using the generated probe models.
- The model can be used in studying and modeling calibration standards and their effect on calibration.

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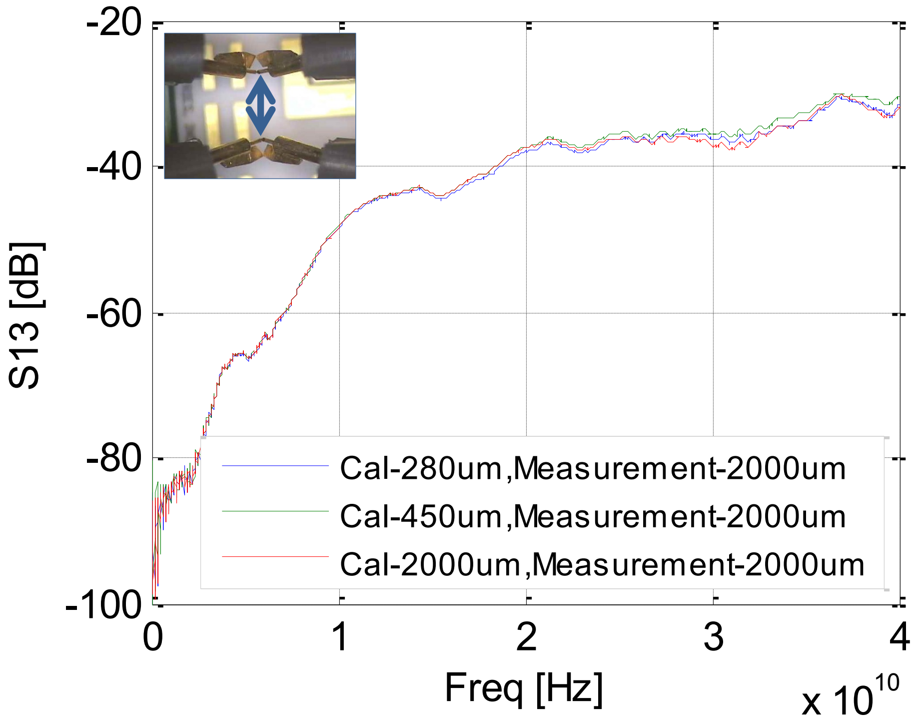
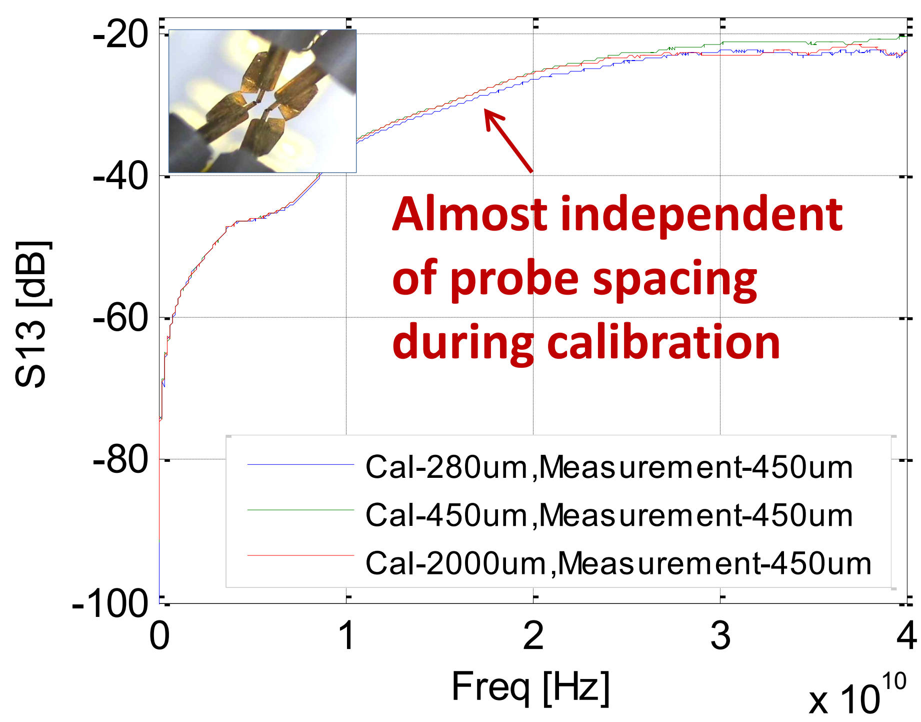
Near-end crosstalk (NEXT); Different Probe Spacing During Calibration

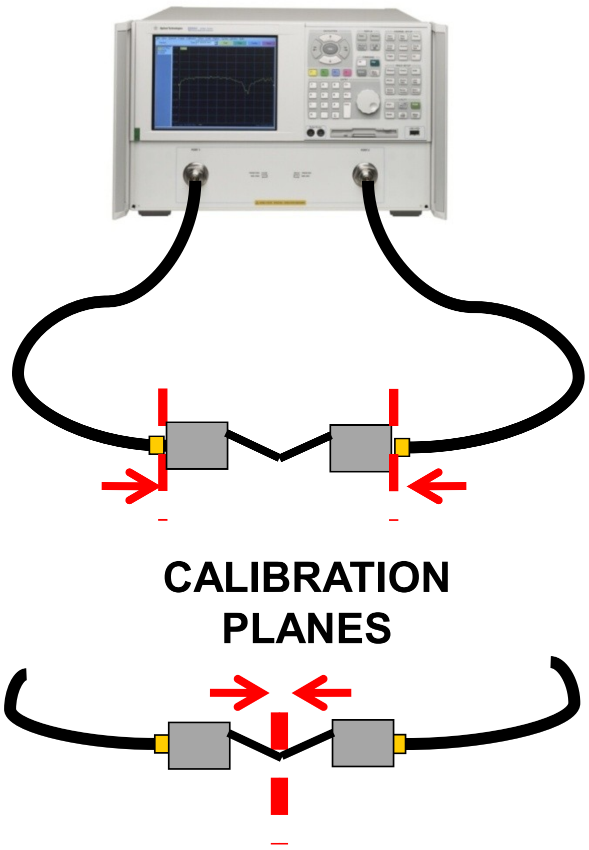
Measurement with 2000 µm Probe spacing

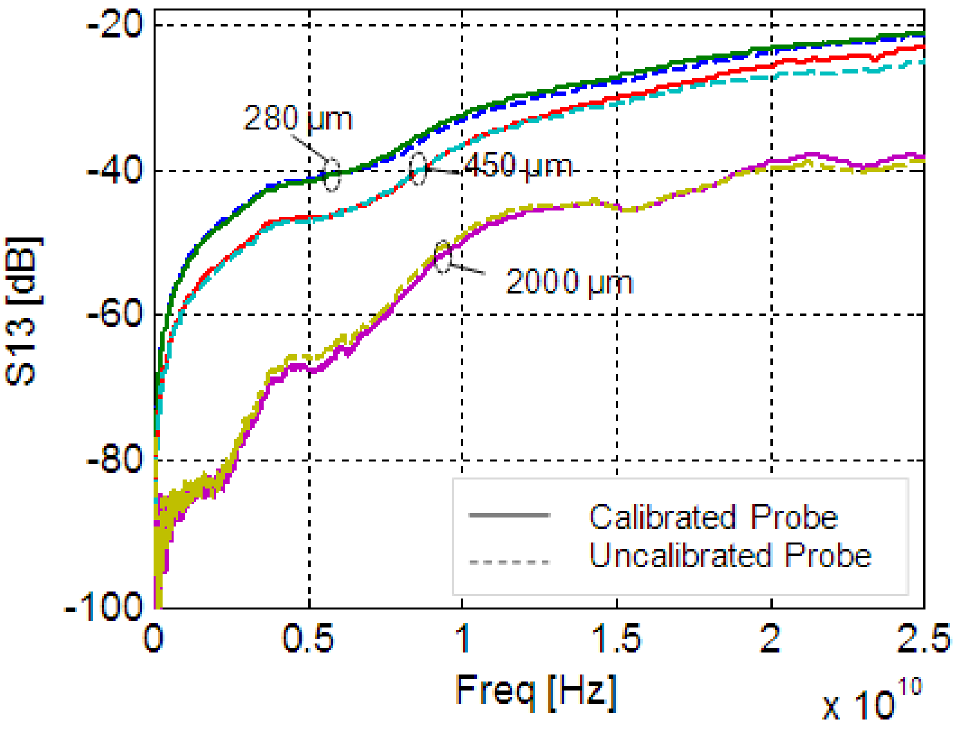


Measurement with 450 µm Probe spacing



Near-end crosstalk (NEXT); For Calibrated and Un-calibrated Probes

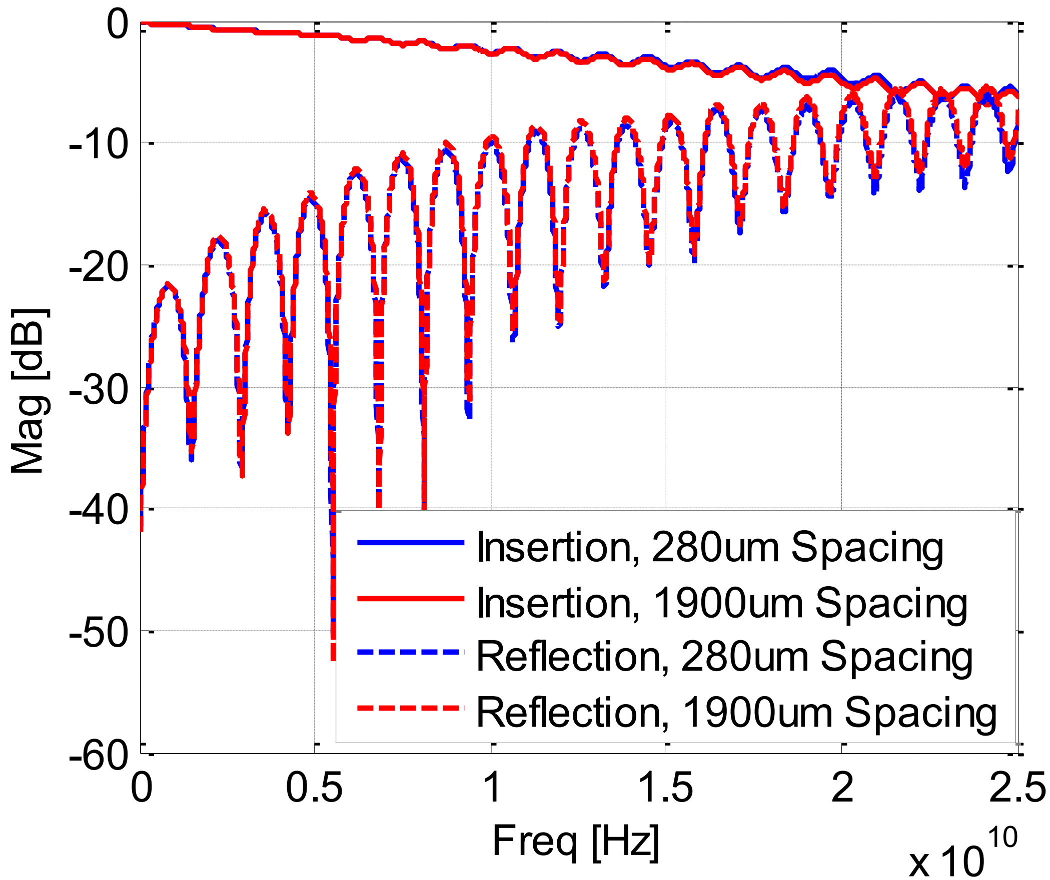




By performing an SOLT calibration, the coupling between the probes *is not de-embedded* from the measurement

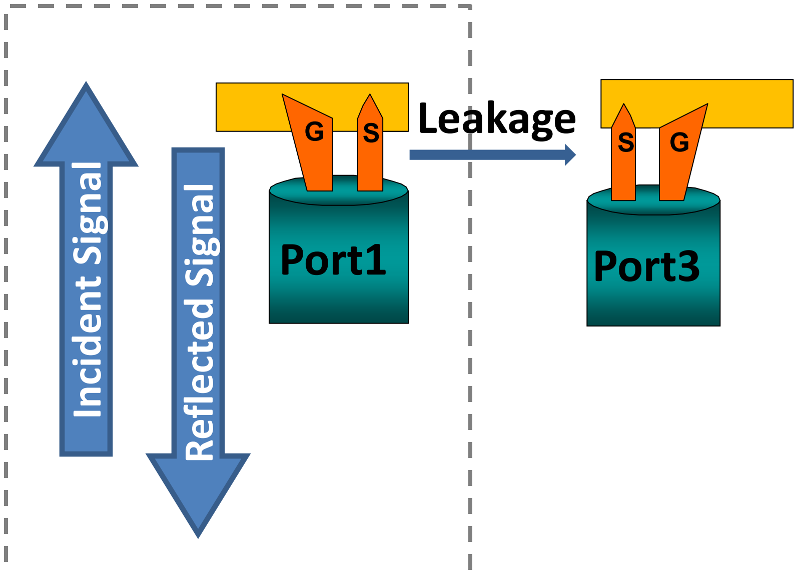
IL and RL for Different Calibrations

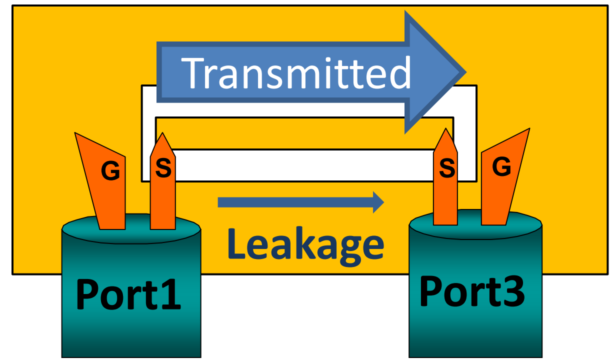
Two different calibration with 280 µm and 1900 µm probe spacing



Probe spacing had *negligible* effect on insertion and reflection loss!

Probe Spacing During Calibration

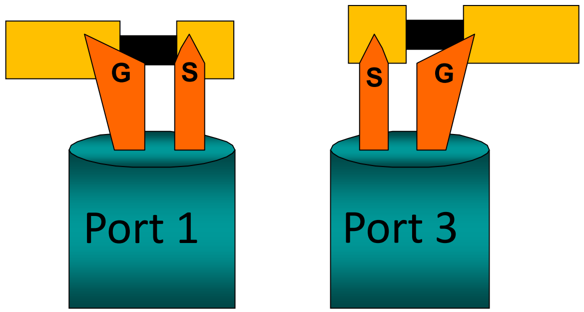




The ratio of leaked/measured power is small and has minor effect in the calibration result.

Measuring loop-back showed *no effect* on the measured near-end crosstalk between two probes.

Why Crosstalk is Not Being Captured?

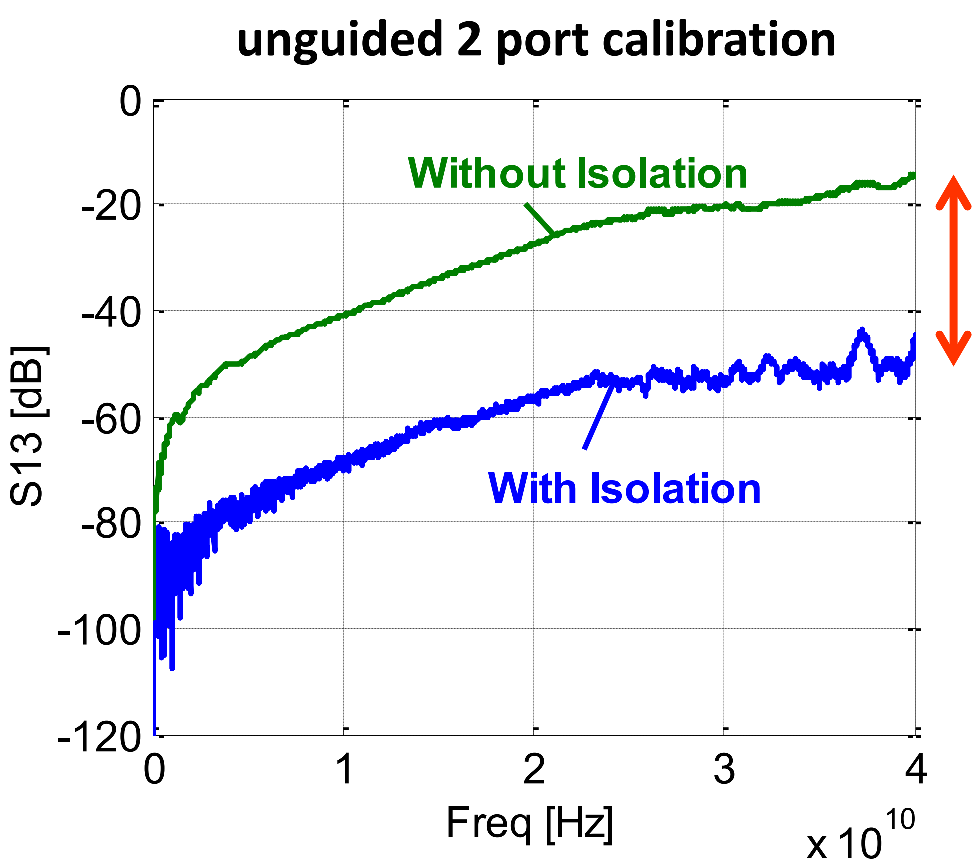


Isolation or crosstalk error terms are computed by S13 and S31 measurements, using load standards.

- The internal isolation between the receivers is lower than the noise floor.

- When the network analyzer uses isolation error correction, it could end up raising the noise floor by 3dB.
- Isolation is usually not included in the guided cal process which is where all cals greater than 2 ports are completed.

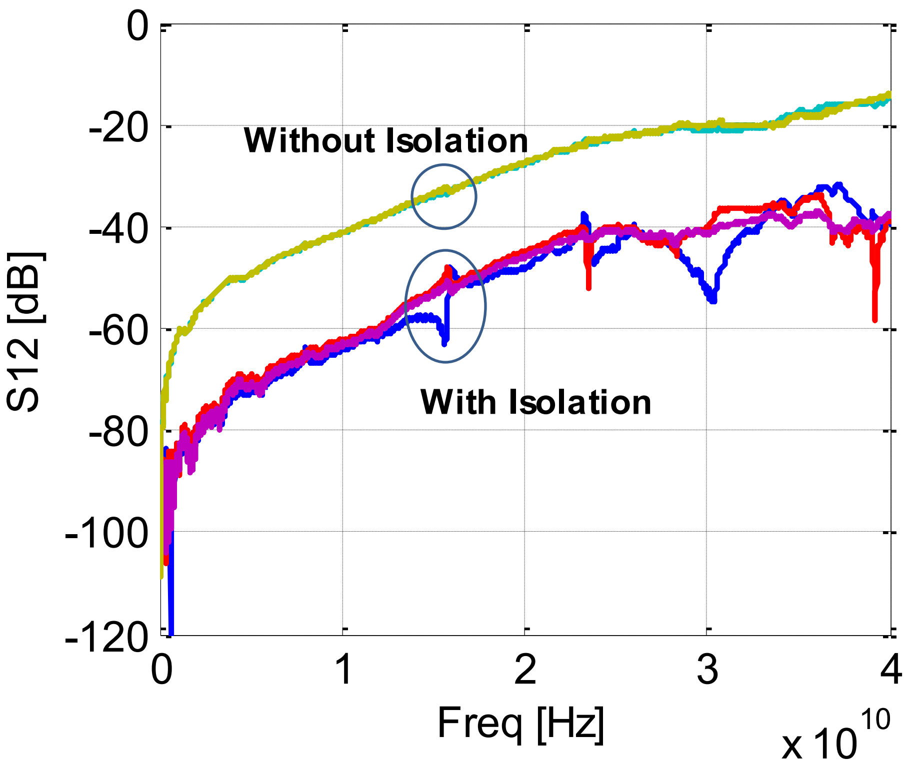
Effect of Isolation on NEXT

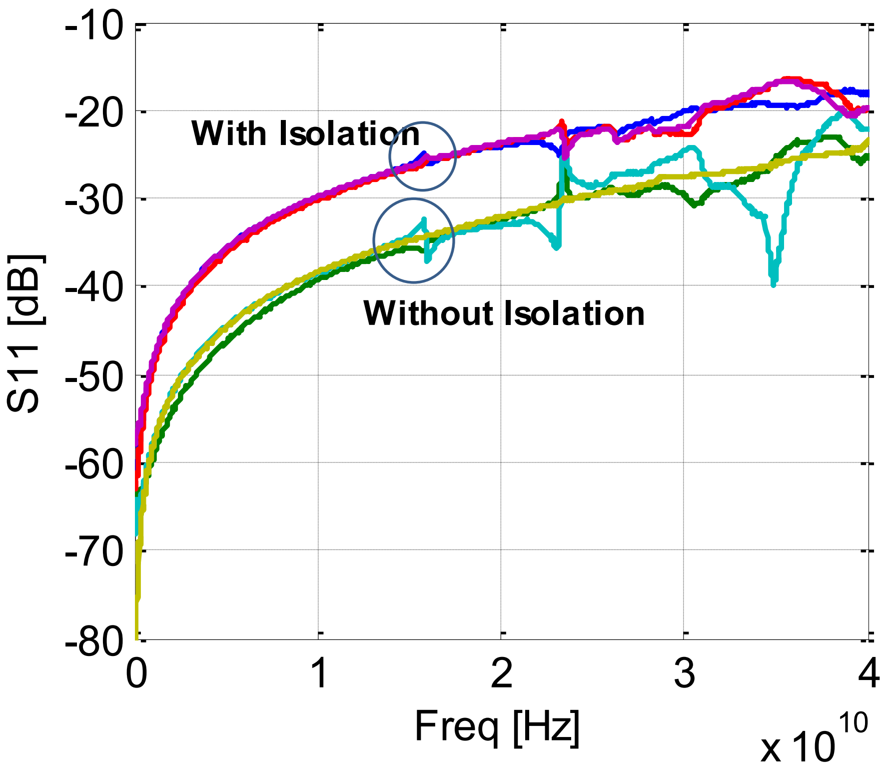


The effect of isolation for measurements done with pico-probes is *significant*!!

The isolation step can not be neglected for pico-probe calibrations

Isolation; Different Load Measurements

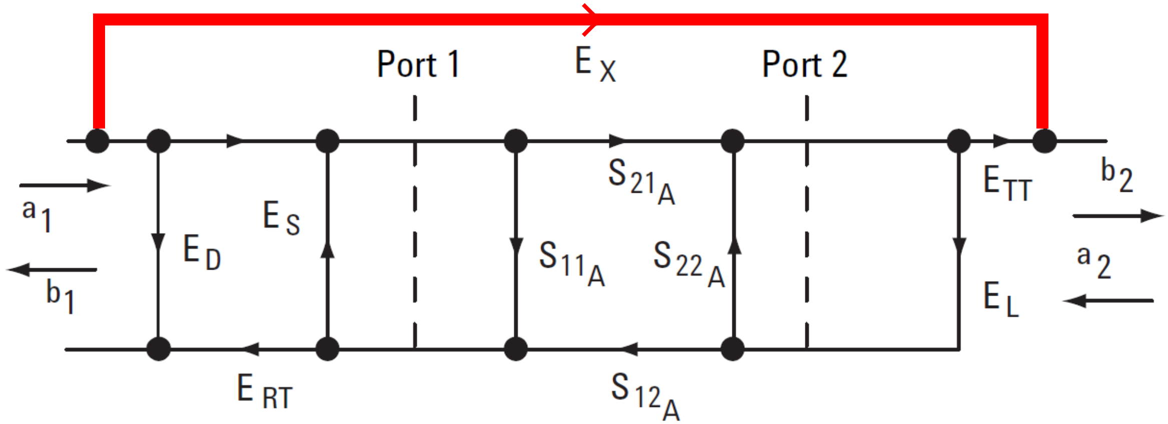




Adding isolation step changes the reflection around 10dB!!!!

When Effect of Crosstalk Term is Significant?

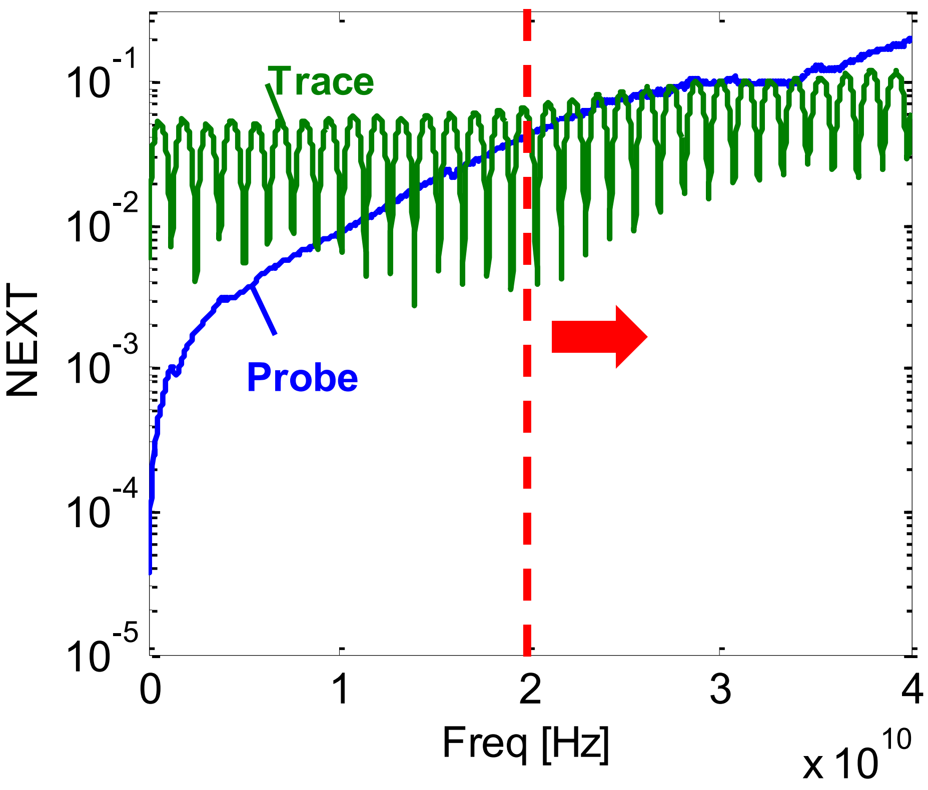
Forward model

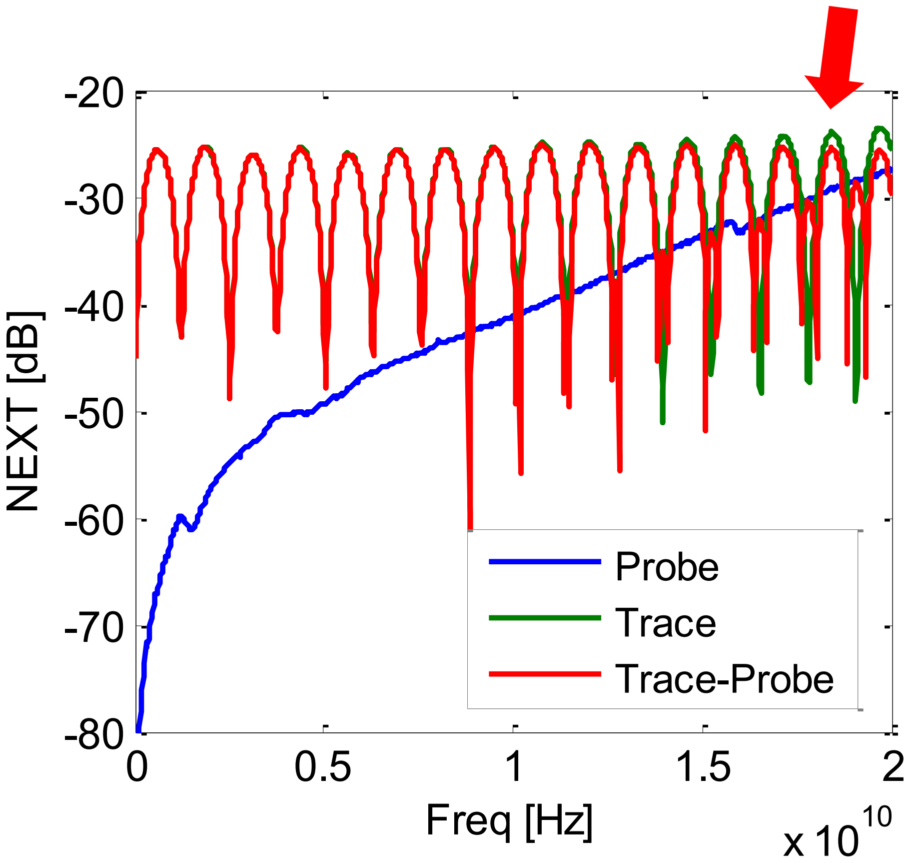


$$S_{11_a} = \frac{\left(\frac{S_{11m} - E_D}{E_{RT}}\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'}E_S'\right) - E_L\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}}E_S\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'}E_S'\right) - E_L'E_L\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}$$

When Effect of Crosstalk Term is Significant?

Probe Spacing of 410 µm

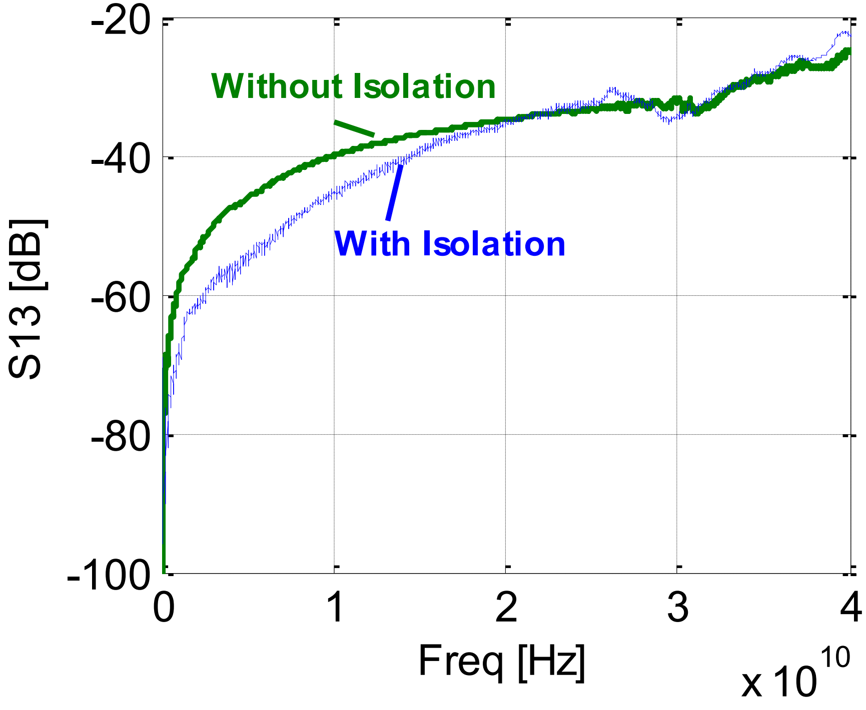




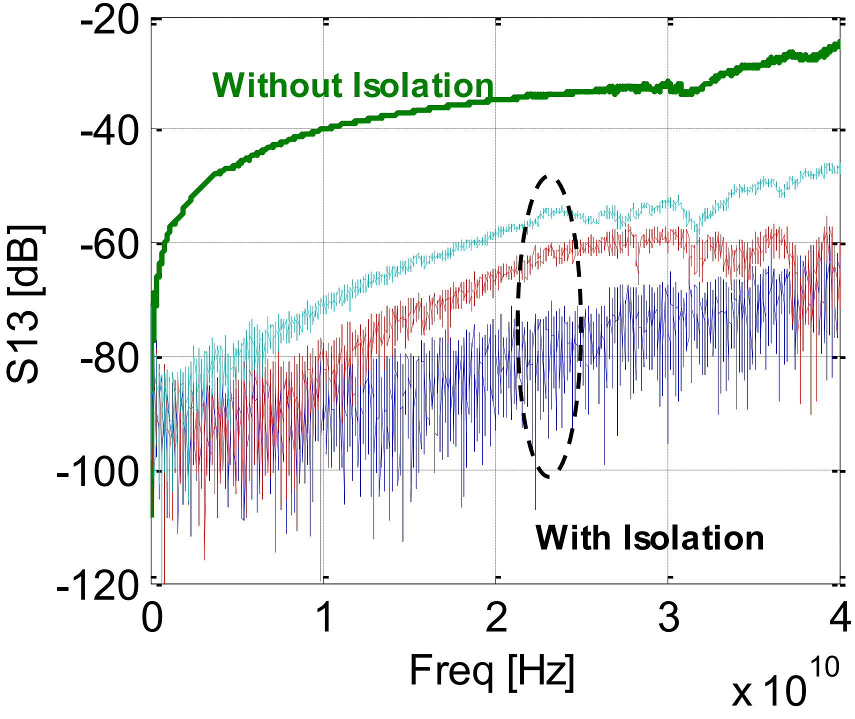
Above 20GHz the effect of probe coupling will be significant.

Effect of Isolation on NEXT

Open Measurement, In Air



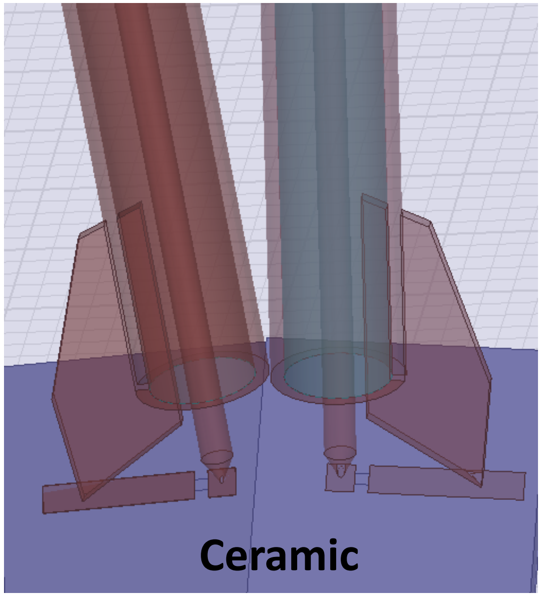
50 ohm Load Measurement



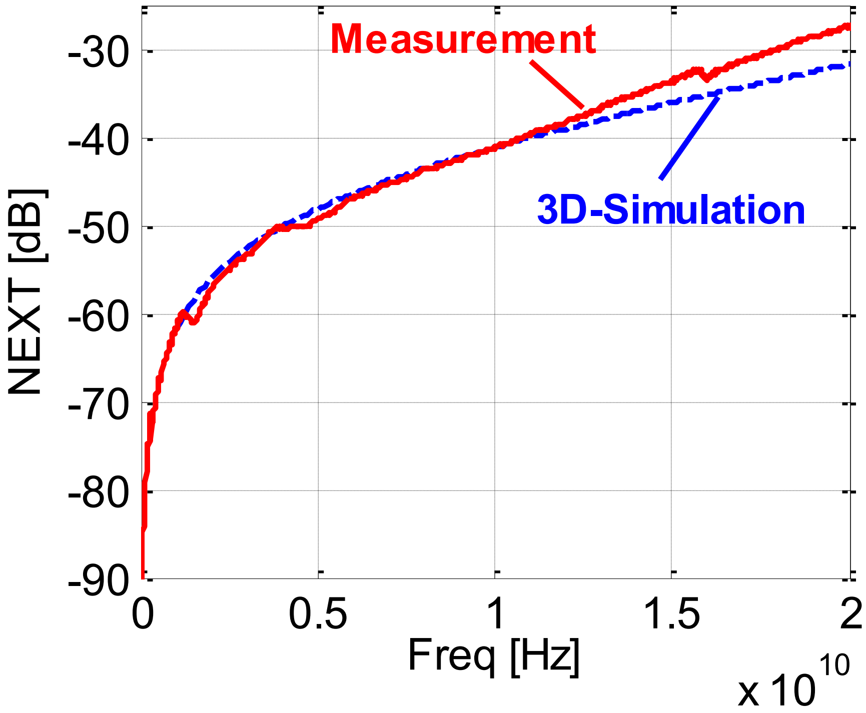
The characteristics of the DUT, directly affects the test system's isolation.

Isolation Study, 3D Field Solver

Landed Probes on 50-ohms Loads

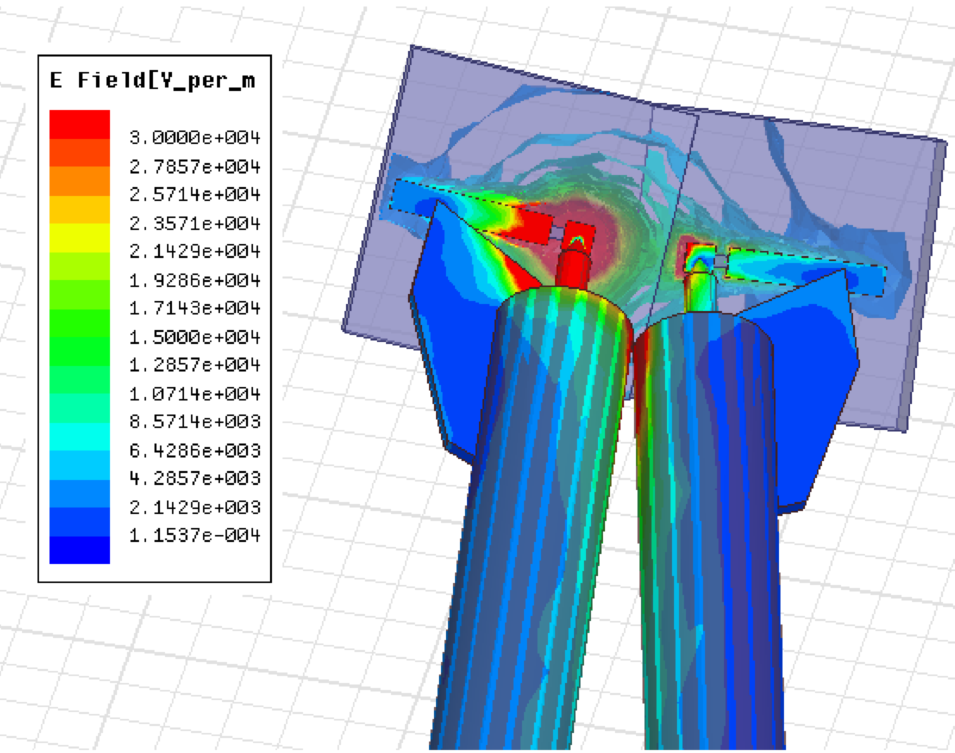


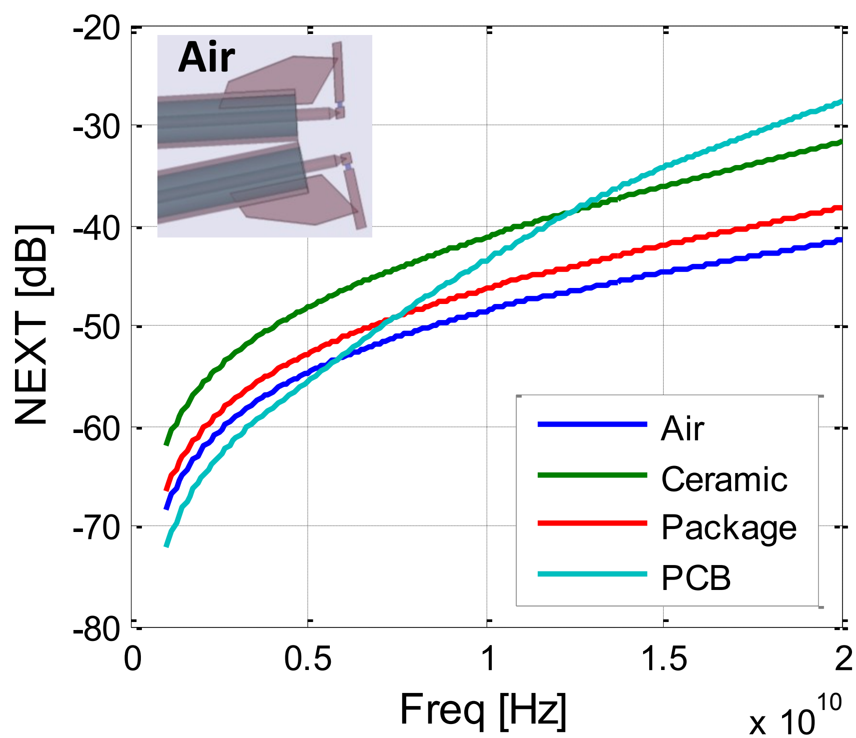
Very Good Correlation Between Measurement and Simulation



The Effect of Substrate on Isolation

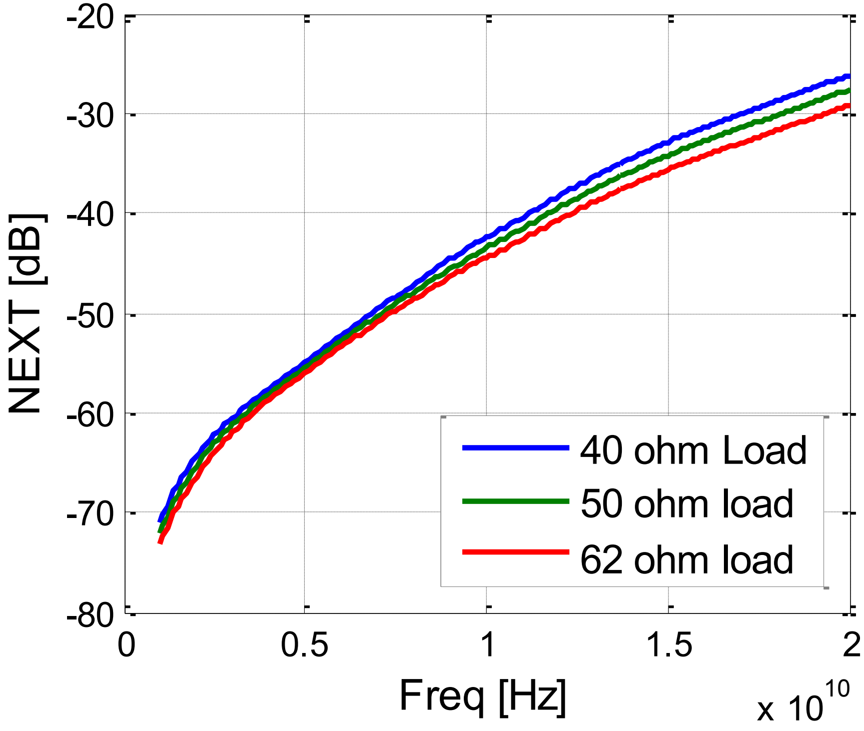
The Effect of substrate can not be neglected





The Effect of Impedance Change on Coupling

The variation in the load dimension, or thickness of the layers will cause inaccuracy in calibration with standards fabricated on PCB.



Is TRL calibration reliable for PCB applications?

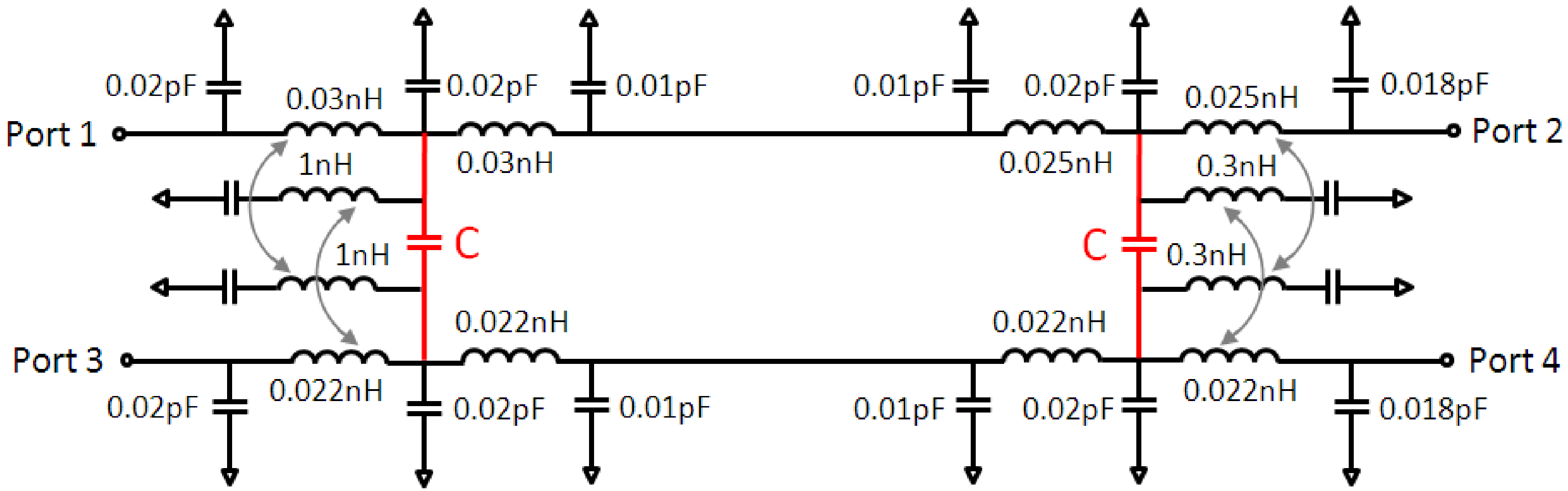
Summary

- The isolation standard substrate should be identical to DUT substrate.
- Differential TRL calibration should be used for calibrating coupling.
- Fabricating an isolation standards with the same impedance of the DUT may not be practical (TRL might not be attractive for PCB measurement)
- If coupling considered during calibration, the spacing between the probes should not be changed.
- There is a possibility of over compensating (or under compensating) for the crosstalk.

Agenda

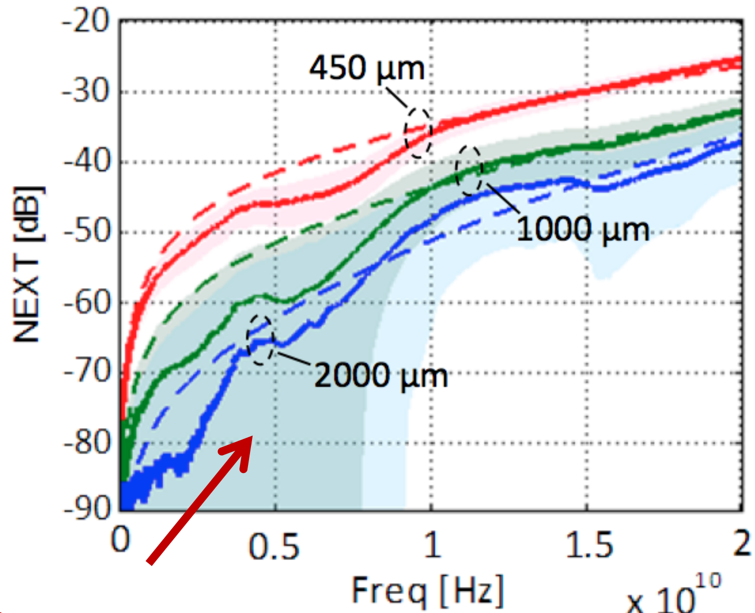
- VNA and measurement accuracy
- Coupling between differential probes
- Verifying the observed coupling with 3-D field solver simulation
- Can we count for coupling during calibration?
- Modeling the calibration residual and probe coupling
- Studying the effect of probe coupling on the measured S-parameters

Equivalent Circuit Model, Touching Probes

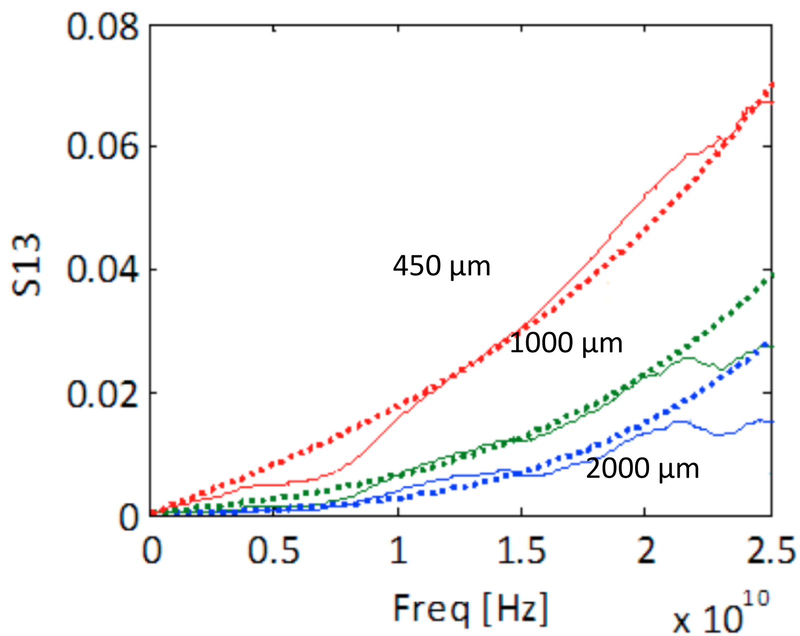


The model was generated based on the calibrated probes and is mainly capturing the probe characteristics that have not been de-embedded during calibration.

Near-end Crosstalk of Equivalent Circuit Model Versus Measurement

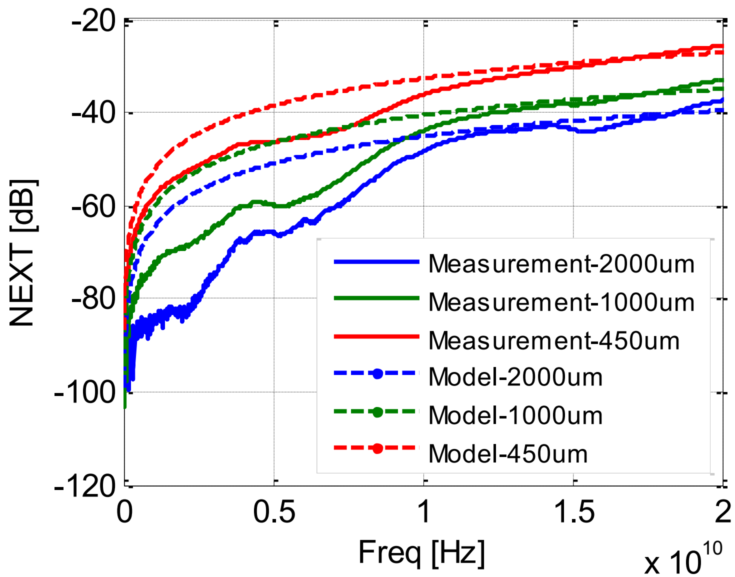


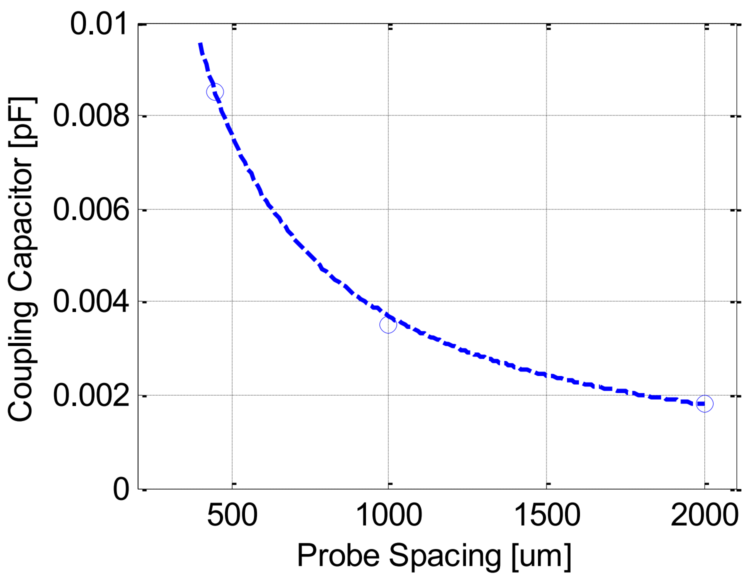
VNA measurement uncertainty



Equivalent circuit model was generated for touching probe with different probe spacings.

Coupling capacitance as a function of spacing between probe tips





$$C_{coupling}(x) = \alpha \ x^{-\beta}$$

α=4.87, β=1.04 x is in microns; C is in picofarads.

Summary

- The amount of coupling is relatively small for frequencies less than 10 GHz.
- Only capacitive model can be used for modeling coupling at high frequencies.
- The probe-to-probe coupling as a function of probe spacing can be captured by changing just the value of the coupling capacitor.

Agenda

- VNA and measurement accuracy
- Coupling between differential probes
- Verifying the observed coupling with 3-D field solver simulation
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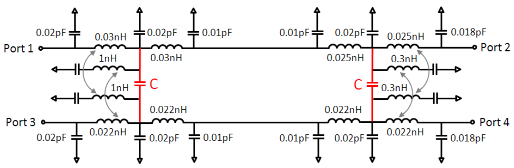
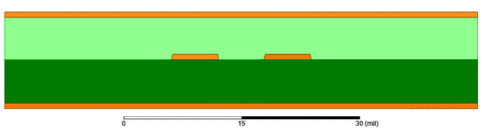
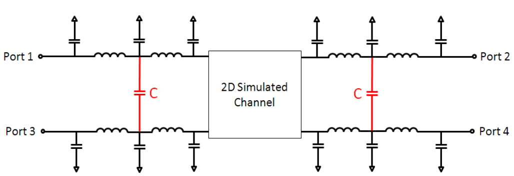
Effect of probe coupling on S-parameters Measurement



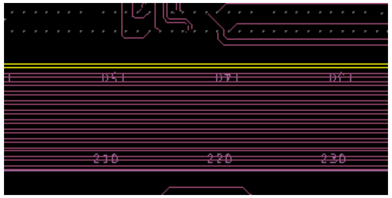


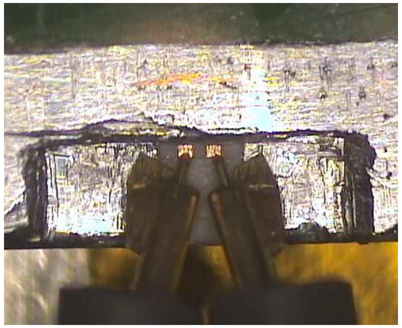


Modeling Probes

Modeling Channel

Measuring Channel

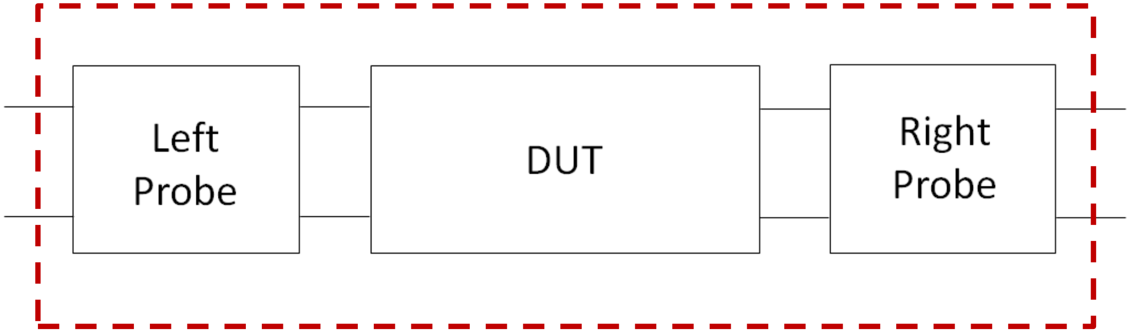


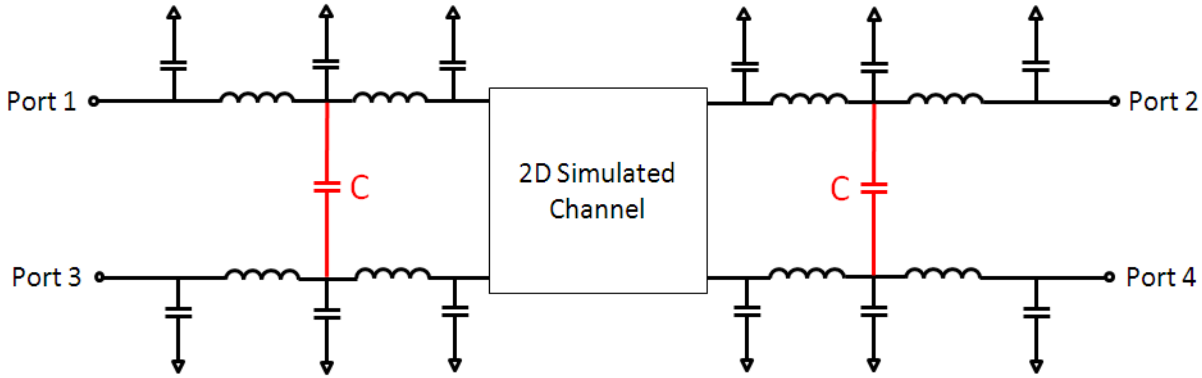


Understanding the Effect of Probes

Understanding the Effect of Probes

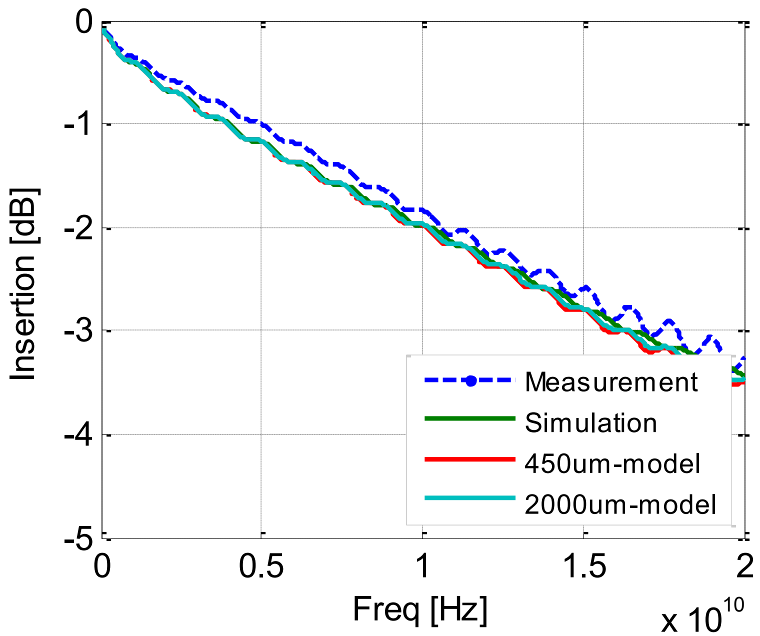
Measurement





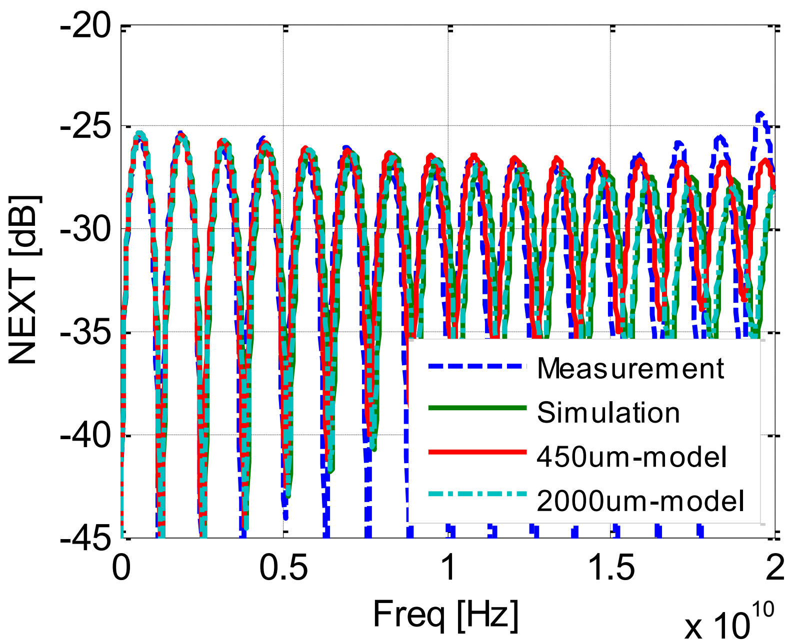
Effect of Probe Coupling on S-parameters

Insertion Loss



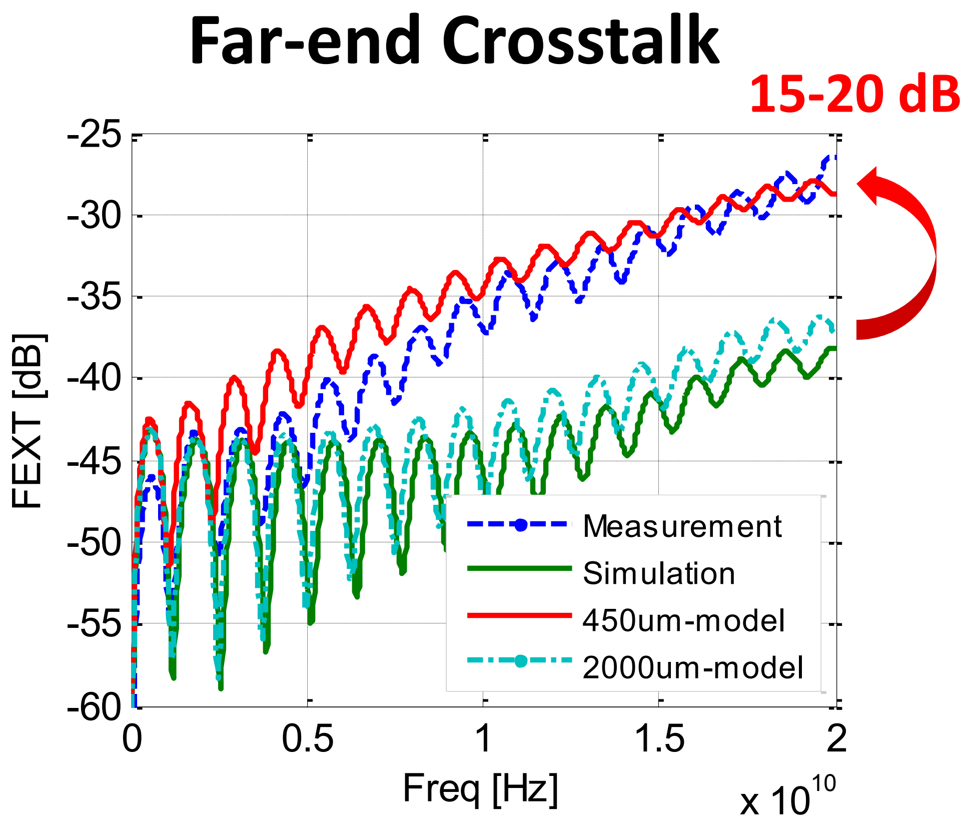
The effect of probe coupling on insertion loss is ***not Significant***

Near-end Crosstalk



The added probe model ***slightly improves*** the simulation to measurement correlation

Effect of Probe Coupling on S-parameters

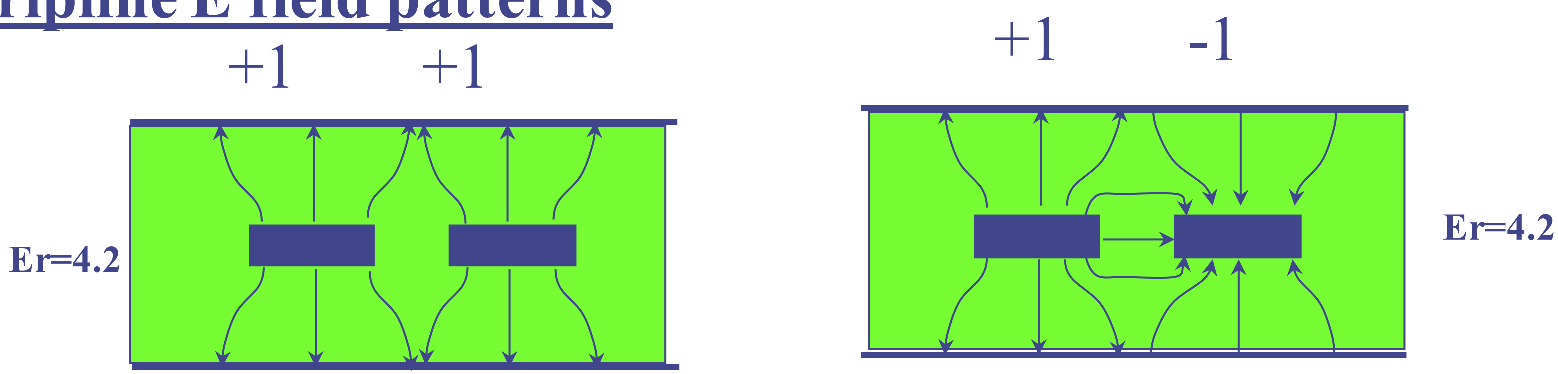


Probe coupling has ***Significant effect*** on far-end crosstalk

Far-end Crosstalk

$$Crosstalk(far\_stripline) = -\frac{V_{input} X \sqrt{LC}}{2T_r}\left[\frac{L_{12}}{L_{11}} - \frac{C_{12}}{C_{11}}\right]$$

Stripline E field patterns



The effective dielectric constant, and subsequently the propagation velocity depends on the electric field patterns

Far-end Crosstalk

The constant velocity in a homogeneous media (such as a stripline) forces far end crosstalk noise to be zero

$$TD_{odd} = TD_{even}$$

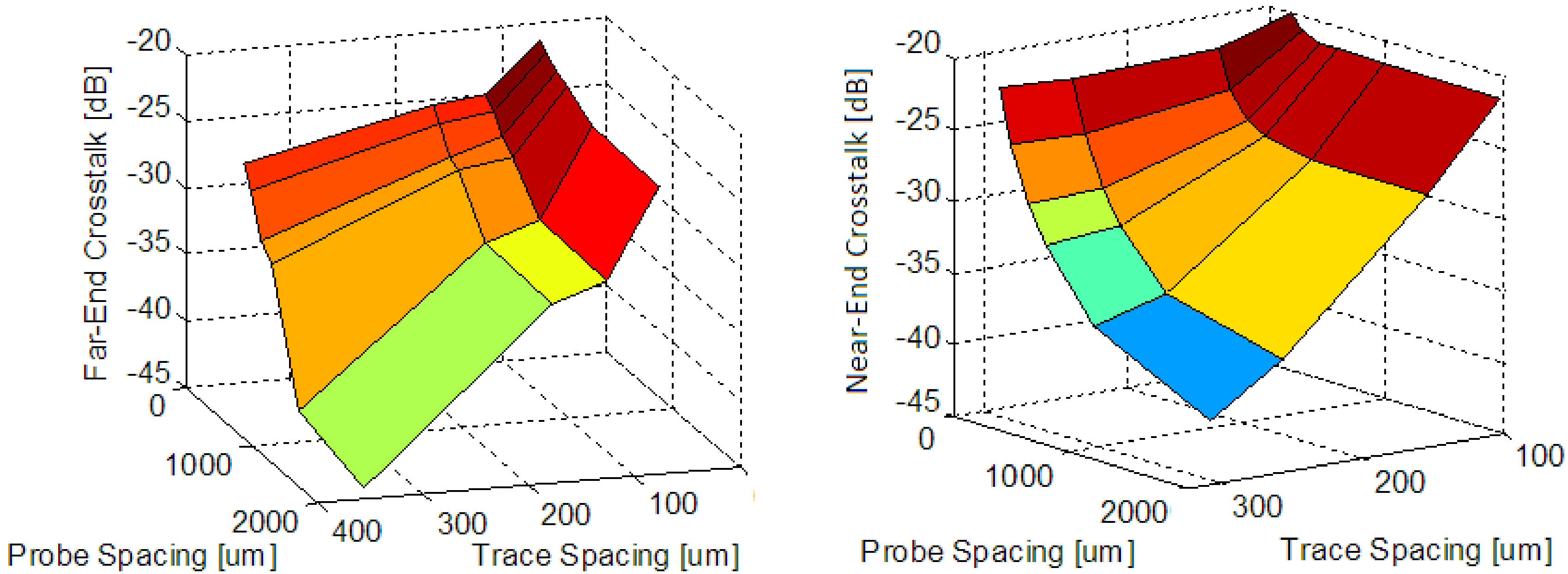
$$\sqrt{(L_{11} - L_{12})(C_{11} + C_{12})} = \sqrt{(L_{11} + L_{12})(C_{11} - C_{12})}$$

$$-L_{12}C_{11} + L_{11}C_{12} = -L_{11}C_{12} + L_{12}C_{11}$$

$$\frac{L_{12}}{L_{11}} = \frac{C_{12}}{C_{11}}$$

$$Crosstalk(far\_stripline) = -\frac{V_{input} X \sqrt{LC}}{2T_r}\left[\frac{L_{12}}{L_{11}} - \frac{C_{12}}{C_{11}}\right] = 0$$

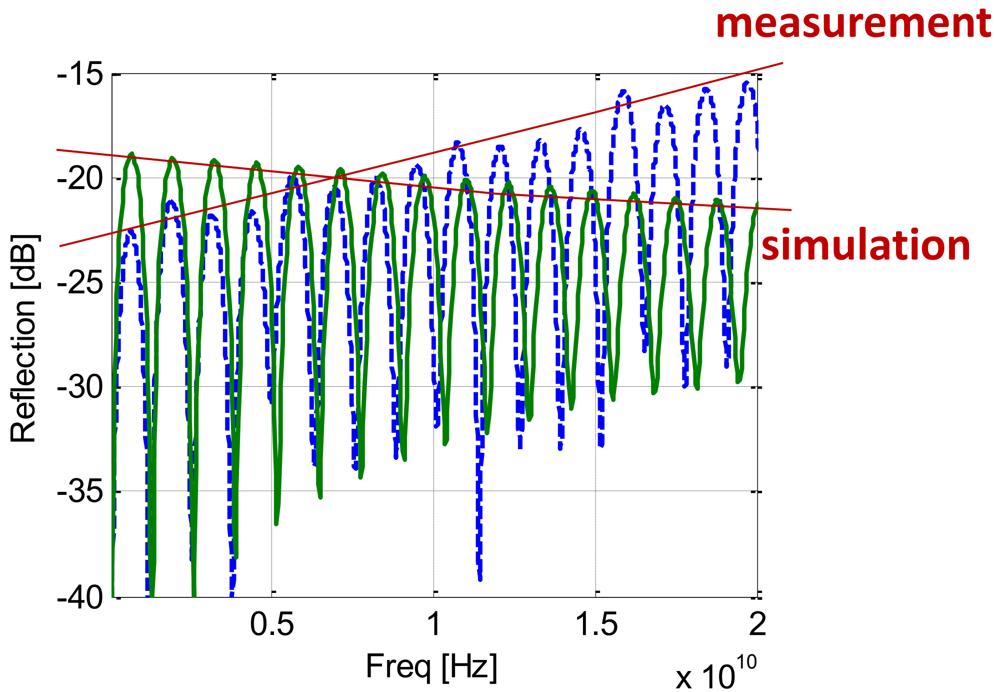
Far-end and Near-end crosstalk as a function of trace spacing and probe spacing

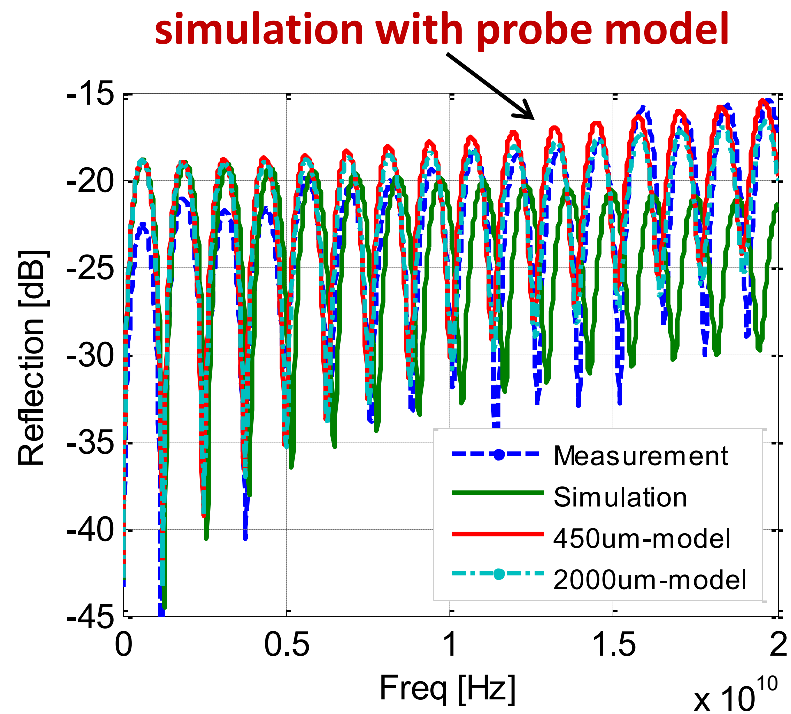


The significance of probe coupling effect depends on the amount of coupling between the measured traces.

Effect of Probe Coupling on S-parameters

Reflection Loss

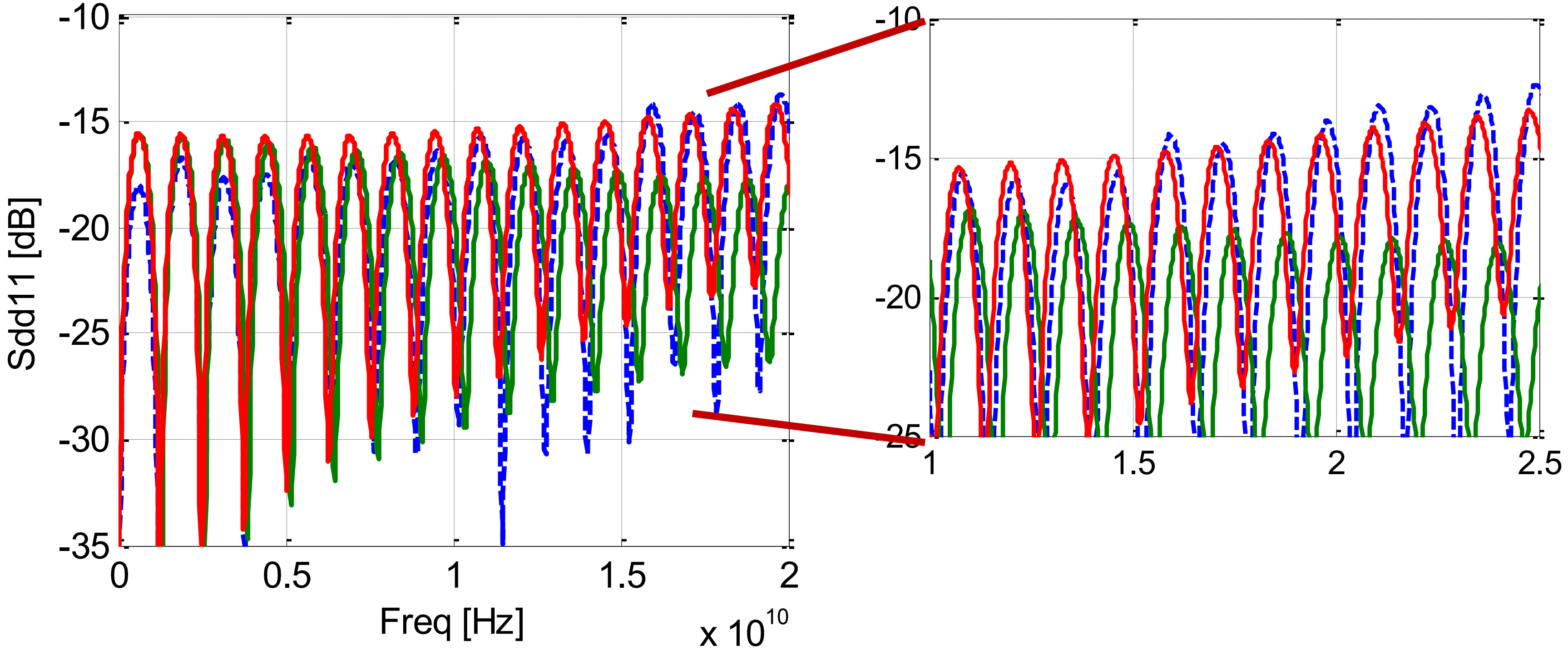




The probe parasitic capacitance and inductance manifest as an ***upward slope*** with increasing frequency

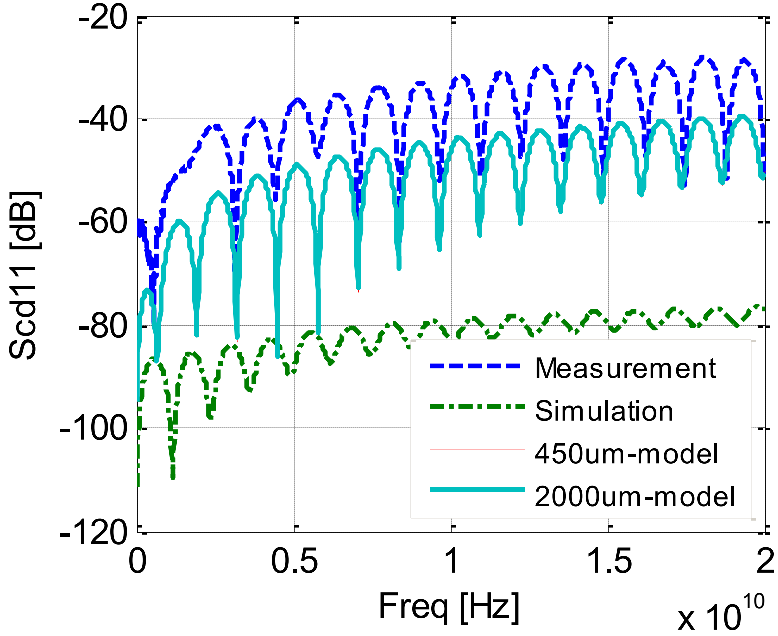
Effect of Probe Model on S-parameters

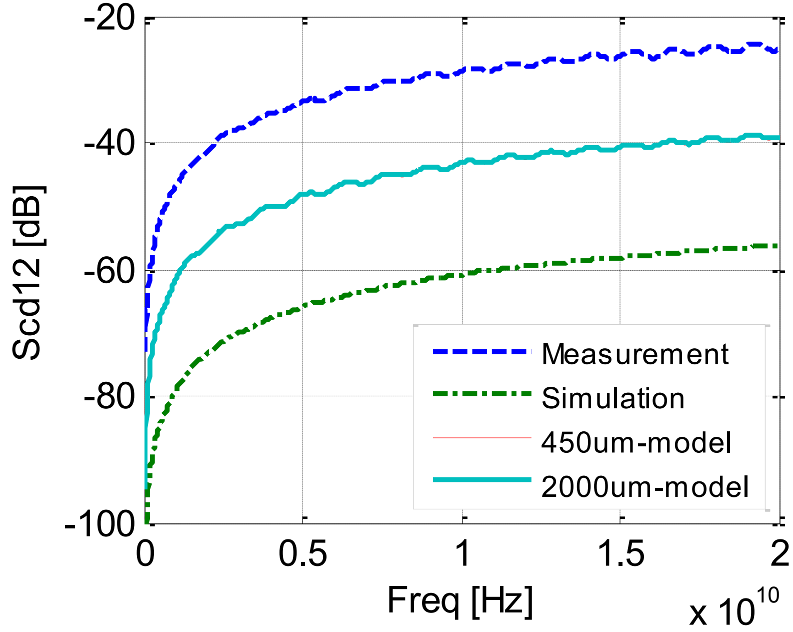
Differential Reflection Loss



Mode Conversion

Differential to Common Mode Conversion





Scd11=(S11+S31-S13-S33)/2

Scd21=(S21+S41-S23-S43)/2

Even after calibration the reflection from probes were slightly different.

Conclusion

- Counting for coupling during calibration will restrict us to a constant probe spacing during calibration and measurement
- TRL method should be used for considering coupling
- TRL method for PCB applications is not attractive
- Including the probe characteristics in simulations will help to close long standing wafer probe measurement and simulation discrepancies.
- Probe coupling has significant effect on far-end crosstalk