SI Design & Measurement Principles and Best Practices

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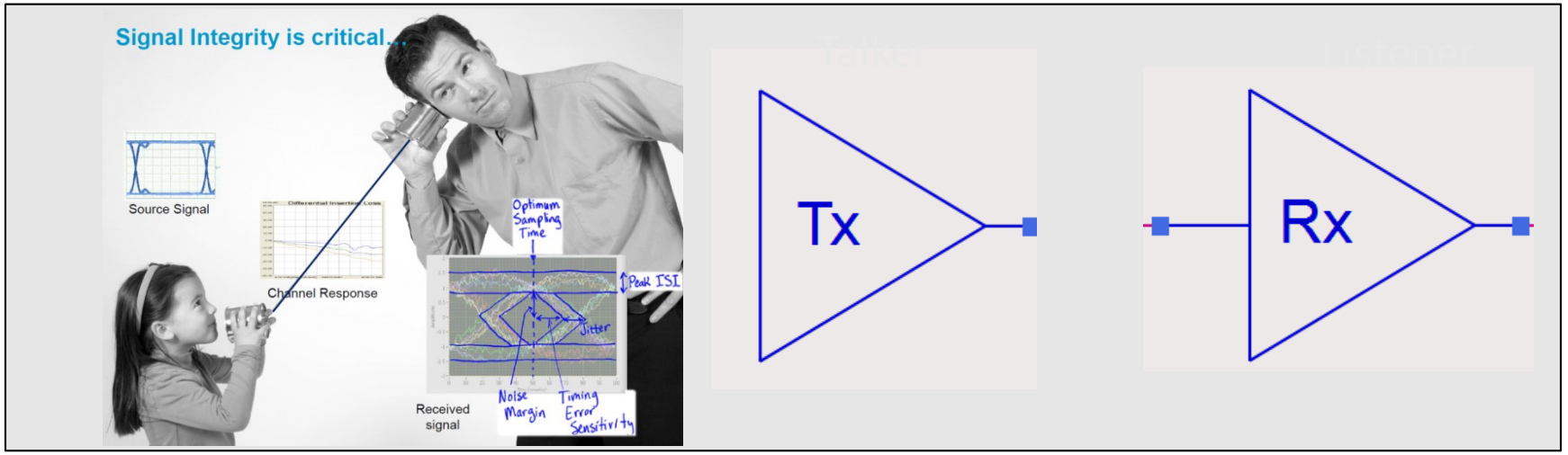
KEYSIGHT TECHNOLOGIES

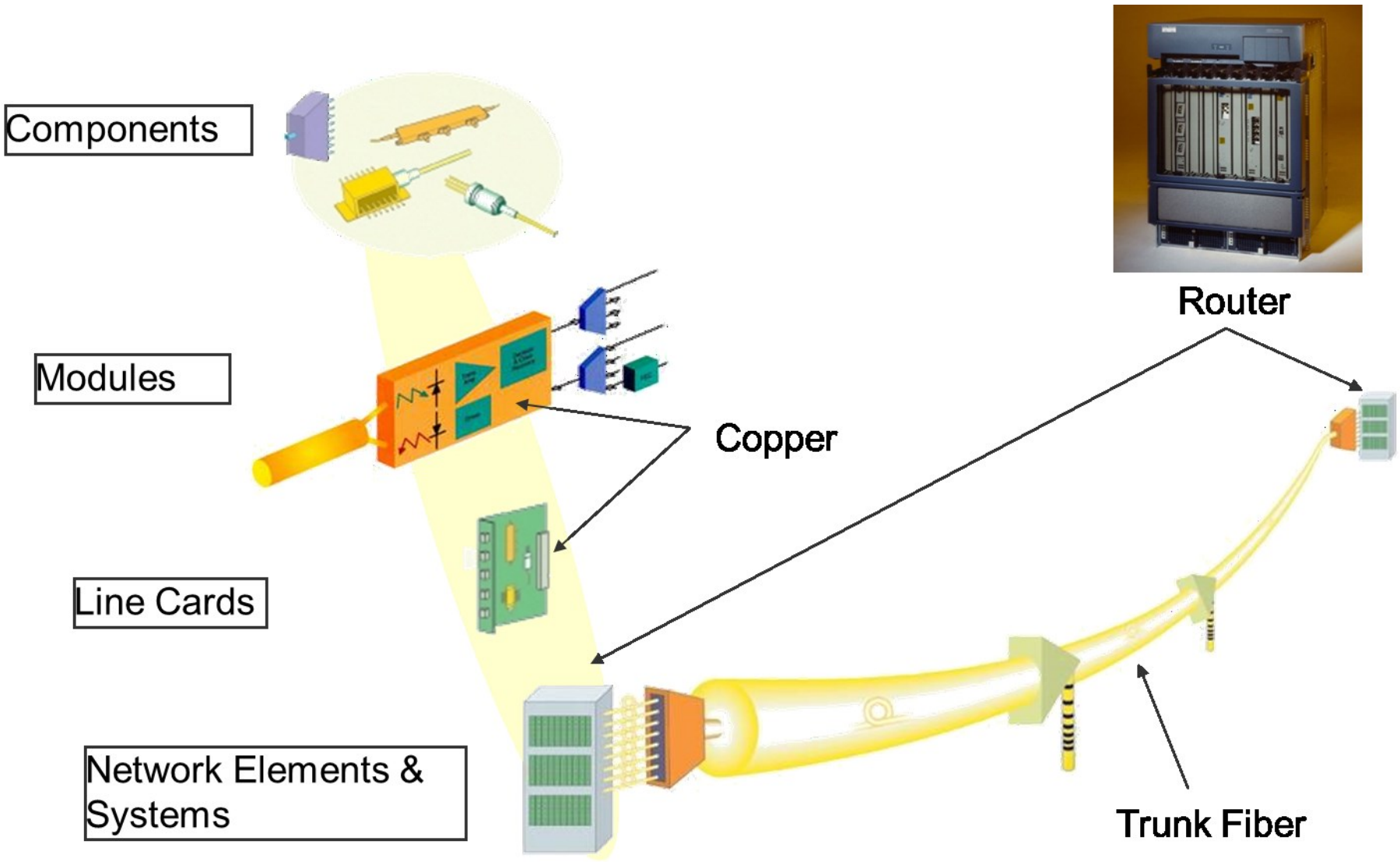
Signal Integrity



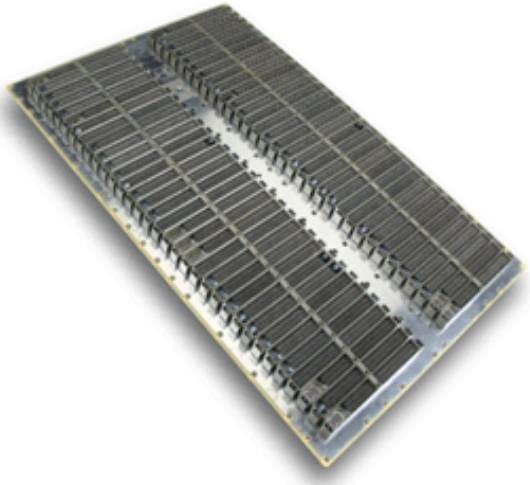
The Tx to Rx connection:

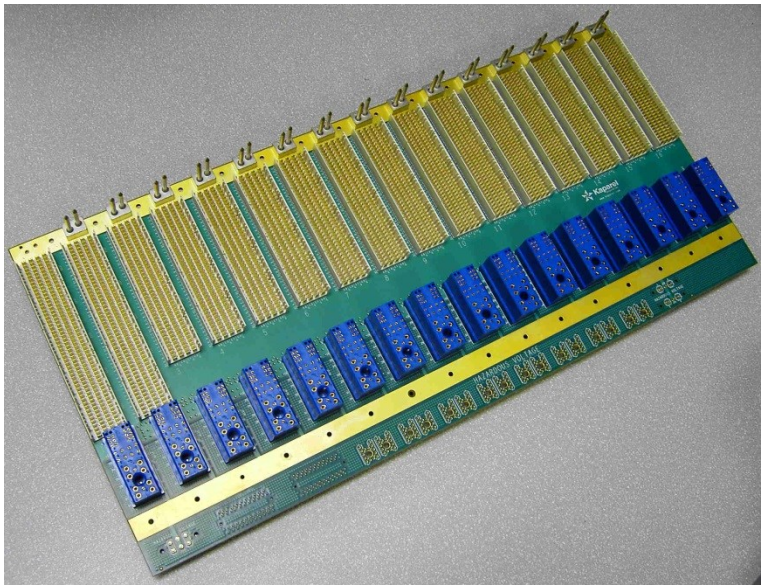
- Digital standards refer to it as the Physical Layer or “the PHY” for short.
- Simulation tools call it the channel

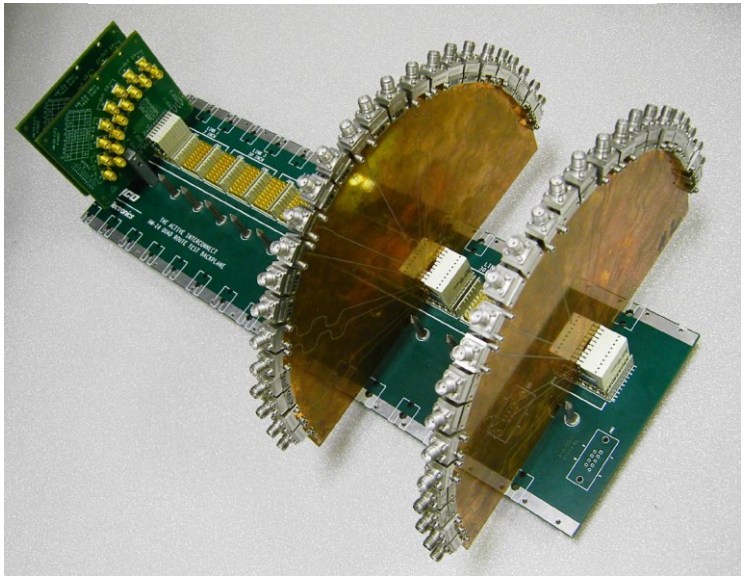
Typical 100 Gbps Telecom System

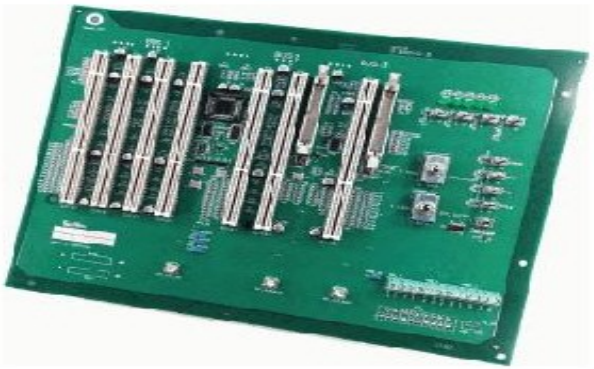


Backplanes are a Critical Link

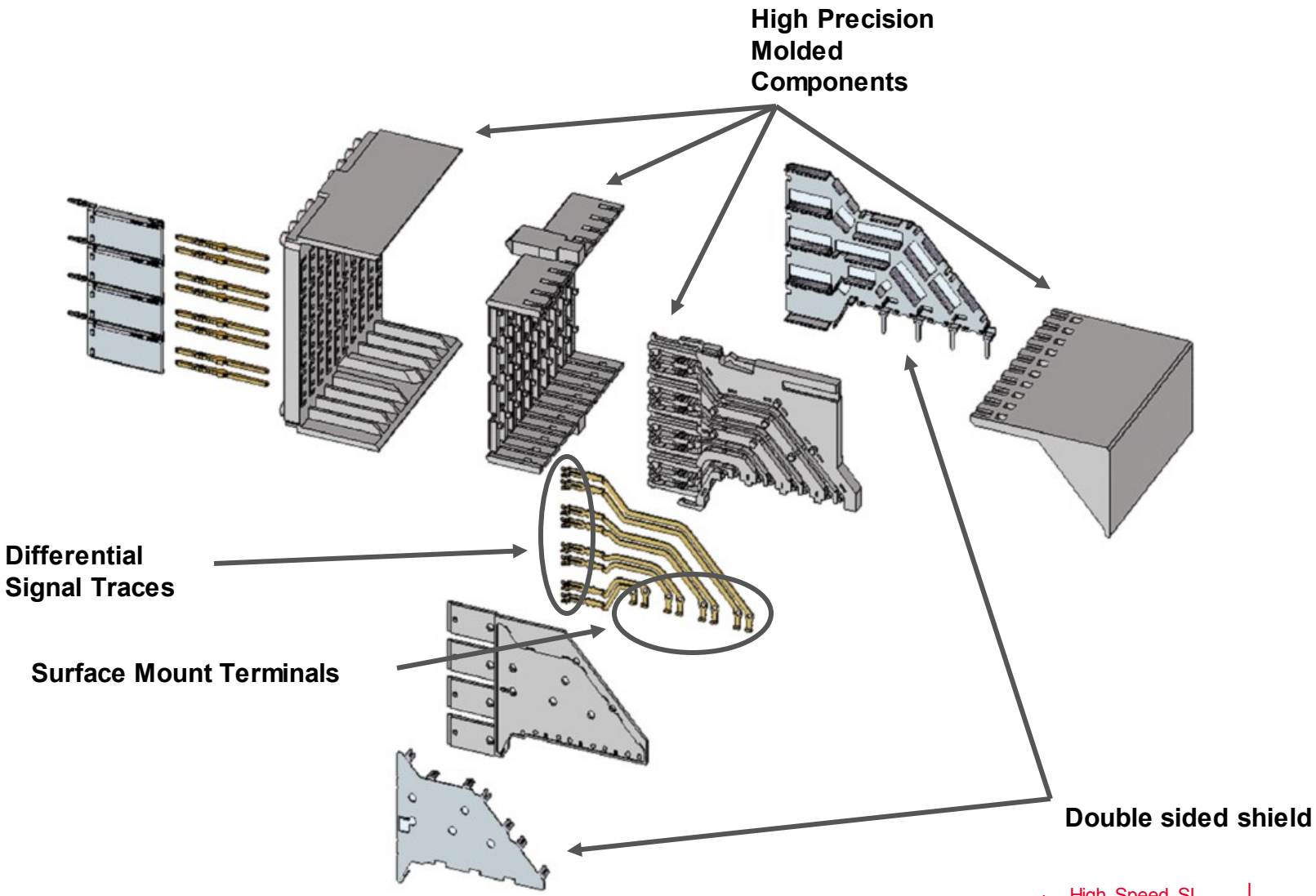




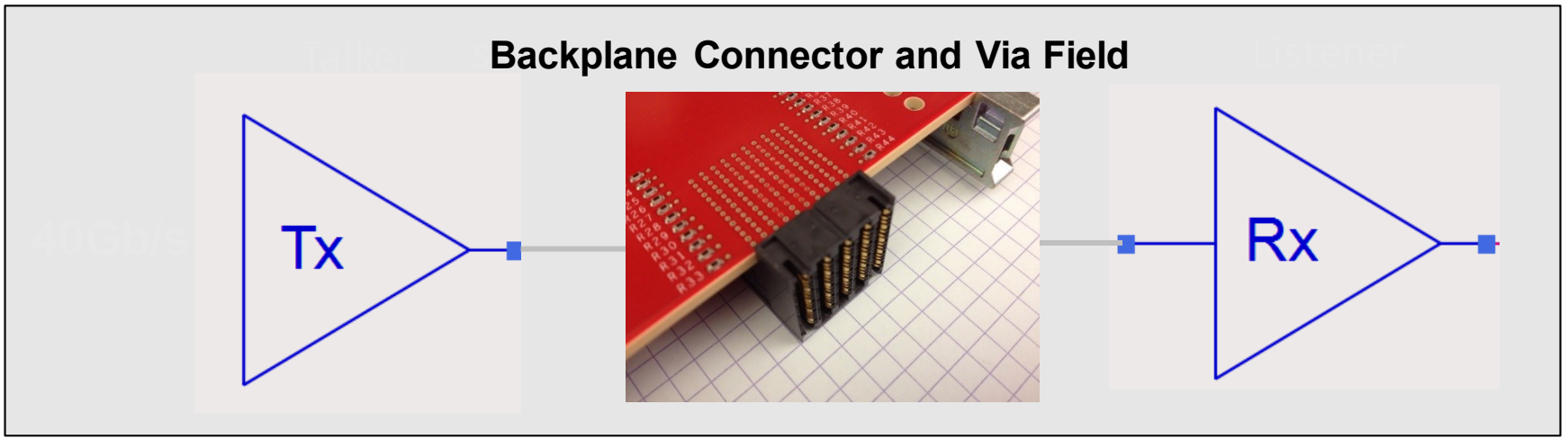




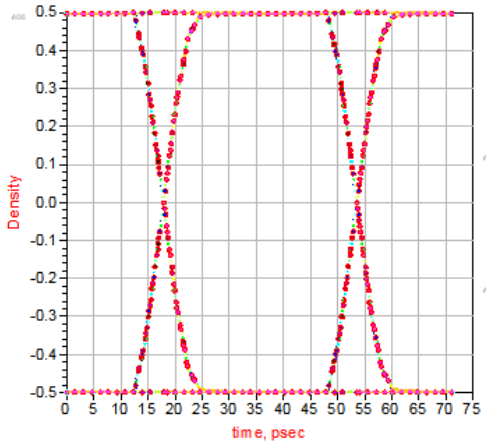
Backplane Connectors Are Advanced



Why Do I Need Signal Integrity?

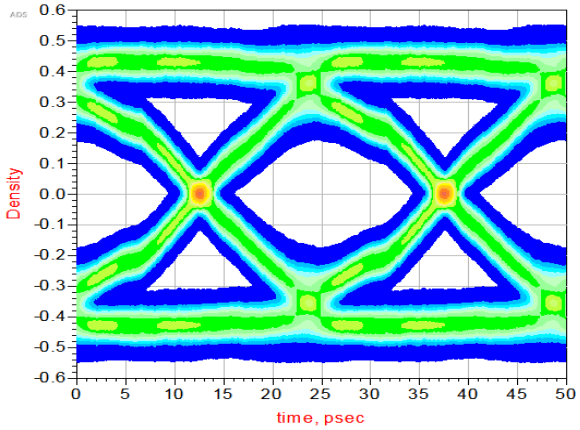


What I Simulate



A Transparent Connector

What I Measure



Connector + Fixture

1) **I should find a new job.**
2) **What is the fixture?**
3) **As-fabricated materials?**
4) **How can I tell what is wrong?**
5) **What should I fix first?**

Eric Bogatin's Rule #9

Rule # 9: Never do a measurement or simulation without first anticipating what you expect to see.

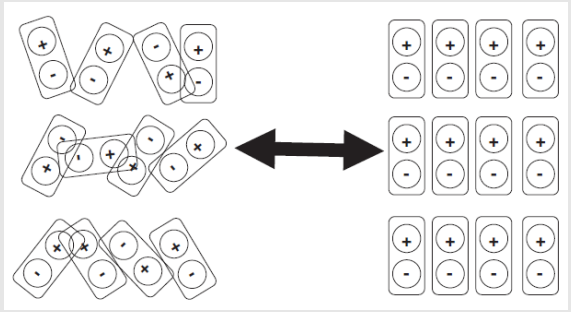
- Simulations and measurements minimize risk
- Knowing what to expect saves time and money
- If you get it right you feel good
- If you get it wrong you will learn something

Signal and Power Integrity expert Eric Bogatin is the author of:
Signal Integrity and Power Integrity Simplified,
Prentice Hall, 2nd edition 2010

Signal Integrity Basics

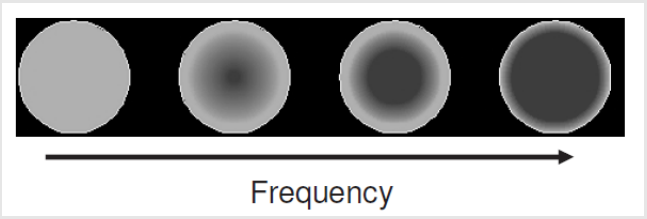
- Material Loss :
  - Conductor
  - Dielectric
- Impedance Loss and S-Parameters
  - Reflections
  - Crosstalk

Frequency Dependent Channel Loss from Materials



$$\text{Dielectric Loss} \approx 2.3\, f\, \sqrt{\varepsilon_r}\, \tan\delta \ \text{ dB/inch}$$

$$\text{example}: \ 2.3\,(1\text{GHz})\,\sqrt{4}\,(0.02) \approx 0.092 \text{ dB/inch}$$



$$1\text{oz Copper Loss} \approx \frac{36}{w\, Z_0}\, \sqrt{f}\, \tan\delta \ \text{ dB/inch}$$

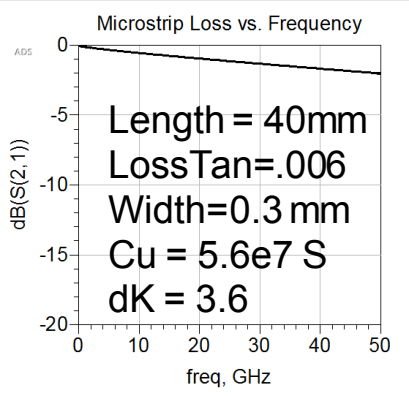
$$\textit{example}: \frac{36}{(10\textit{mils})(50\Omega)} \sqrt{1\textit{GHz}} \approx 0.07 \text{ dB/in}$$

Losses from materials:

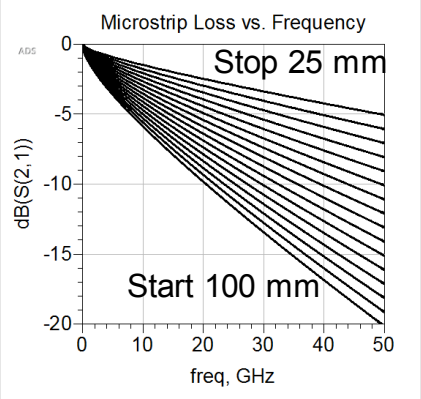
- Dielectric loss caused by dipole movement with rapidly changing fields. Proportional to frequency.
- Conductor loss with skin effect pushing currents to lowest inductance path. Proportional to square root of frequency.

Example: Channel Loss with PCB Materials

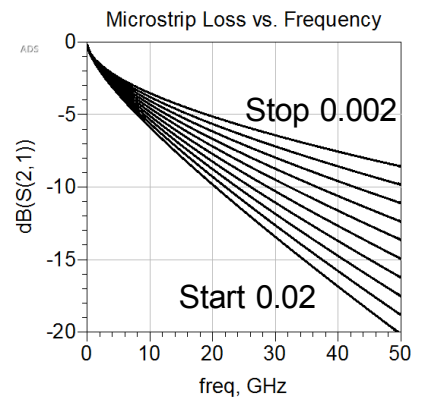
Application



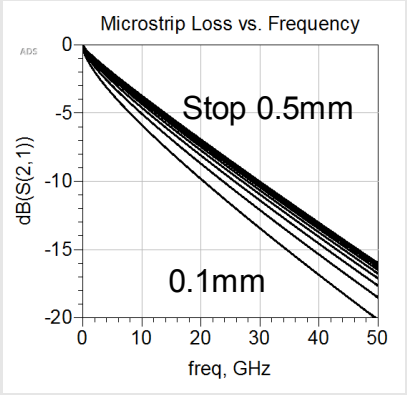
Worst Case vs Length 100mm to 25mm



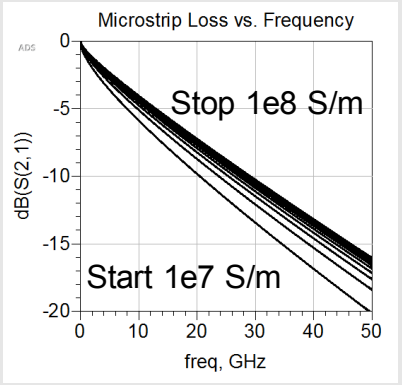
Worst Case vs Loss Tangent 0.02 to 0.002



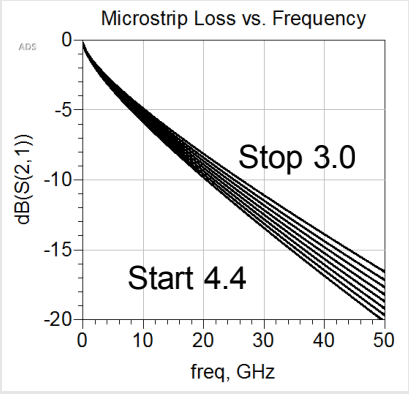
Worst Case vs Width 0.1mm to 0.5mm



Worst Case vs Conductivity 1e7 S/m to 1e8 S/m



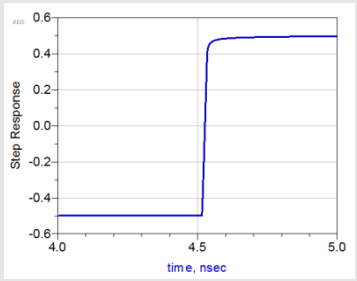
Worst Case vs dK 3.0 to 4.4



Worst Case: 100mm Length, 0.02 LossTan, 0.1mm Width, 1e7 S/M, 4.4 dK

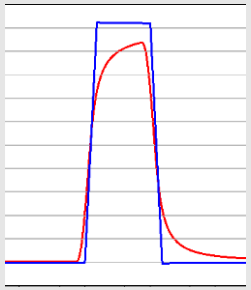
PCB Material Loss in the Time Domain

Step Response

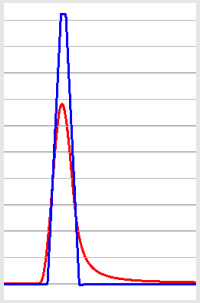


Single Bit Response (SBR)

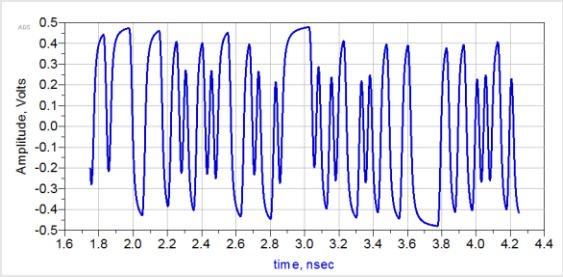
10 Gb/s



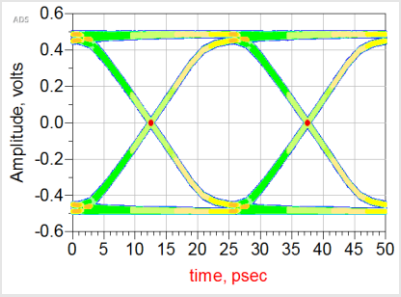
40 Gb/s



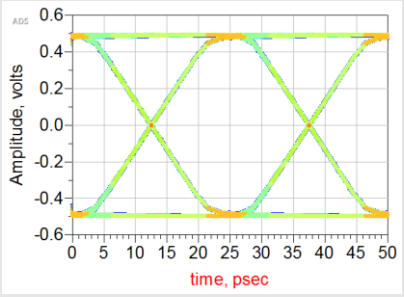
40 Gb/s PRBS9 Waveform Worst case PCB Materials



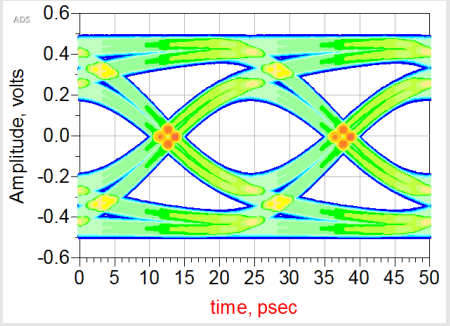
Eye Diagram Socket Application



Best Case PCB Material



Worst Case PCB Material



Real World PCB - Effective Loss Tangent

Leveraging old PCB technology

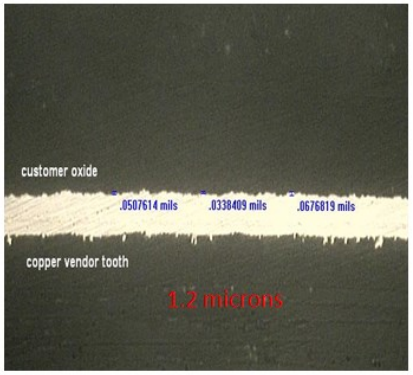
New SI requirements for the PCB fabrication document:

-Glass Weave
-Copper Profile
-Test Structures for as-fabricated PCB losses.

Pictures from Lee Ritchey of Speeding Edge, "13-TU2 Breaking the 32 Gb/s Barrier: PCB Materials, Simulations, Measurements", DesignCon2015

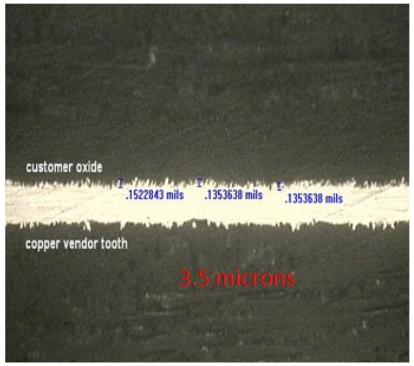
Copper Foil Profile – surface roughness

Supplier # 1 Oxide



Good Loss

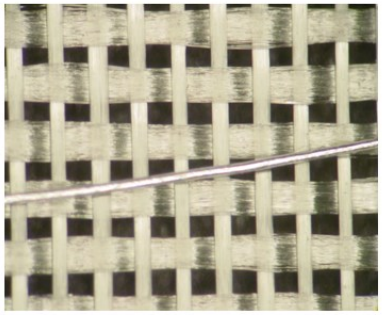
Supplier # 2 Oxide



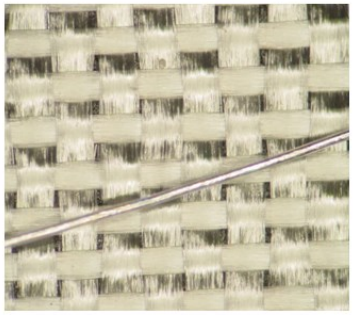
Poor Loss

Glass Weave – dK variation

Two Common Glass Weaves Styles



1080 GLASS WEAVE
(very open weave)



3313 GLASS WEAVE
(uniformly spread weave)

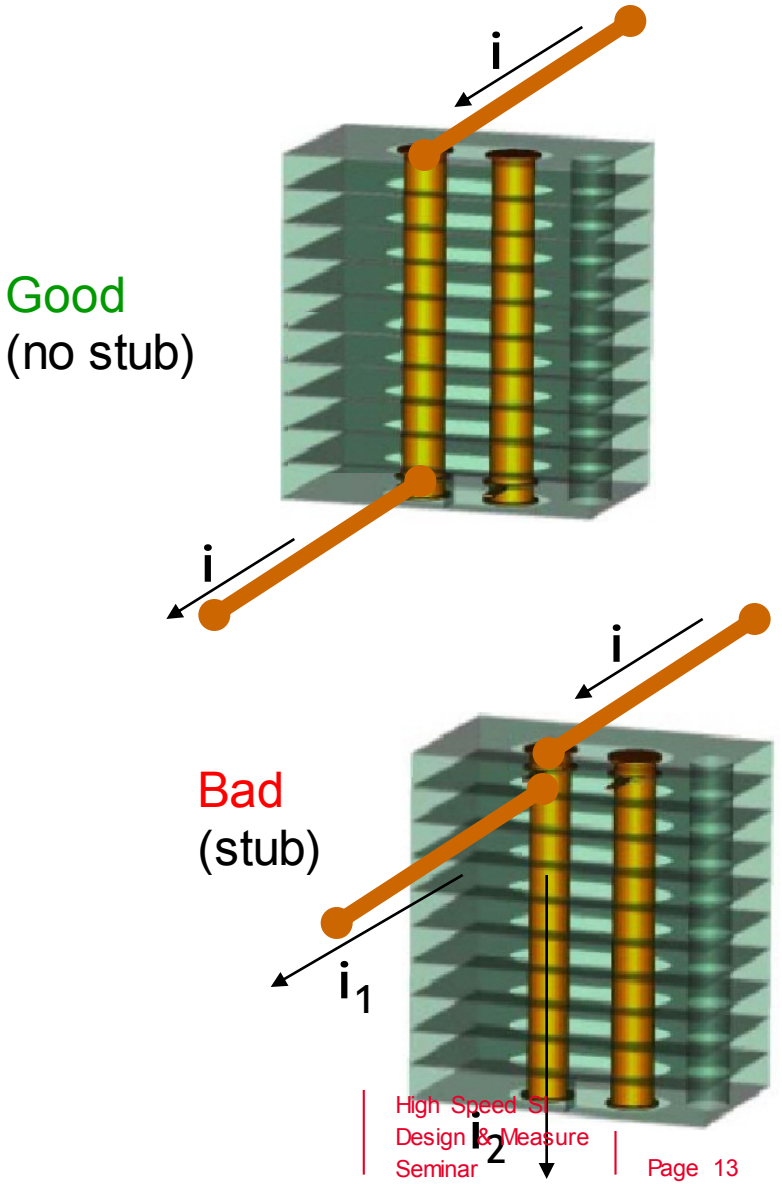
A 3.5 MIL WIRE IS SPREAD ACROSS THE WEAVE TO PROVIDE SCALE OF A TYPICAL TRACE

KEYSIGHT TECHNOLOGIES

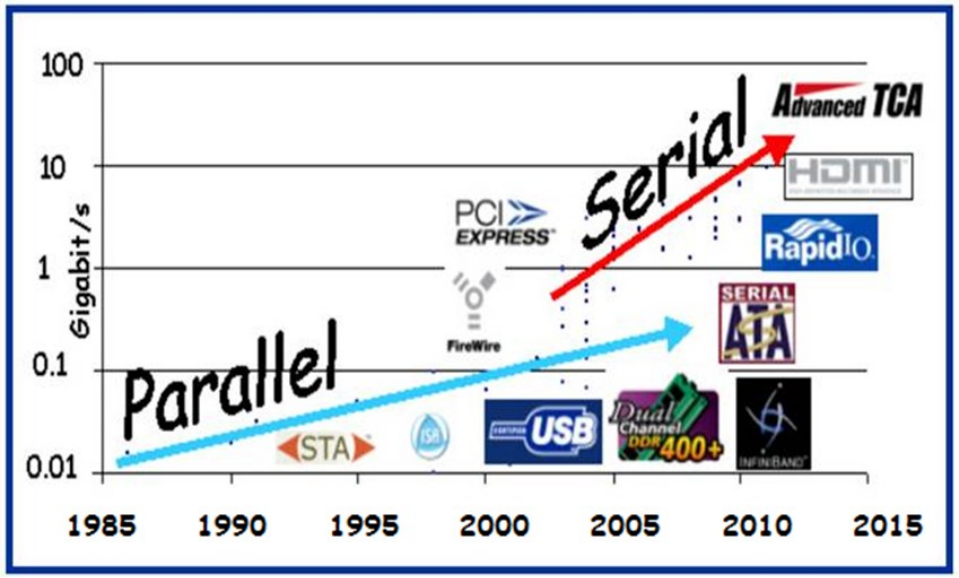
Via Stubs Create Capacitive Loads

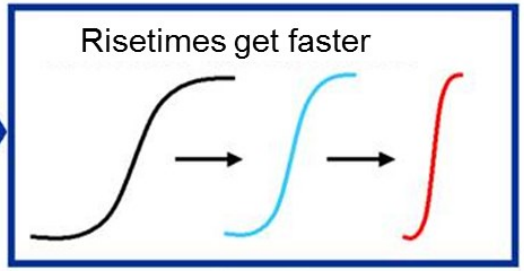
How is a Via Stub Created?

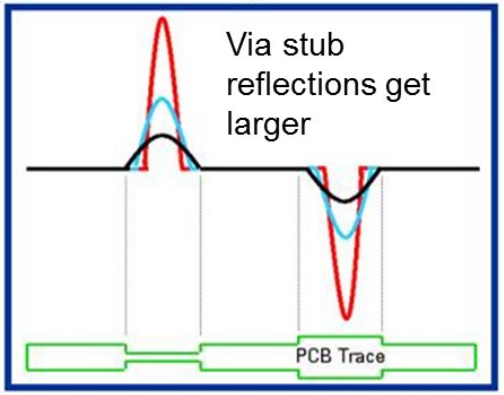
- Signal current splits in two directions and sees two 50 ohm lines in parallel (25 ohms)
- Excess capacitance is created by a 25 ohm segment of equivalent circuit
- Reflections and poor signal integrity results



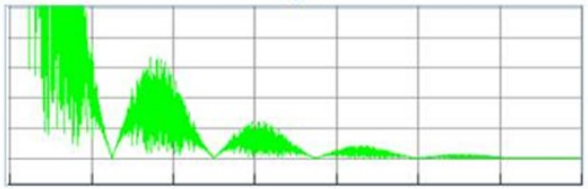
Backplane Data Rates are Increasing





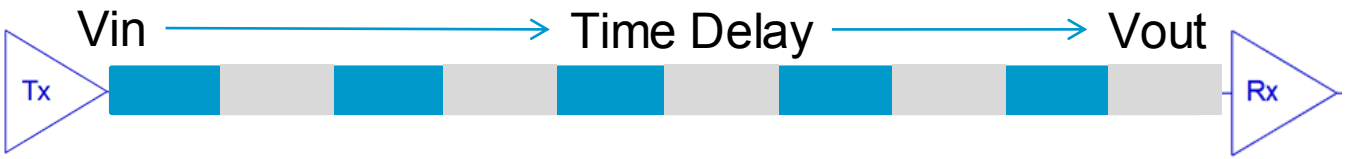


Frequency domain data is now required



Impedance Reflections

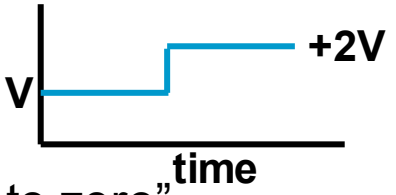
"Reflections are the reality when time traveling is not allowed"



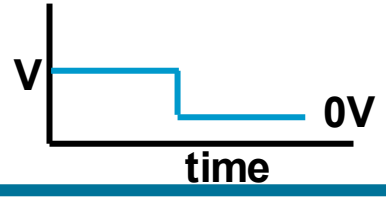
Vin does not show up instantaneously at Vout, and therefore Vin requires a round trip delay to adjust to the Vout termination. Initial Vin only sees the "characteristic impedance" Zo.

Thought Experiment for Impedance Reflections

OPEN - Positive Voltage Reflection "Current must flow back to the source"



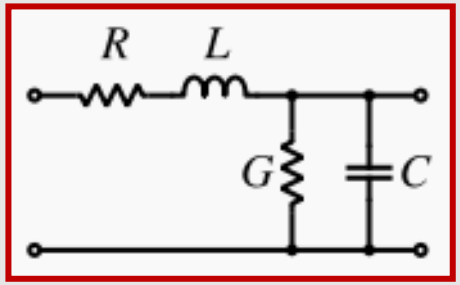
SHORT - Negative Voltage Reflection "Voltage must go to zero"



Telegrapher's Equations

Oliver Heaviside
1850-1925

Voltages and Currents are changing with Time and Distance (Magnitude and Phase)



- Create a simple model of a transmission line.
- Utilize calculus to analyze the model when summing a series of incremental length sections.

For small R and G

$$\frac{\partial^2}{\partial t^2}V = \frac{1}{LC}\frac{\partial^2}{\partial x^2}V$$

$$\frac{\partial^2}{\partial t^2}I = \frac{1}{LC}\frac{\partial^2}{\partial x^2}I$$

Sinusoidal Input

$$E = E_o.e^{-j\omega(\frac{x}{c}-t)}$$

$$\frac{\partial^2 V(x)}{\partial x^2} + \omega^2 LC \cdot V(x) = 0$$

$$\frac{\partial^2 I(x)}{\partial x^2} + \omega^2 LC \cdot I(x) = 0$$

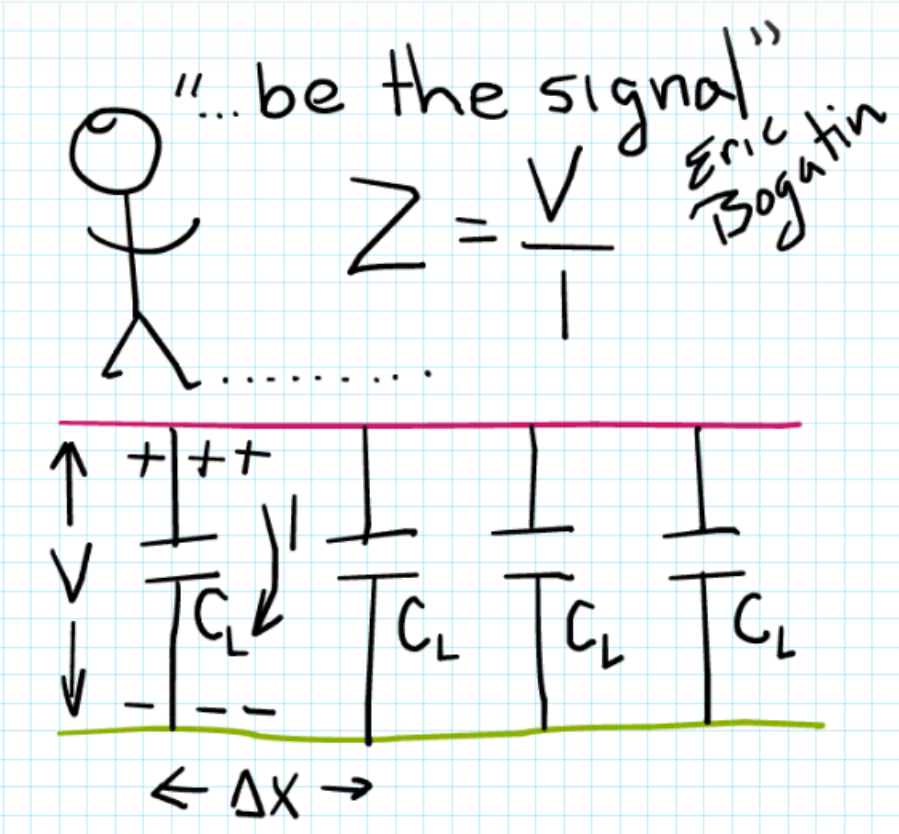
Resulting Relationships

$$v = \frac{1}{\sqrt{LC}}$$

$$Z_0 = \sqrt{\frac{L}{C}}$$

$$\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S}$$

Characteristic Impedance Z_0



Derivation from Telegrapher Equations:

$$Z_0 = \sqrt{\frac{L}{C}}$$

Derivation from transmission line charging:

Independent of Length

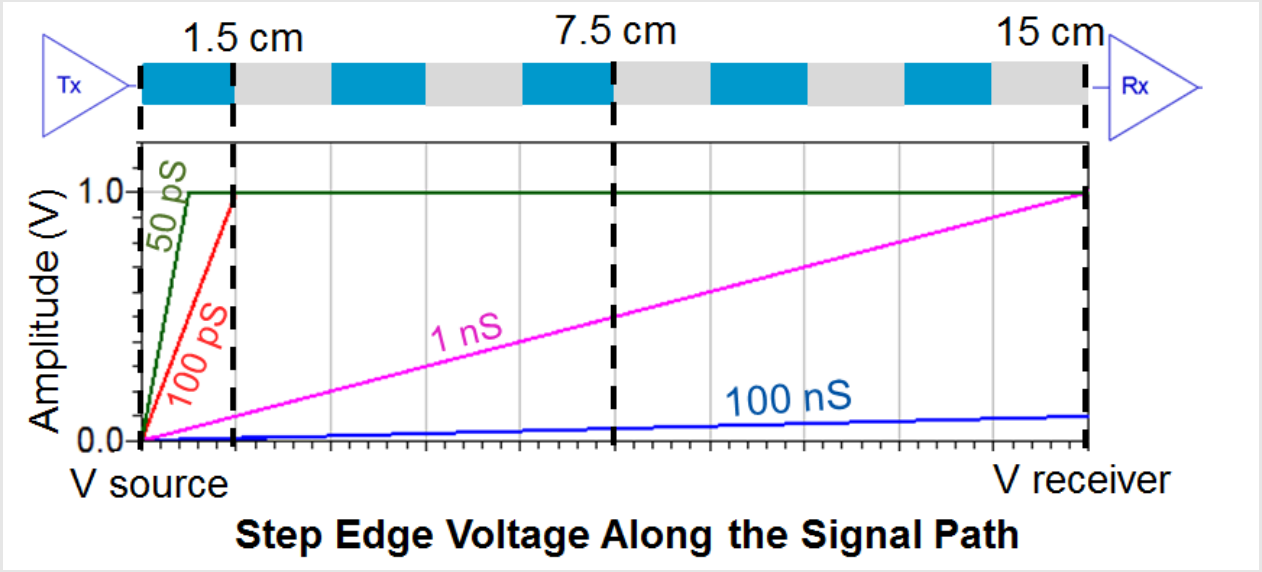
$$Z_0 = \frac{1}{vC_L}$$

$$C = C_L \Delta x \quad , \quad I = \frac{\Delta Q}{\Delta t} \quad , \quad \Delta Q = CV \quad \Delta t = \frac{\Delta x}{v}$$

$$\text{then } I = \frac{C_L \Delta x V}{\frac{\Delta x}{v}} = vC_L V \text{ and } Z = \frac{V}{I} = \frac{1}{vC_L}$$

Time Travel is not Allowed

V≠IR



Transient.avi

The Channel has finite length:

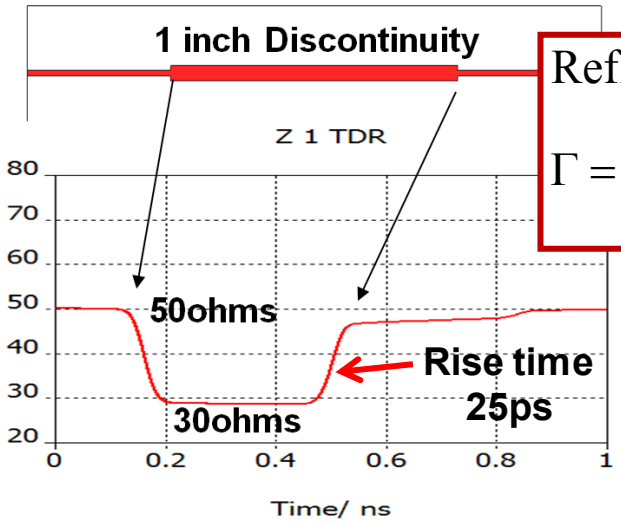
- Speed of Tx : *Signal Rise-time*
- Type of Data : *Data Rate Gb/s*
- Speed of Channel: *Time Delay*

$$\text{Rise Time}_{20-80\%} = \frac{0.22}{Frequency_{3dB}}$$

$$\text{Unit Interval} = \frac{1}{DataRate_{NRZ}}(ps)$$

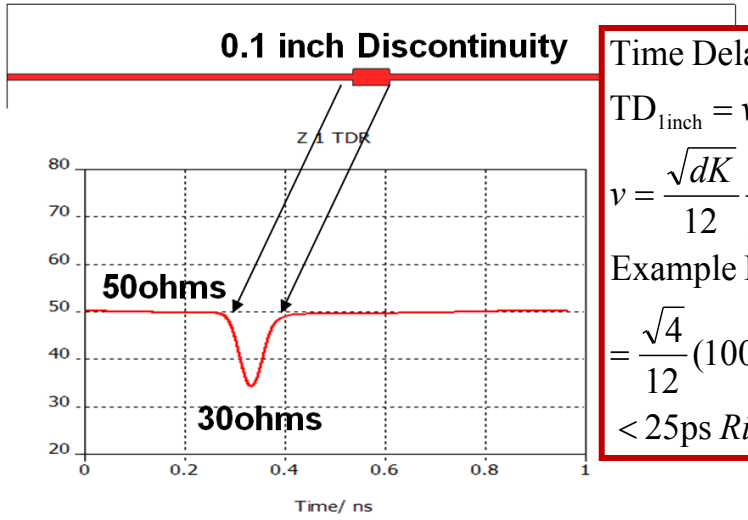
$$velocity = \frac{12}{\sqrt{Dk}}\left(\frac{mils}{ps}\right)$$

Magnitude of the Reflection



Reflection :

$$\Gamma = \frac{Z_{\Delta x} - Z_0}{Z_{\Delta x} + Z_0}$$



Time Delay :

$TD_{1inch} = vL$

$v = \frac{\sqrt{dK}}{12}\frac{ns}{mil}$

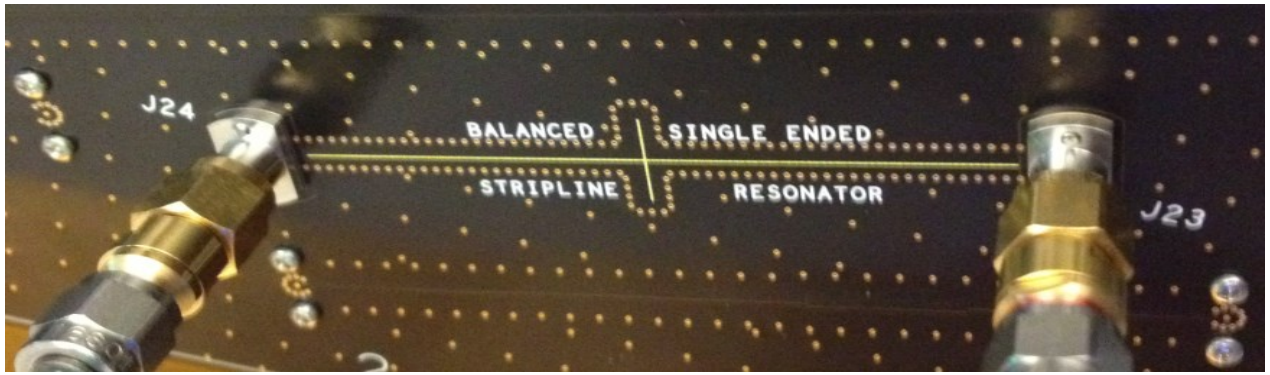
Example FR4 :

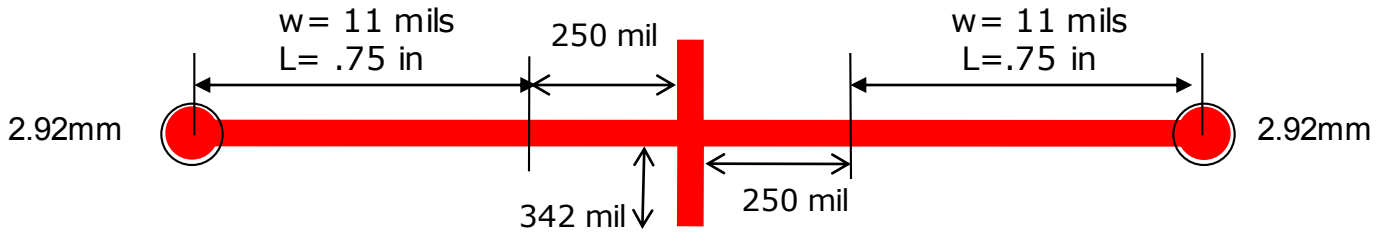
$= \frac{\sqrt{4}}{12}(100) \approx 17\,ps$

< 25ps *Rise time*

Bit Rate	~1/10th Rise Time Feature Size	High Speed Feature Size
1 MBit	3 m (10 ft)	Matched Termination
10 MBit	30 cm (12 in)	T-Line Zo
100 MBit	3 cm (1.2 in)	Connector Zo
1 GBit	3 mm (120 mils)	Passive SMT Zo
5 GBit	0.6 mm (24 mils)	Via Zo
10 GBit	0.3 mm (12 mils)	Die, Package, PCB Co-sim
40 GBit	0.075 mm (6 mils)	Machining Tolerances

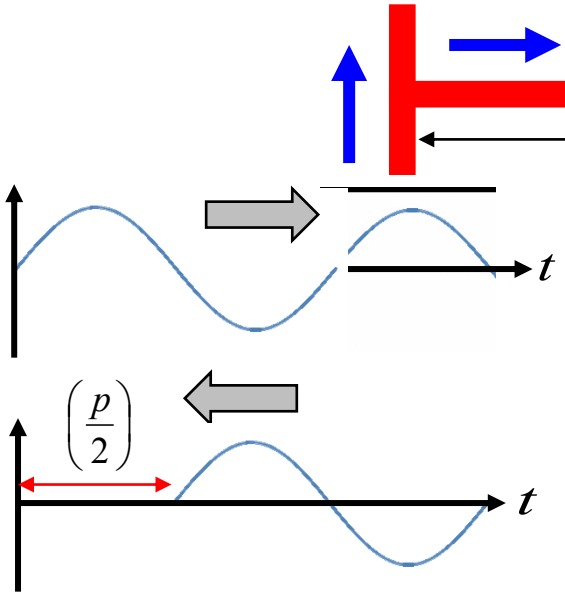
Reflections from a Stub Resonator





Stub Resonator (L=λ/4)

L= ¼ of the wavelength or electrical length *p*/4



OPEN

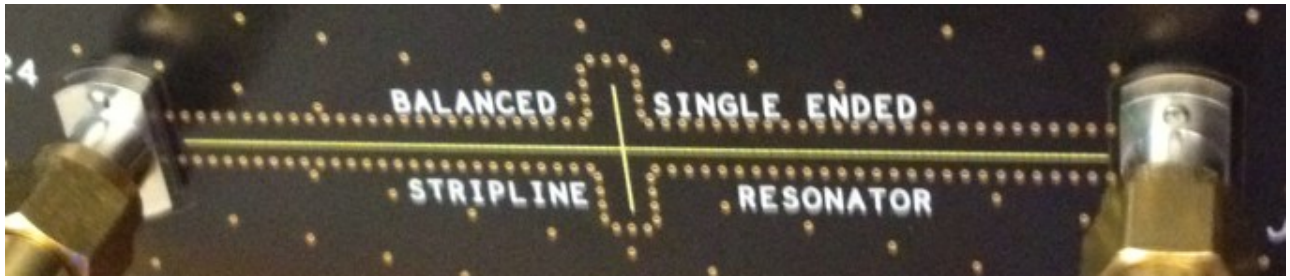
$$\Gamma = 1$$

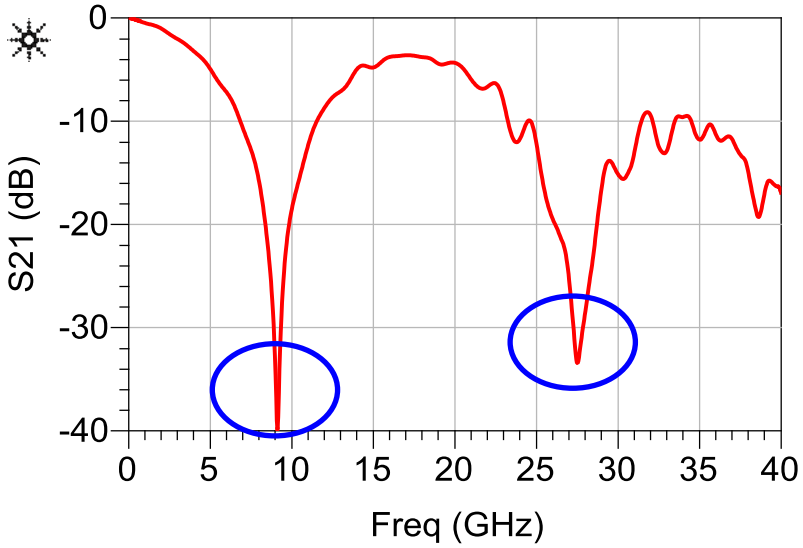
p= time to travel 1 wavelength

$$\text{Given: } p = \frac{\lambda_g}{v_p}$$

Destructive Interference

Parallel Stub Resonator (L=λ/4)



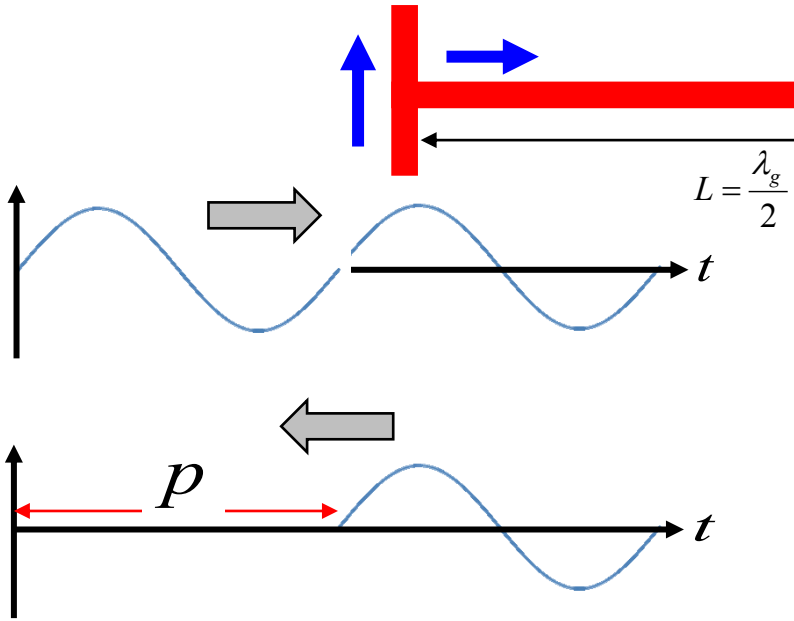


Quarter-wavelength stub (L=λ/4)

1. Destructive interference
2. Virtual short
3. Cancellation of waves
4. Minimum transmission (S21)

Stub Resonator (L=λ/2)

L= ½ of the wavelength or electrical length *p*/2



OPEN

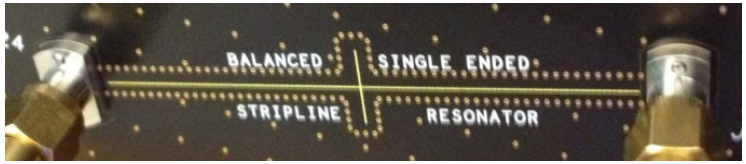
$$\Gamma = 1$$

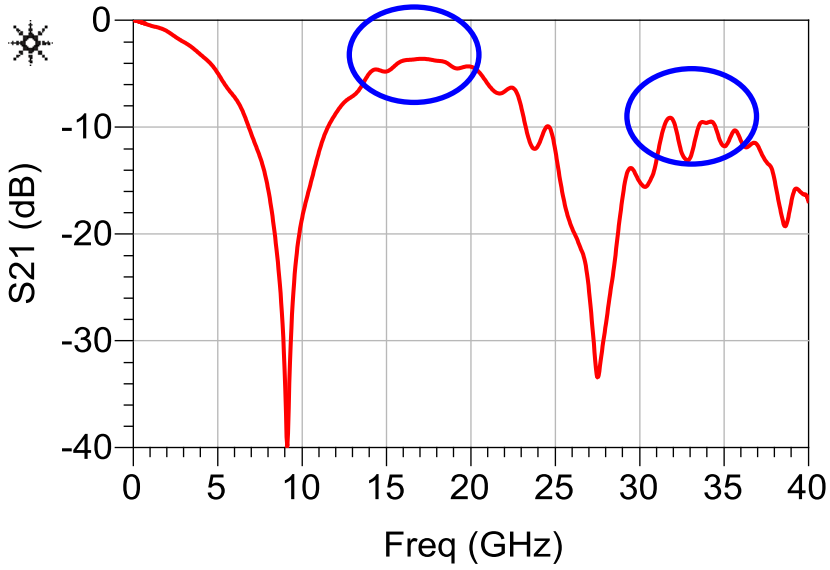
p= time to travel 1 wavelength

$$\text{Given: } p = \frac{\lambda_g}{v_p}$$

Constructive Interference

Parallel Stub Resonator (L=λ/2)



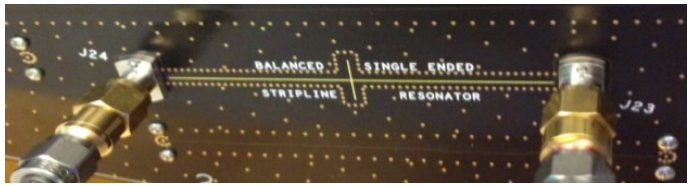


Half-wavelength stub (L=λ/2)

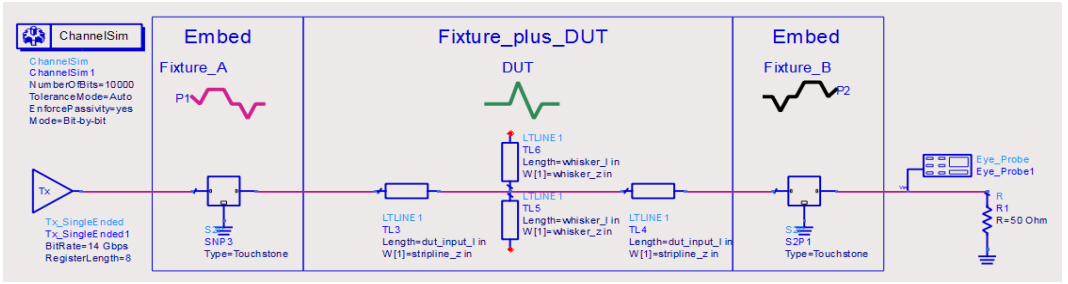
1. Constructive interference
2. Virtual open
3. Addition of waves
4. Maximum transmission (S21)

Full-Path Simulation to Measurement Correlation

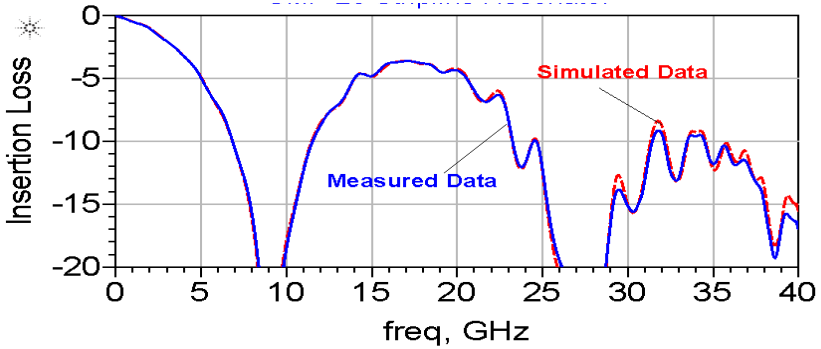
Parallel Stub Resonator Test Structure



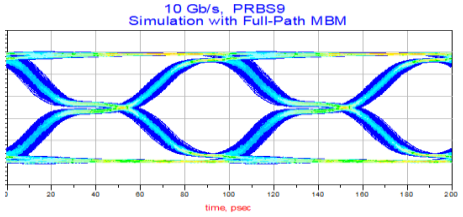
ADS Line-Type Model with Embedded Fixture



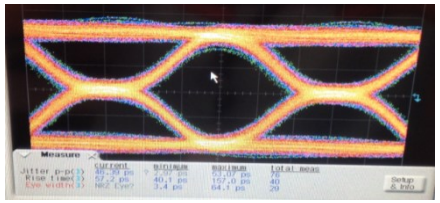
Measurement vs. Simulation in ADS CMP-28 Stripline Resonator



10 Gb/s , PRBS 9



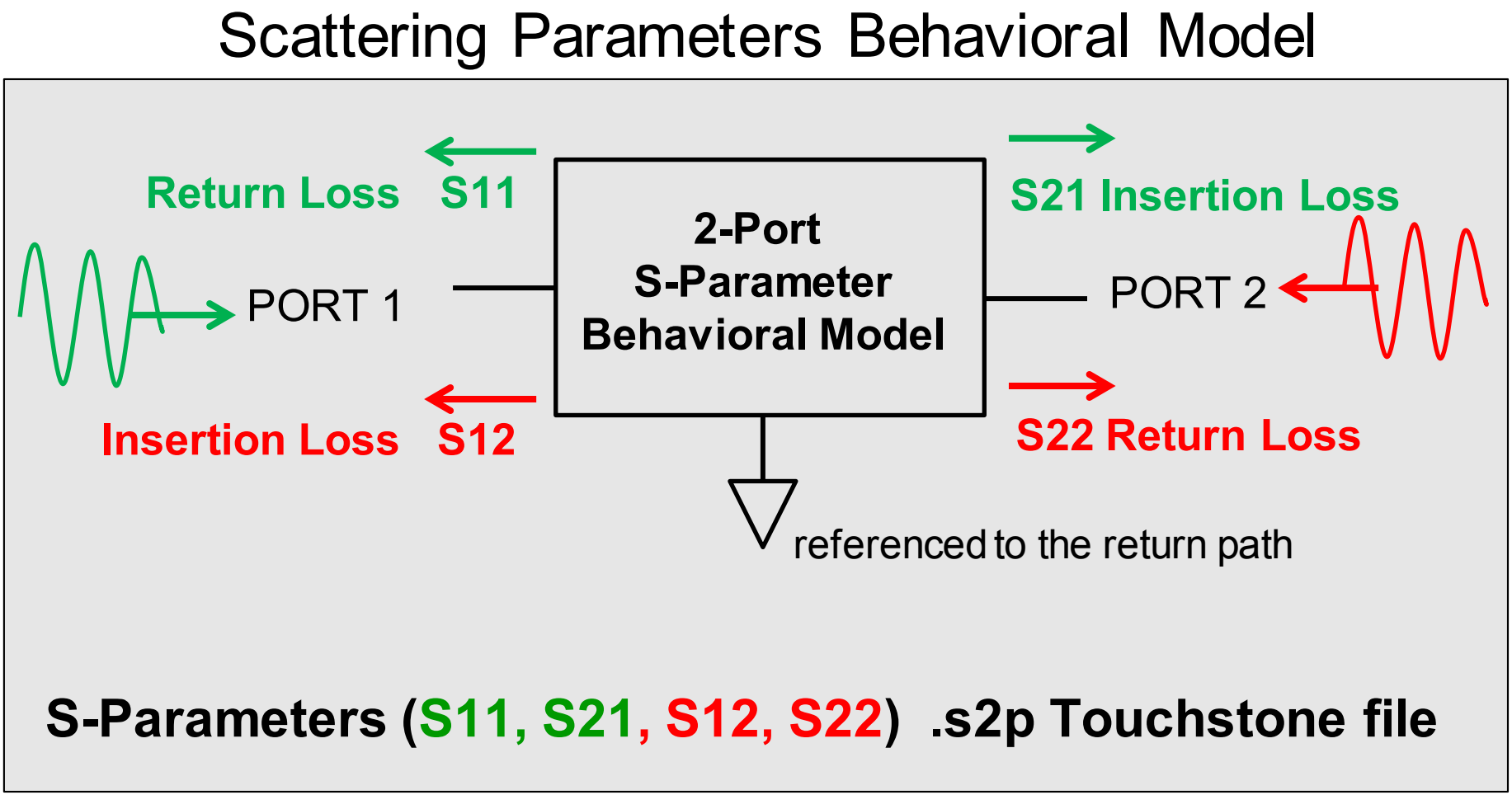
SIMULATED



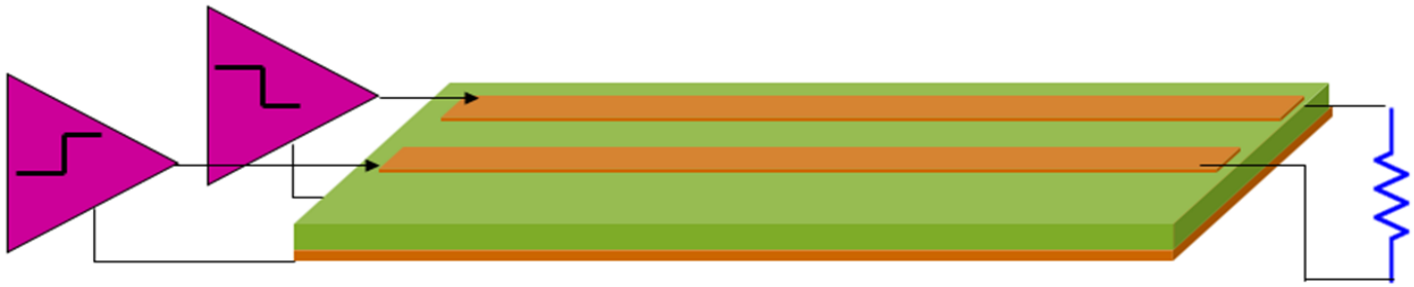
MEASURED

N4951A Pattern Generator

Circuit Model with Reflections



Transmission Lines are Differential



Two traces carrying complementary data, commonly used for high data rates

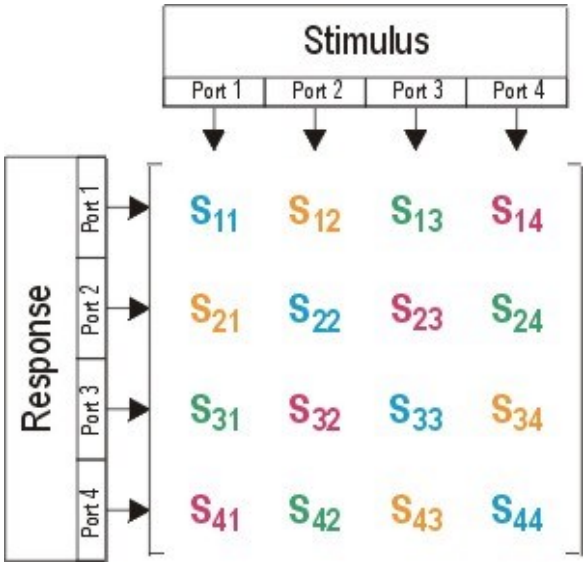
Why?

- Receiver can reject any signal that is common to both lines
- Radiation reduced (cancellation of fields)

Impedance measurements have slightly different meaning compared to single-ended measurements

Single Ended Parameters

Four-port single-ended device

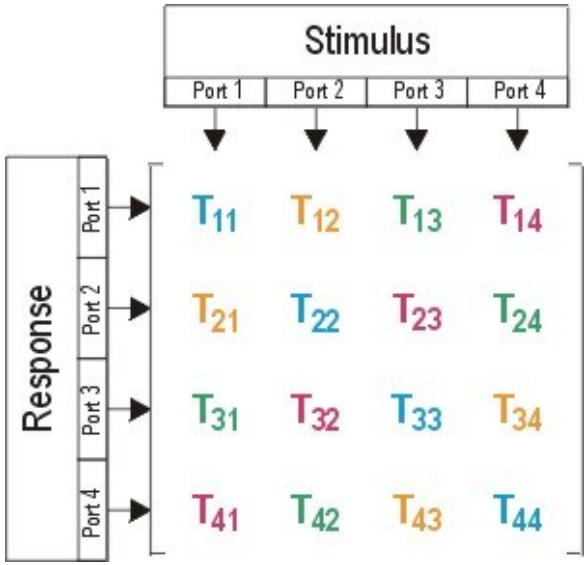


Return Loss or TDR

Insertion Loss or TDT

Near End Crosstalk (NEXT)

Far End Crosstalk (FEXT)

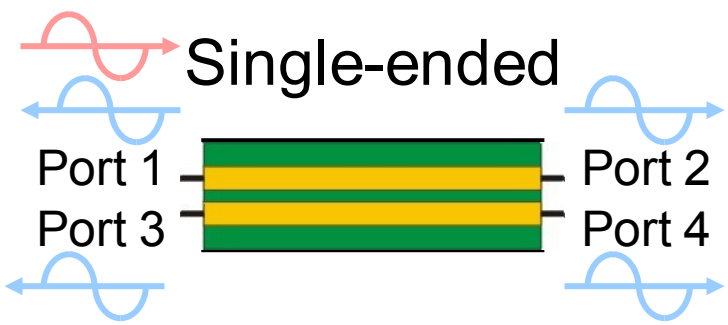


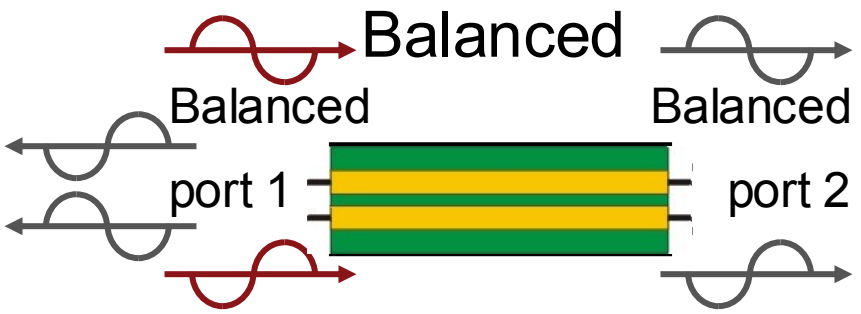
Frequency Domain Parameters

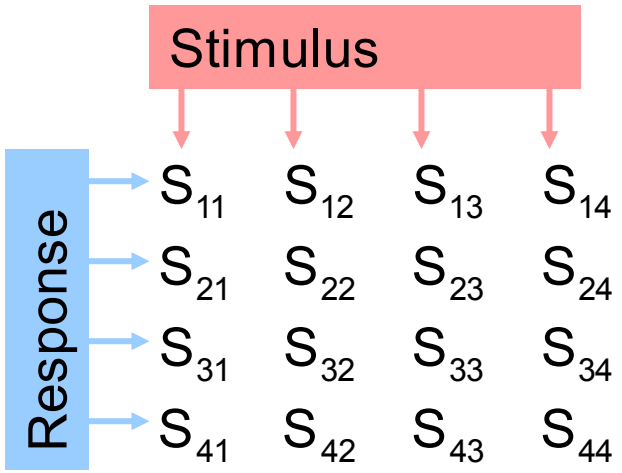
Time Domain Parameters

FFT or IFFT

Single-ended to Differential S-Parameters







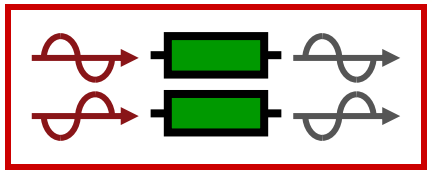
		Differential-Mode Stimulus		Common-Mode Stimulus	
		Port 1	Port 2	Port 1	Port 2
Differential-Mode Response	Port 1	S_{DD11}	S_{DD12}	S_{DC11}	S_{DC12}
	Port 2	S_{DD21}	S_{DD22}	S_{DC21}	S_{DC22}
Common-Mode Response	Port 1	S_{CD11}	S_{CD12}	S_{CC11}	S_{CC12}
	Port 2	S_{CD21}	S_{CD22}	S_{CC21}	S_{CC22}

Naming Convention:

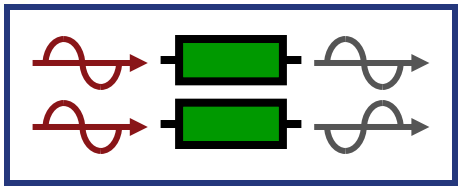
$S_{\text{mode res., mode stim., port res., port stim.}}$

Differential S-parameters

Differential in, differential out:
Behavior of differential signals



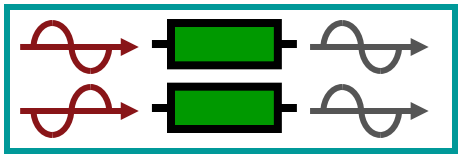
Common in, differential out:
Behavior of mode conversion
(EMI Susceptibility)



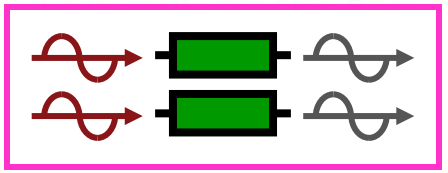
Stimulus

Response		Differential Signal		Common Signal	
		Port 1	Port 2	Port 1	Port 2
Differential Signal	Port 1	S_{DD11}	S_{DD12}	S_{DC11}	S_{DC12}
	Port 2	S_{DD21}	S_{DD22}	S_{DC21}	S_{DC22}
Common Signal	Port 1	S_{CD11}	S_{CD12}	S_{CC11}	S_{CC12}
	Port 2	S_{CD21}	S_{CD22}	S_{CC21}	S_{CC22}

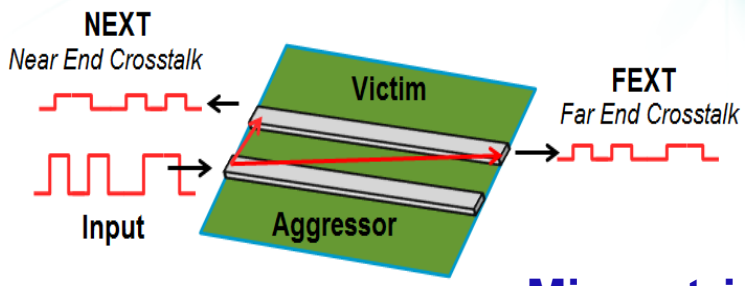
Differential in, common out:
Behavior of mode conversion
(EMI Emissions)



Common in, common out:
Behavior of common signals

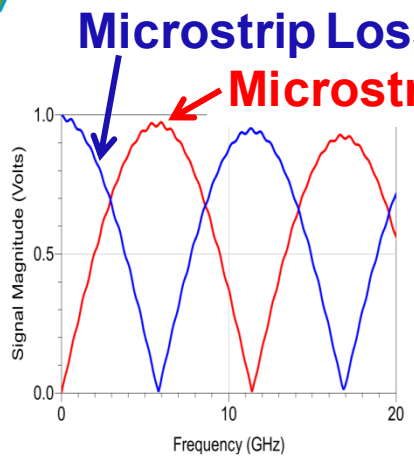


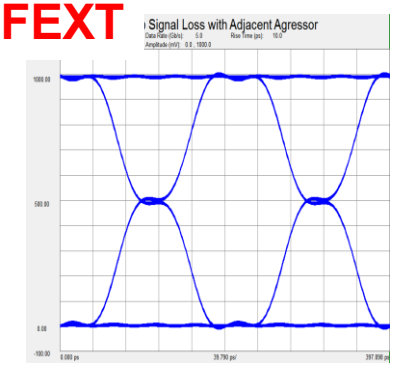
Crosstalk for Microstrip vs Stripline Analysis



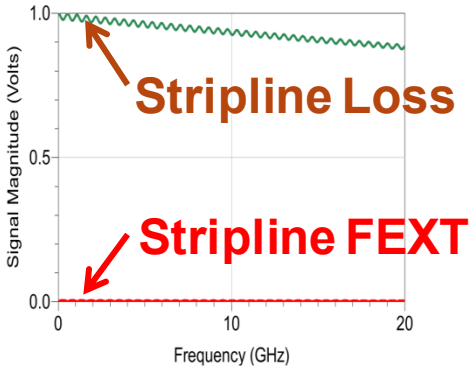
EM simulation for complex radiation and crosstalk.

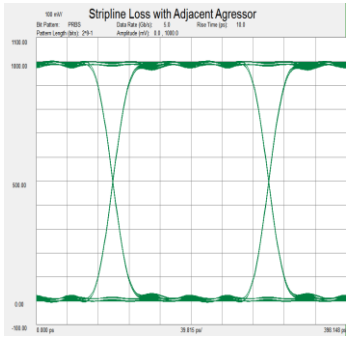
Identical 12mil Traces, 5mil Gap





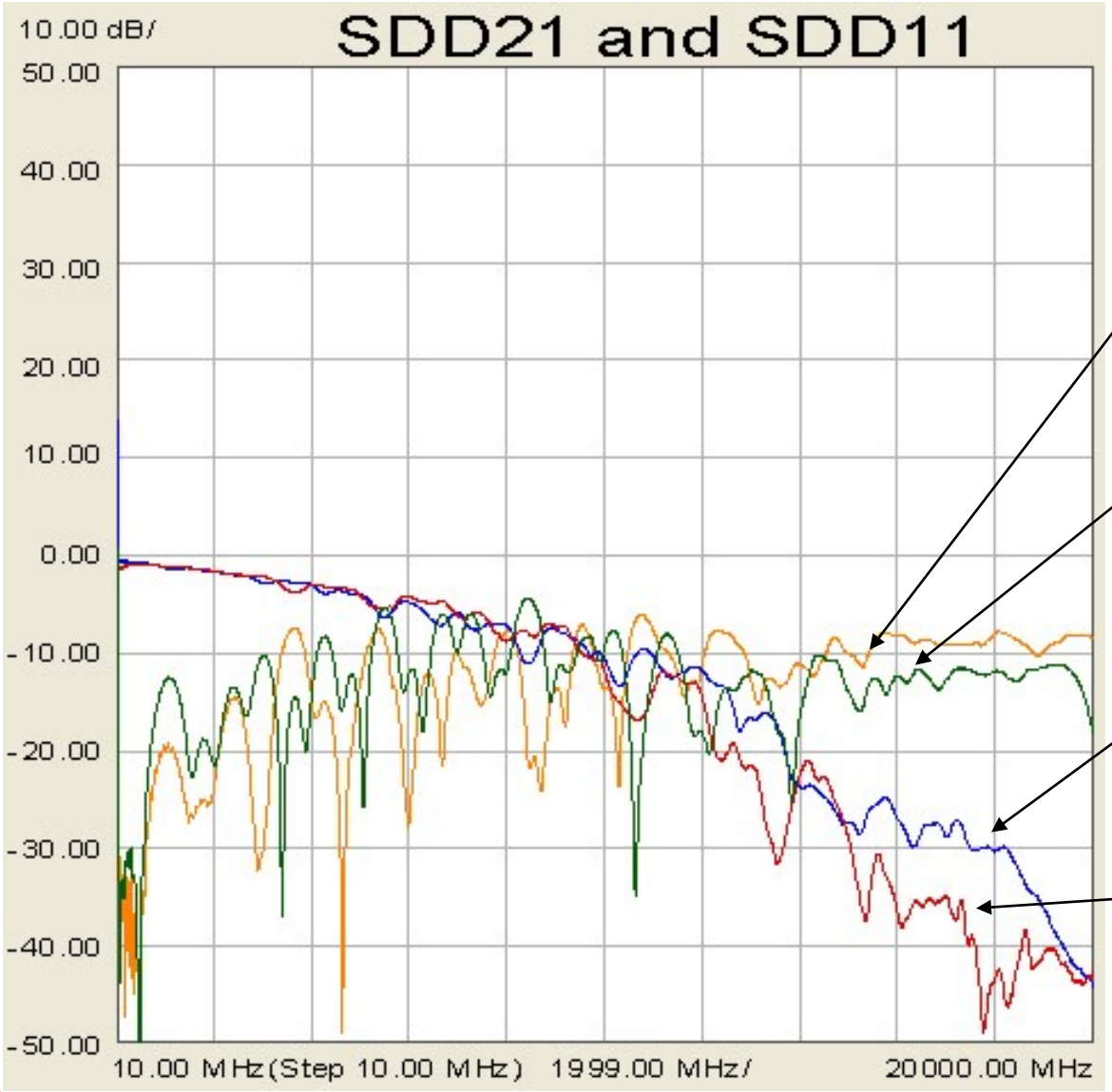
Microstrip 5Gbps Eye





Stripline 5Gbps Eye

Differential Standard Through Vias vs. Short Microvias



S-Parameters

Differential Return Loss of standard via

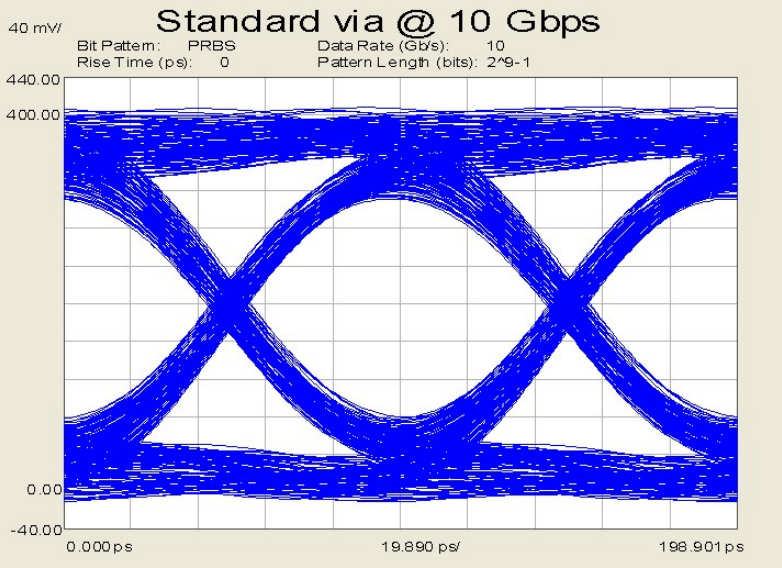
Differential Return Loss of microvia

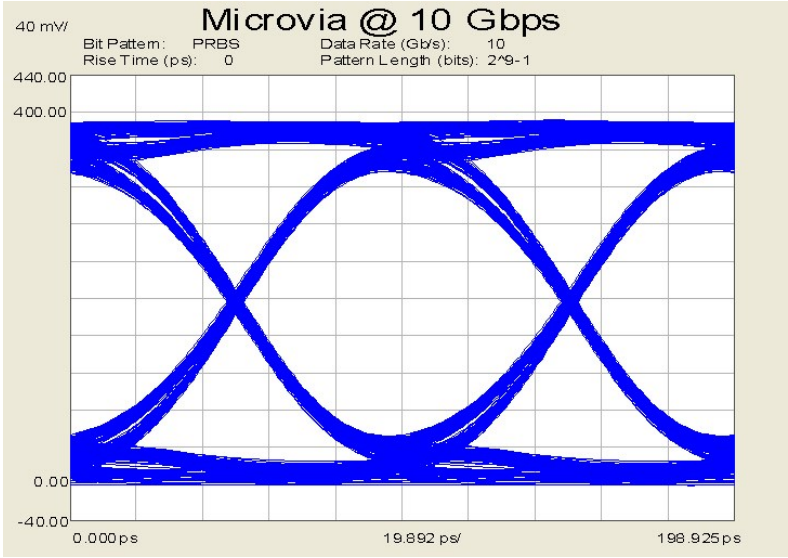
Differential Insertion Loss of microvia

Differential Insertion Loss of standard via

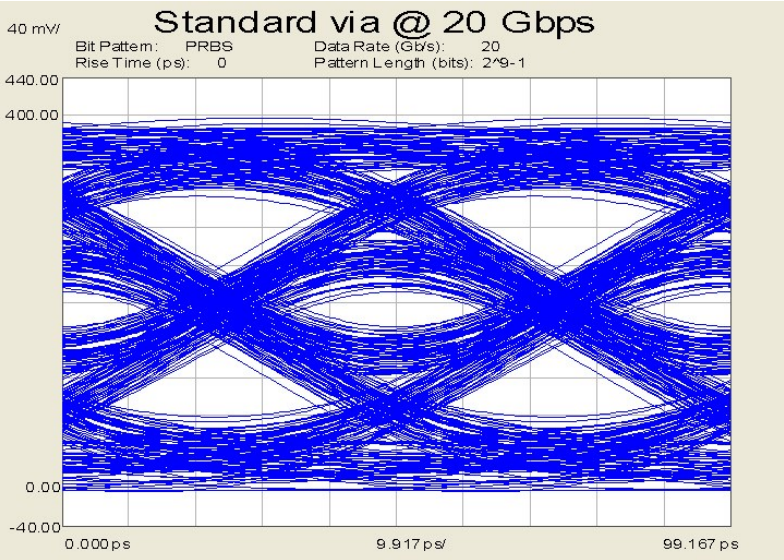
Differential Standard Through Vias vs. Short Microvias

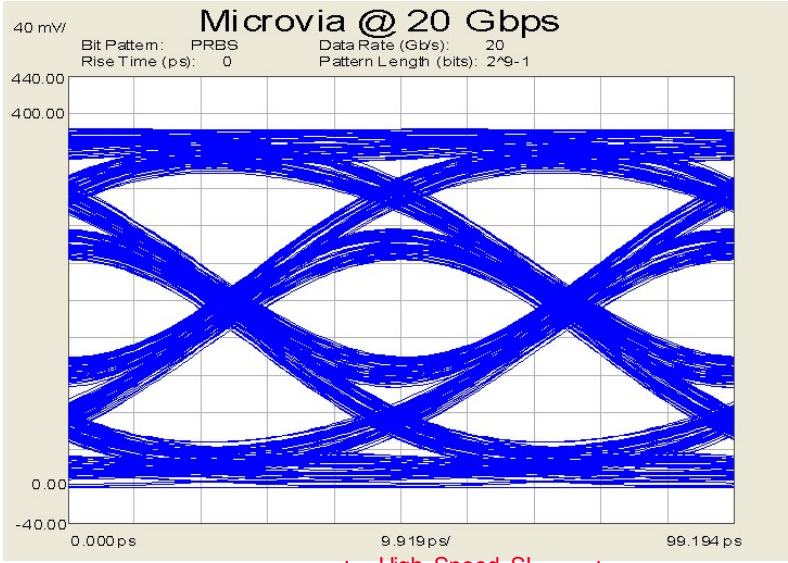
PRBS9
10 Gbps





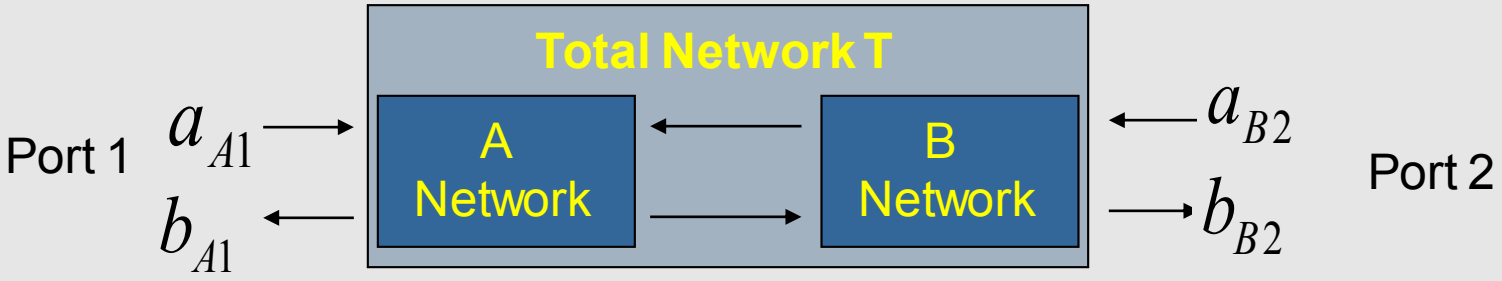
PRBS9
20 Gbps





Cascading S-Parameters

Cascading Two 2-Port Networks



Multiplying S-Parameter Matrices Doesn't Work

$$S_T \neq S_A S_B$$

Convert to Normalized Incident and Reflected Wave T-Matrix

$$T_T = T_A T_B$$

From S to T

$$T_{11} = \frac{-\det(S)}{S_{21}} \qquad T_{21} = \frac{-S_{22}}{S_{21}}$$

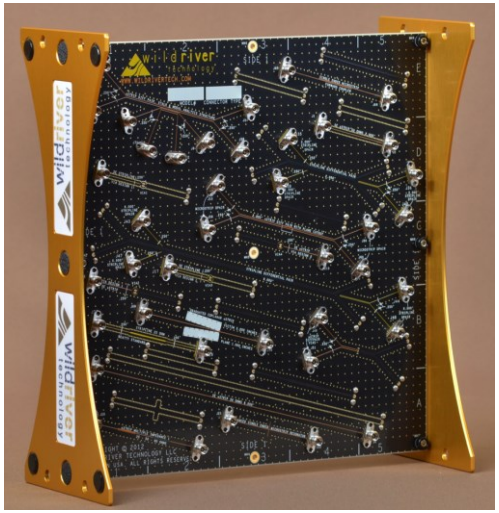
$$T_{12} = \frac{S_{11}}{S_{21}} \qquad T_{22} = \frac{1}{S_{21}}$$

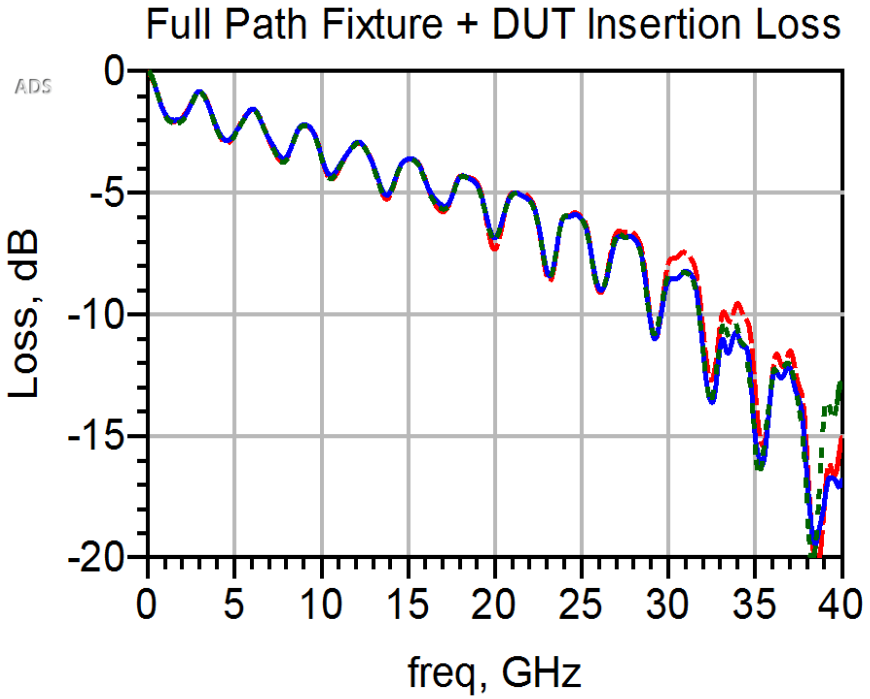
From T to S

$$S_{11} = \frac{T_{12}}{T_{22}} \qquad S_{21} = \frac{1}{T_{22}}$$

$$S_{12} = \frac{\det(T)}{T_{22}} \qquad S_{22} = \frac{-T_{21}}{T_{22}}$$

Simulation to Measurement Correlation
"Down to the last ripple"





Model with AFR Fixture

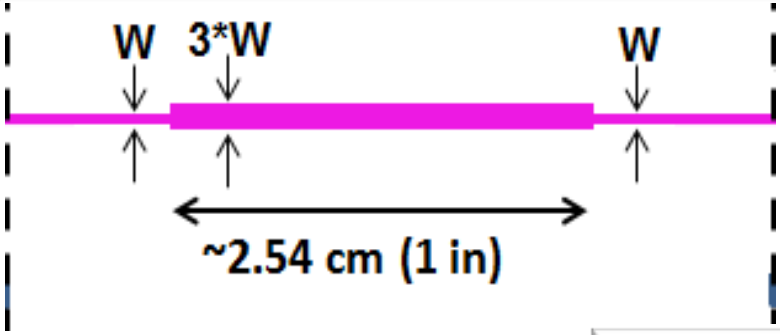
Model with MBM Fixture

Measured Fixture + DUT SOLT Cal

Do I trust the Simulation or the Measurement?

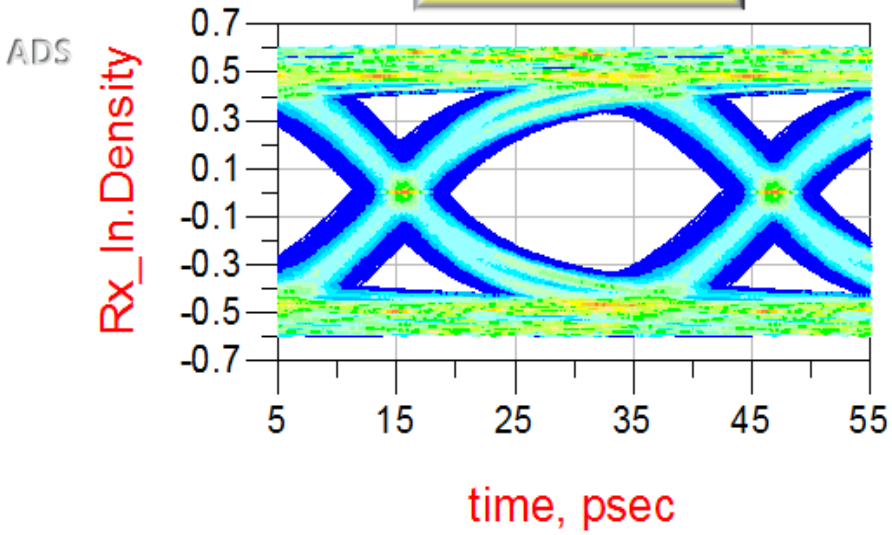
Which one is correct?

SIMPLE CHANGE IN PCB TRACE WIDTH

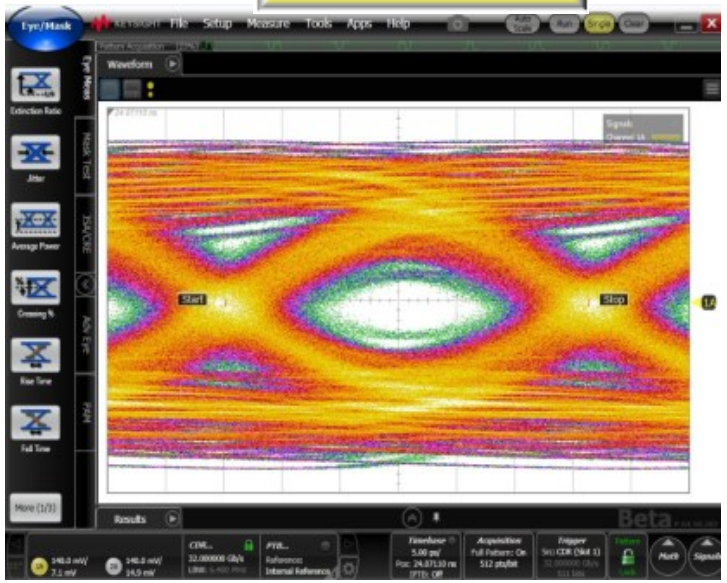


PCB Stripline

SIMULATED



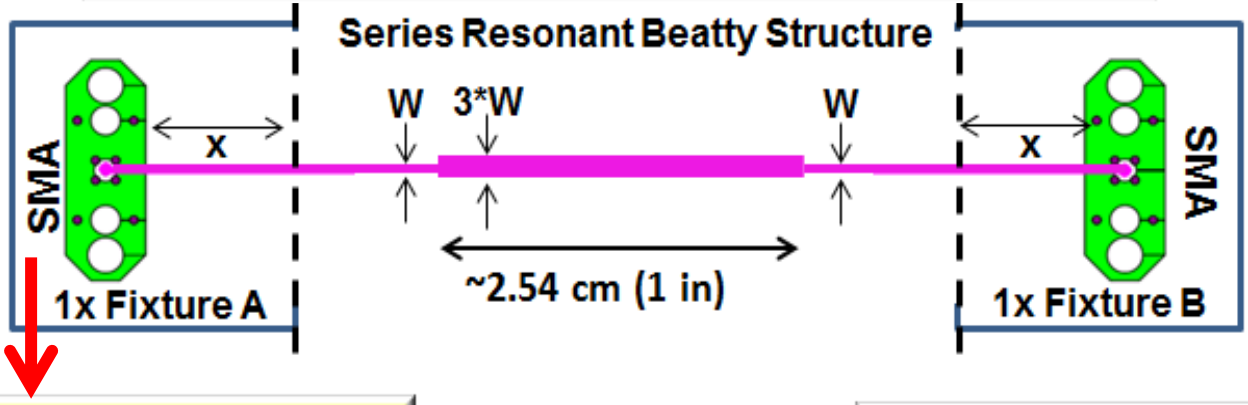
MEASURED



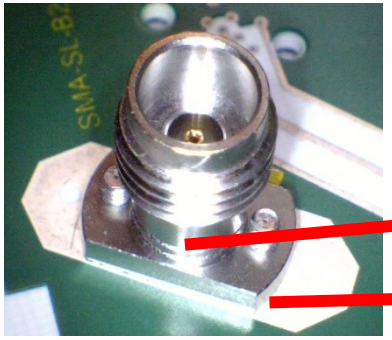
Measurement “Fixtures”

Standard coaxial SOLT Calibrations only calibrate to the end of the coaxial cable!

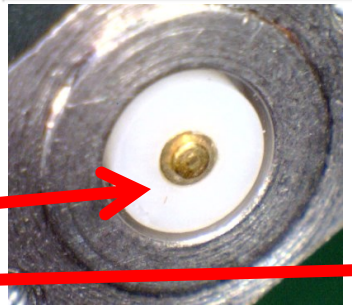
A “PCB Fixture” transitions from the coax connector to the planar PCB transmission line.



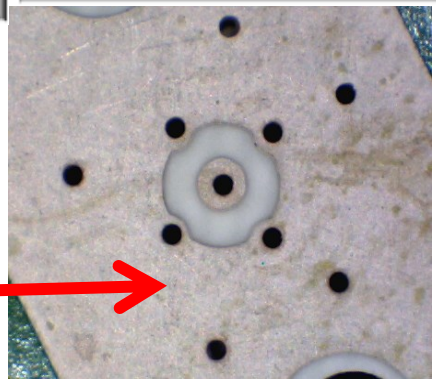
Coaxial Connector



Coaxial Interface



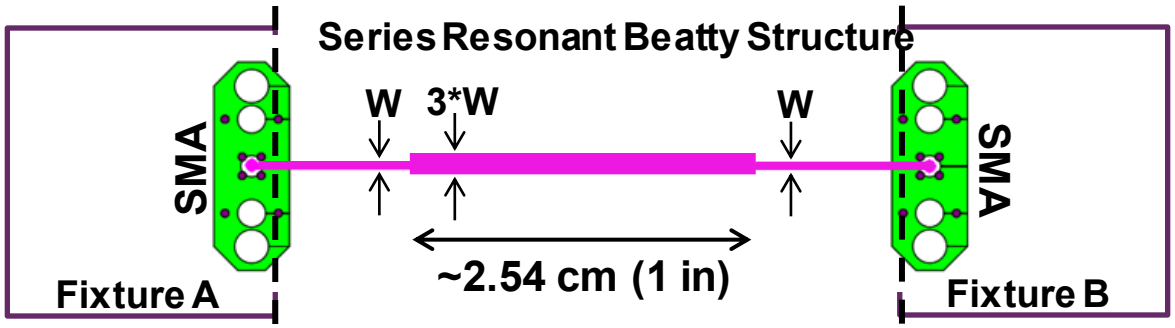
Planar PCB Footprint



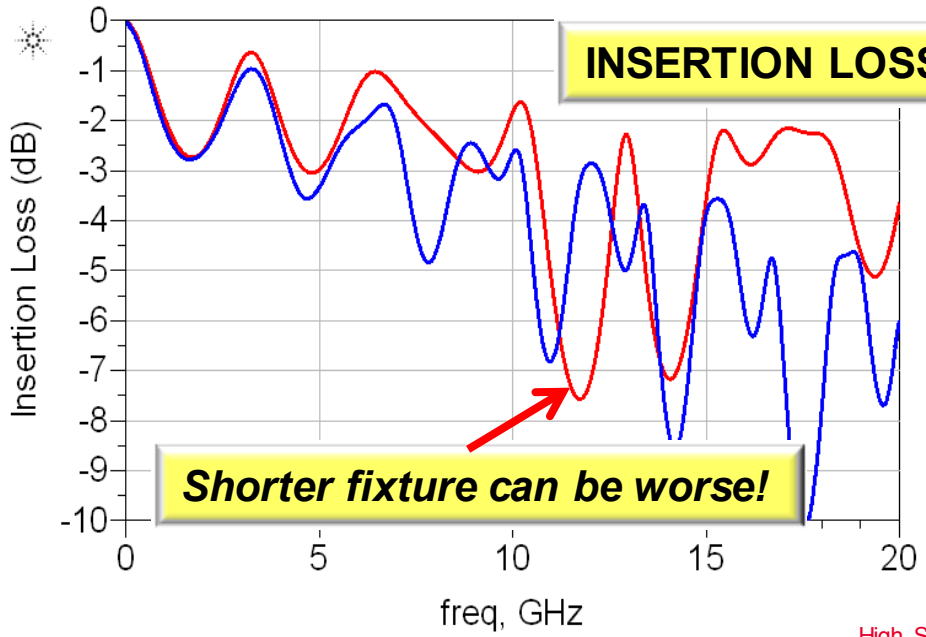
Short Length Fixture

Can I ignore the fixture losses if I shorten the length?

It depends….



A short path does not eliminate impedance reflections from the connector to PCB transition

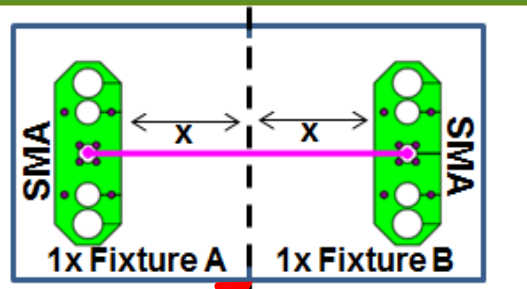


Short 20mil

Long 700mil

What is the “Reference Plane”

SYMMETRICAL 2x FIXTURE THROUGH PATH



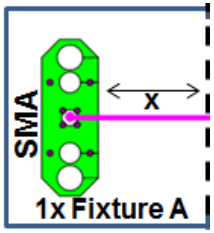
Reference Plane

Step 1

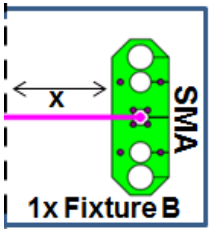
Splitting of the S-Parameters

Agilent PLTS AFR Algorithm

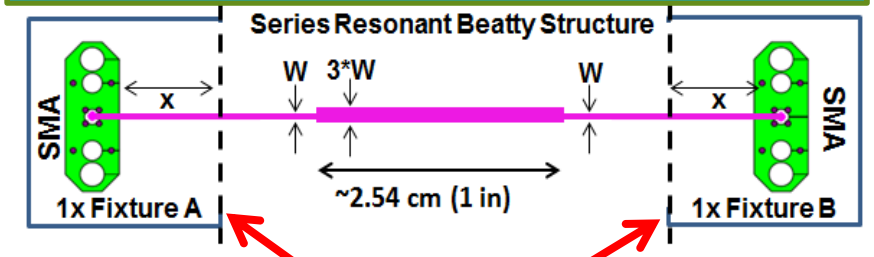
FIXTURE A S-PARAMETERS



FIXTURE B S-PARAMETERS



FIXTURE + Resonant Beatty Structure



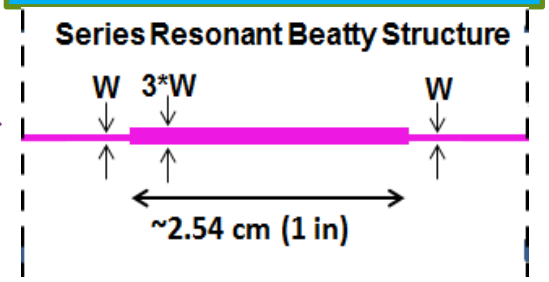
Reference Plane

Step 2

FIXTURE DE-EMBED

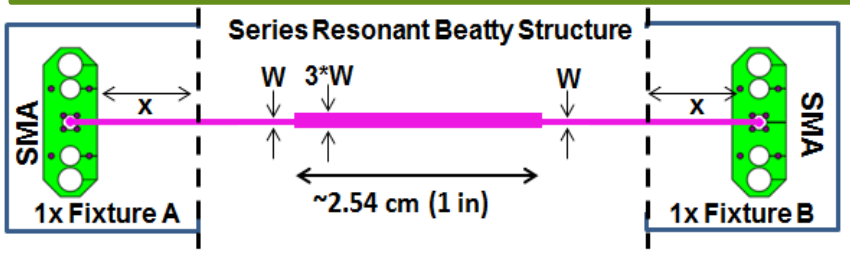
T-Matrix

T-Line Change in Z Fabrication Properties



Fixture Removal Benefits

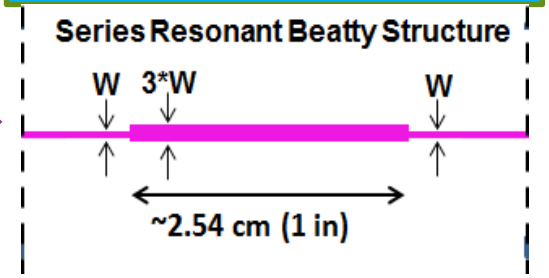
FIXTURE + Resonant Beatty Structure



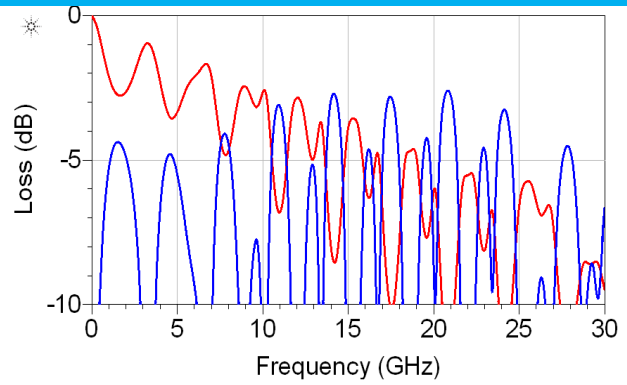
FIXTURE DE-EMBED

T-Matrix

T-Line Change in Z Fabrication Properties



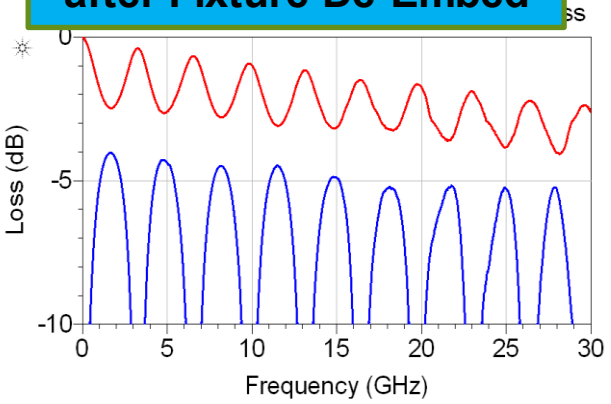
S-Parameters before Fixture De-Embed



FIXTURE DE-EMBED

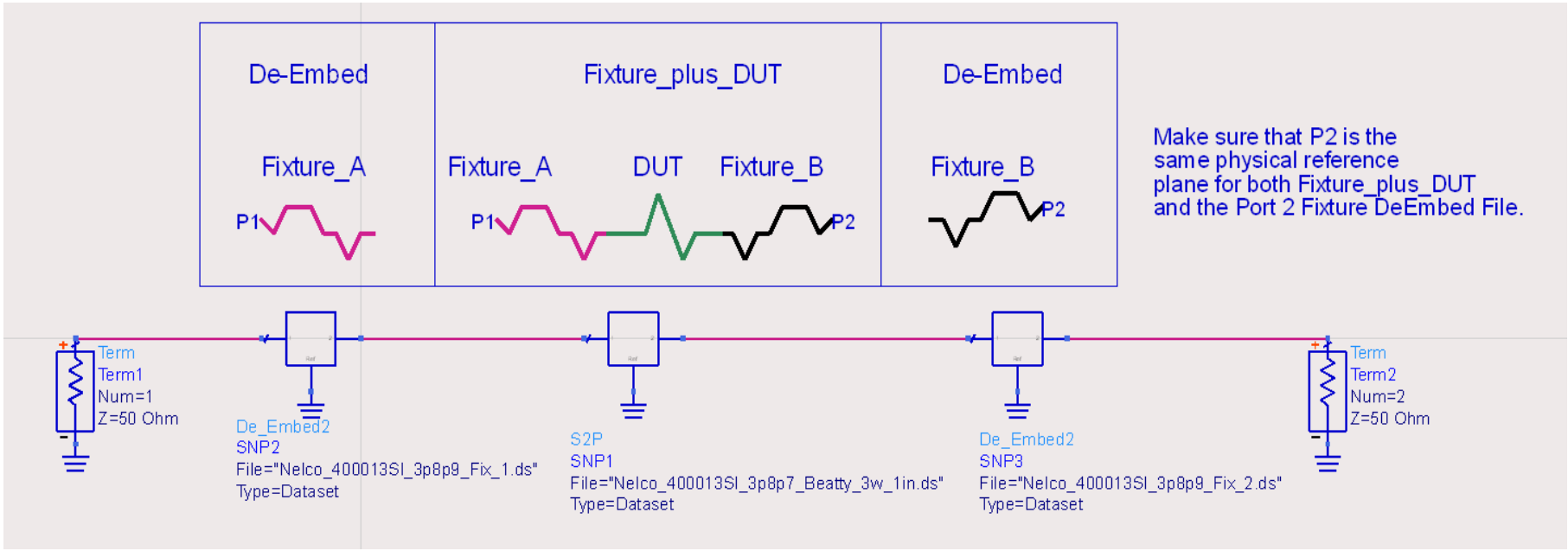
T-Matrix

Measured S-Parameters after Fixture De-Embed



Fixture De-Embedding with S-Parameters

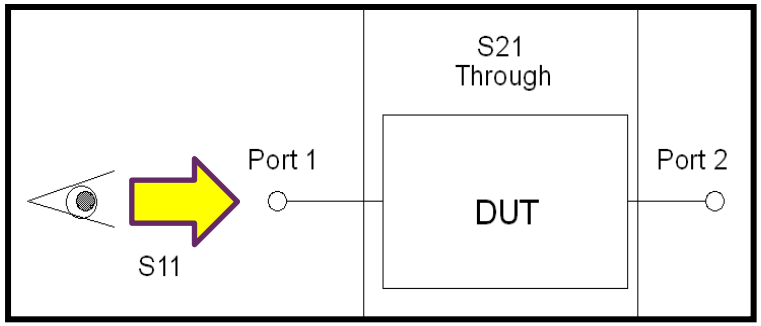
De-Embed Simulation using S-Parameters



Output De-Embedded DUT S_Parameters

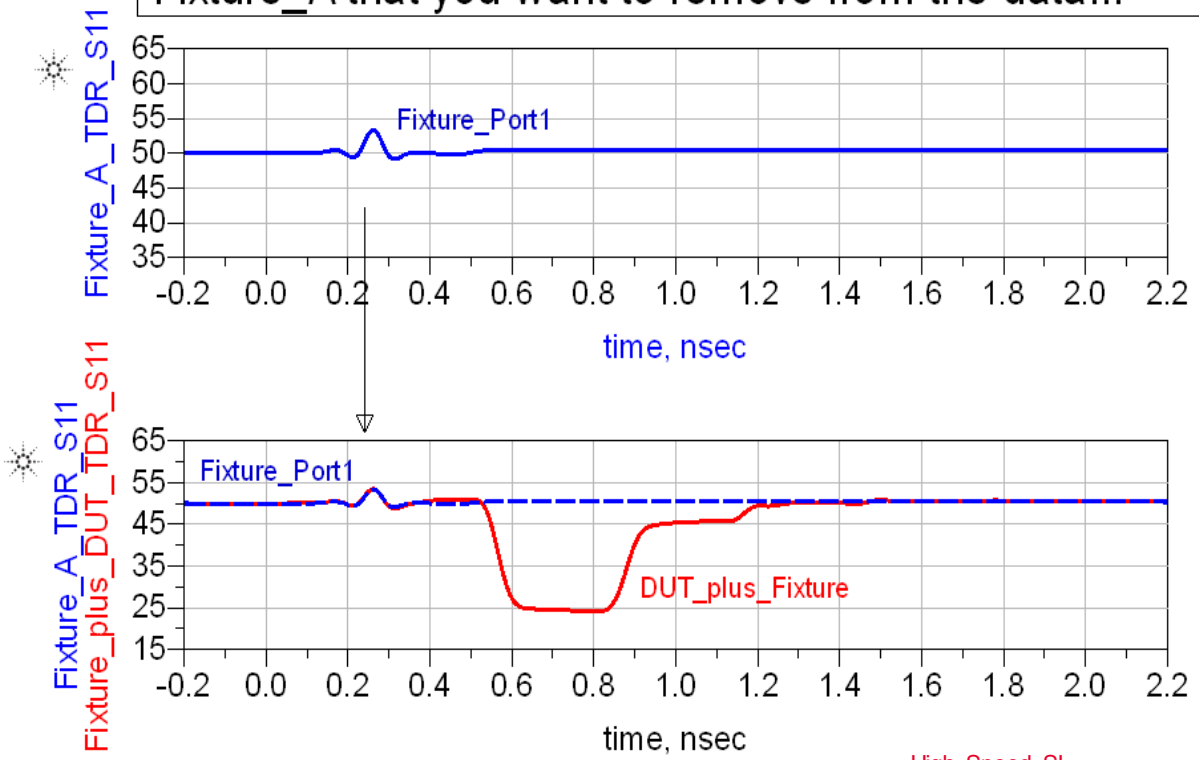
Using TDR to Verify Fixture Port 1

Time Domain Verifies Fixture Data Matches with the DUT Fixture



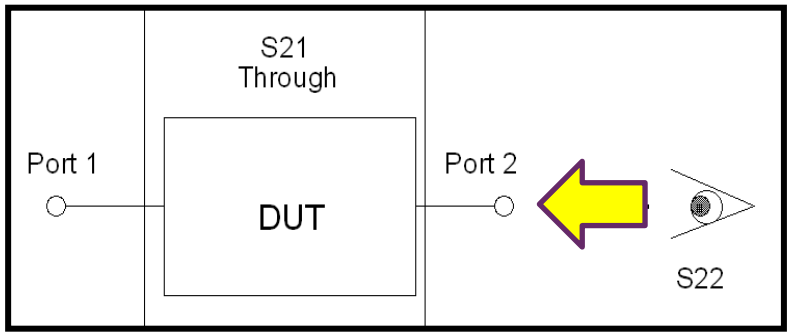
Fixture_A that you want to remove from the data...

TDR from S11



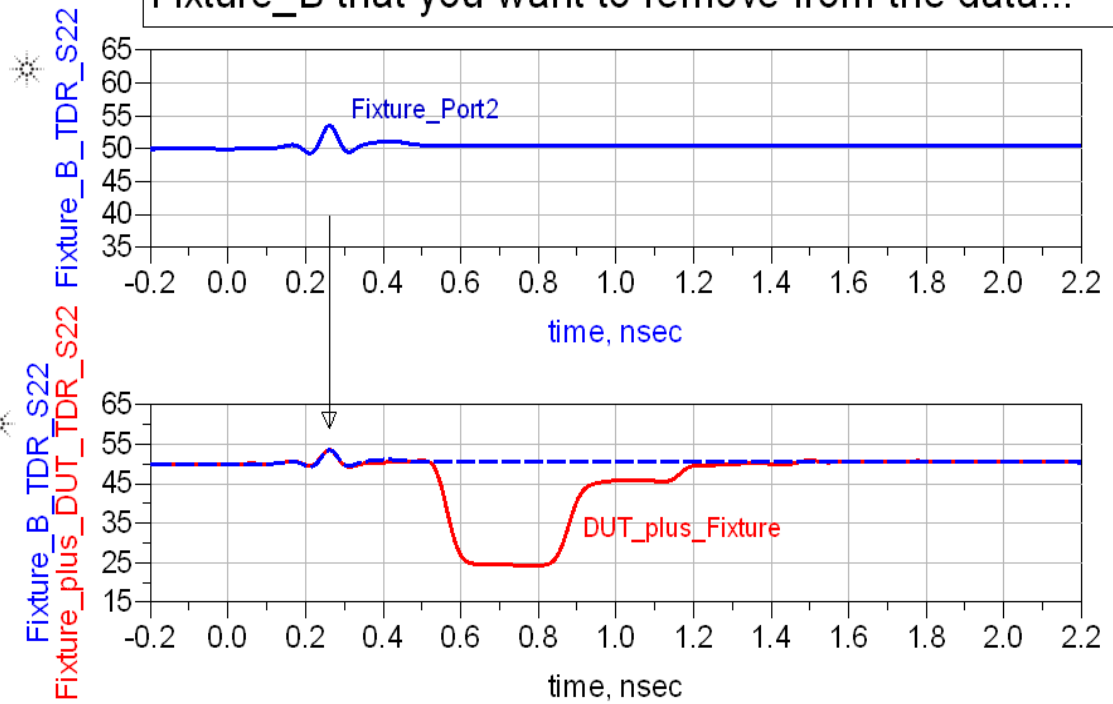
Using TDR to Verify Fixture Port 2

Time Domain Verifies Fixture Data Matches with the DUT Fixture



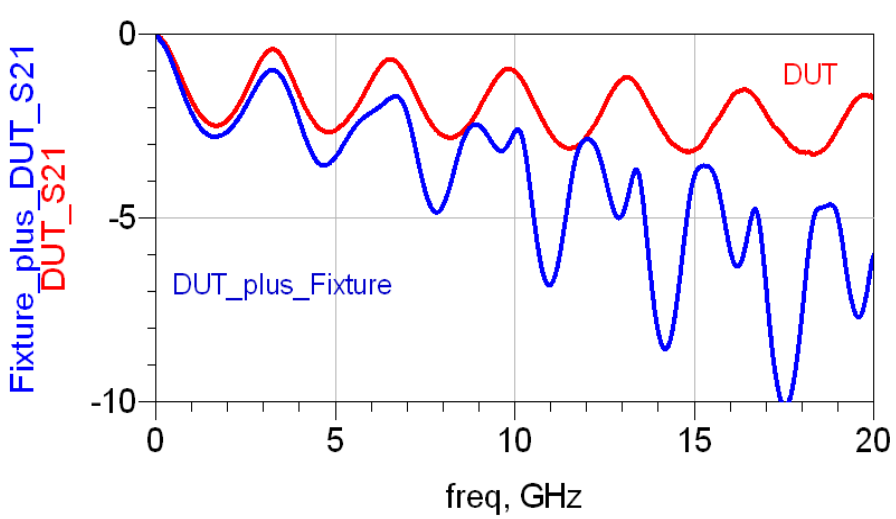
TDR from S22

Fixture_B that you want to remove from the data...

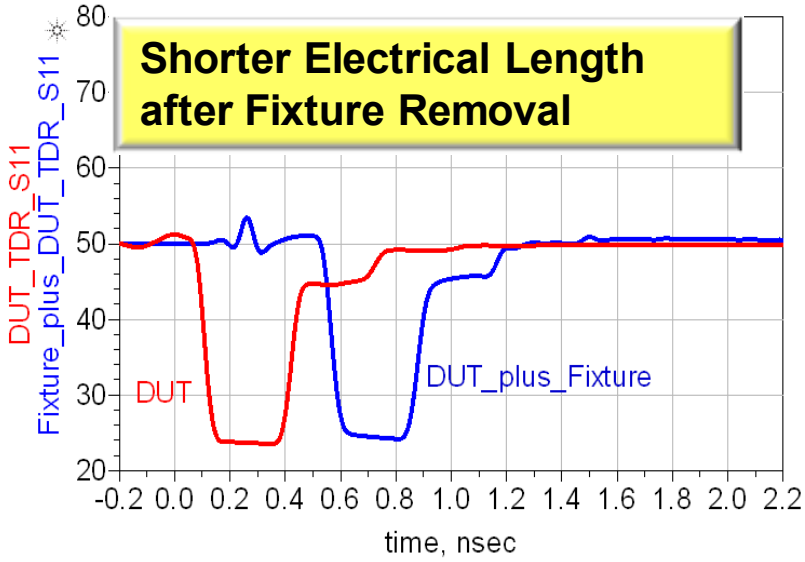


Before and After Fixture Removal

Frequency Domain



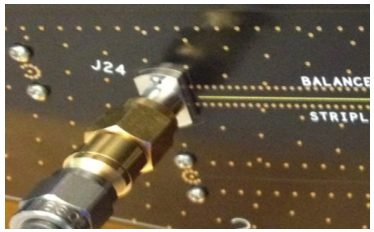
Time Domain

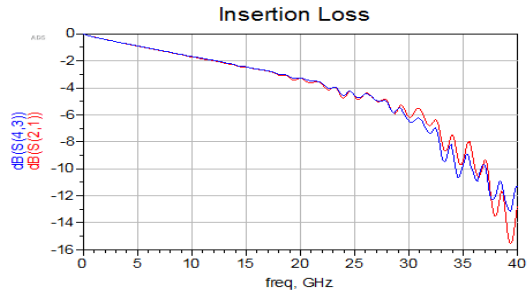


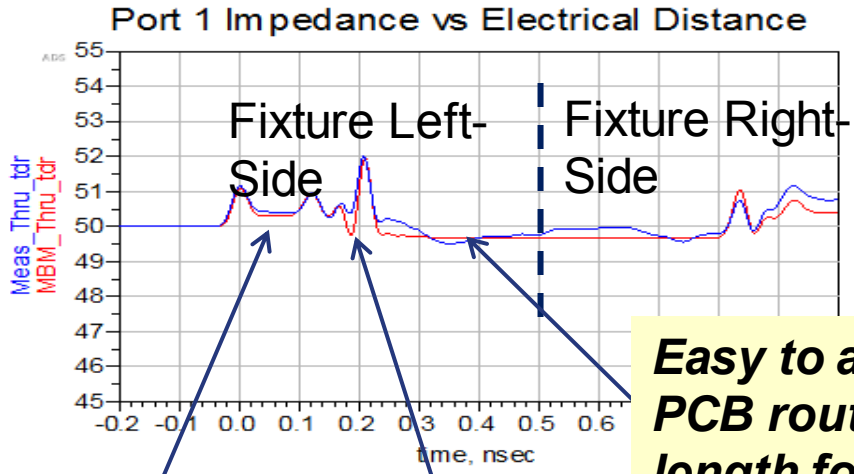
DUT with Fixture Removed in RED
DUT with Fixture in Blue

Fixture Measurement-Based-Model (MBM)

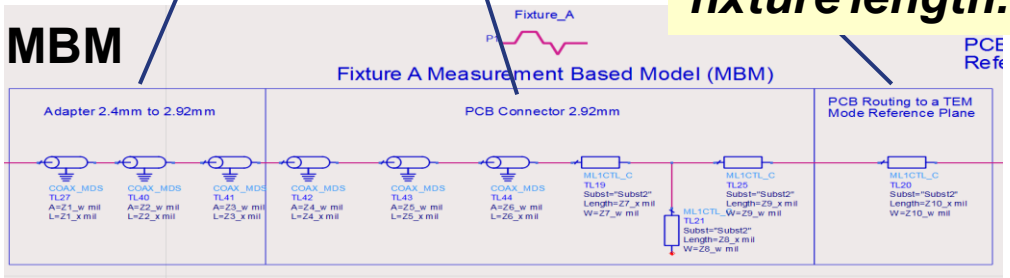
"Model matches in the frequency and time domains"



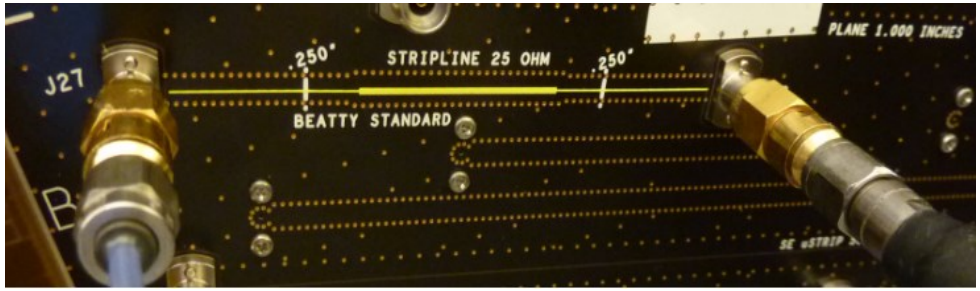


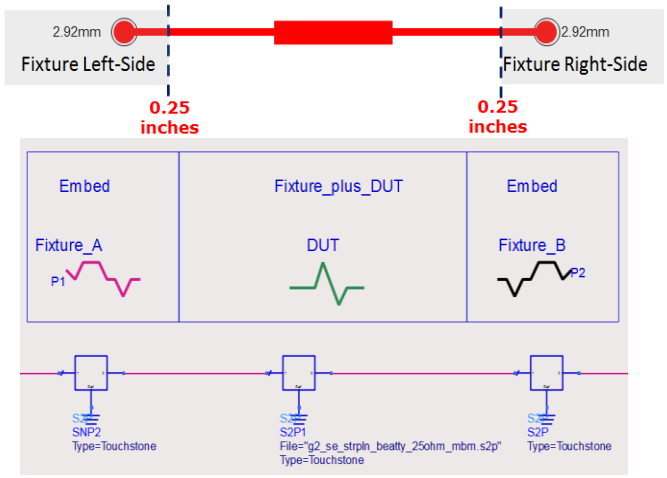


Easy to adjust PCB routing length for flexible fixture length.

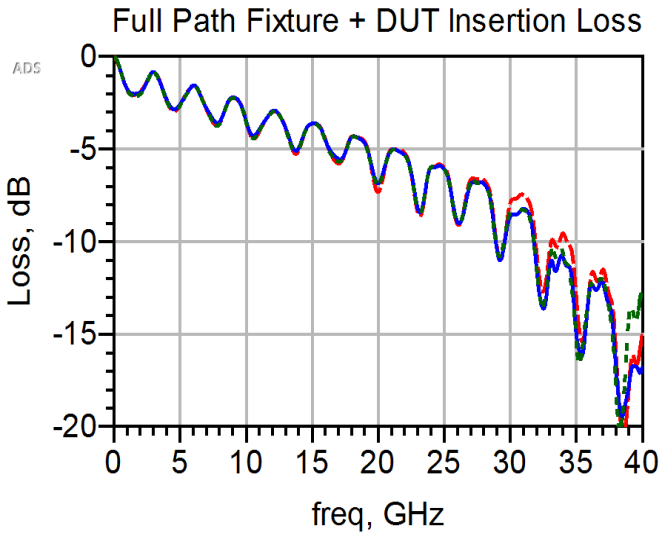


Full Path **Embedded** Fixture + DUT Simulation





Fixture S-Parameter from AFR and from deconstructed MBM



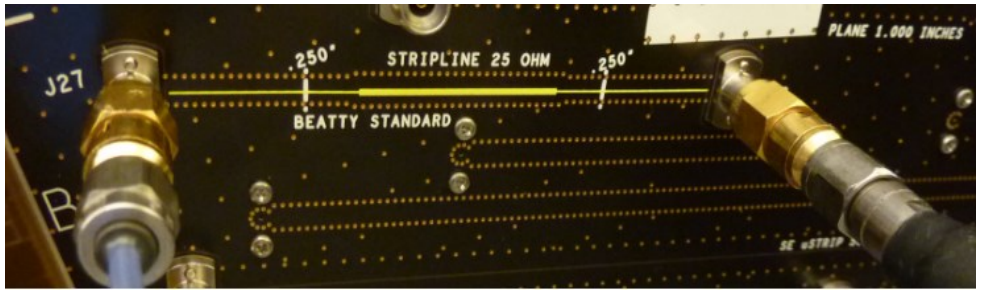
Measured Fixture + DUT

Model with MBM Fixture

Model with AFR Fixture

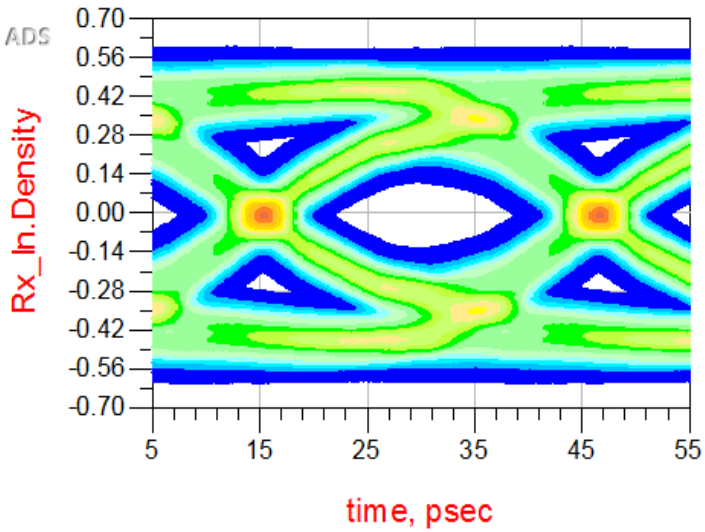
Stellar Measurement to Simulation Correlation with Accurate Fixture Calibrations

Looking Good !

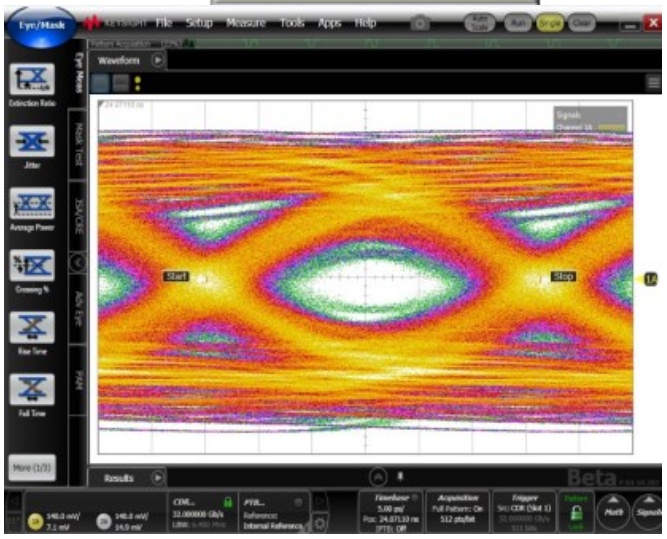


32 Gb/s, PRBS9

SIMULATED



MEASURED



The Future: The Internet of Things (IOT)

More Users

Automotive
Wearables
IOT
More Data Centers

Increased Services

Apps
Security

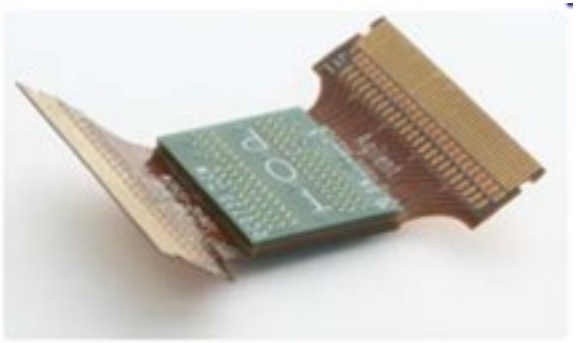
Increased Access Rate

25GE traffic density
Next Gen Data Center

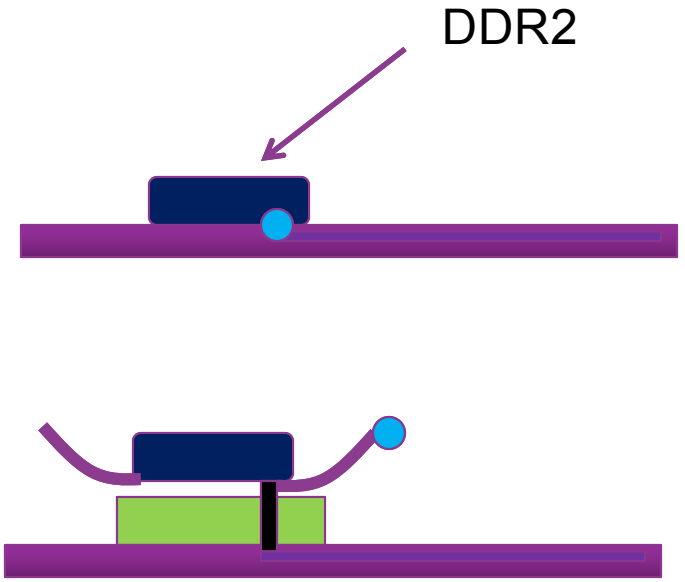
Ethernet Technology Summit

GRL
GRANITE RIVER LABS

Example: DDR2 Device Fixture

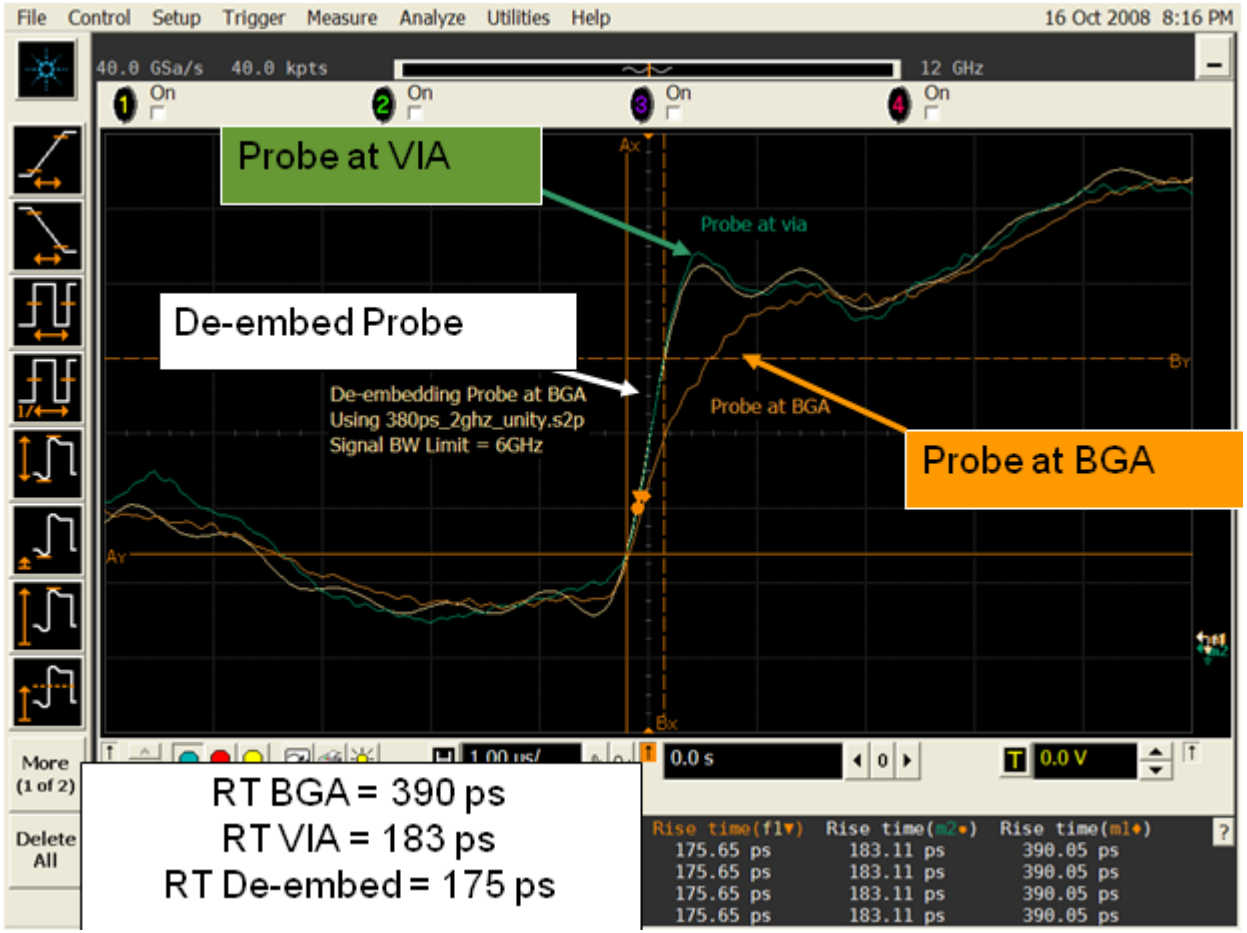


DDR2 BGA probe adapter for oscilloscopes and logic analyzers



How to remove this fixture effect?

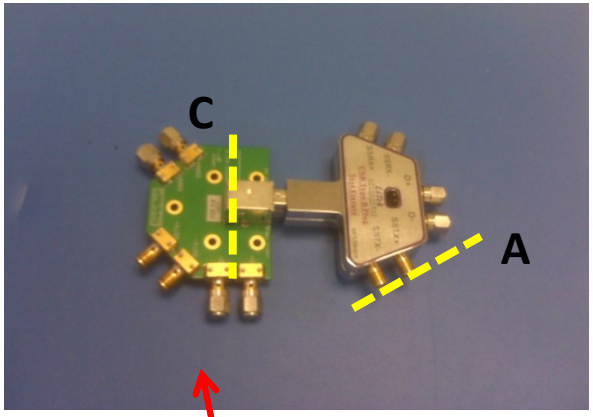
DDR2 Fixture De-Embedding



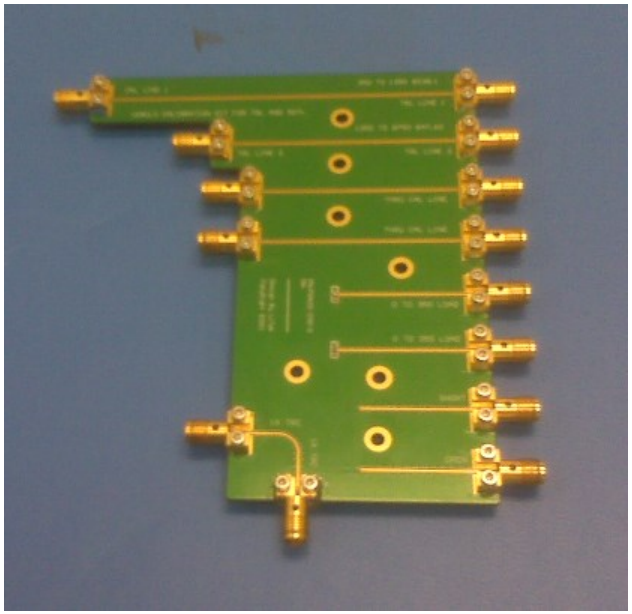
Scope performs de-embedding

SATA De-embedding Example

De-embedding fixture and Calibration board

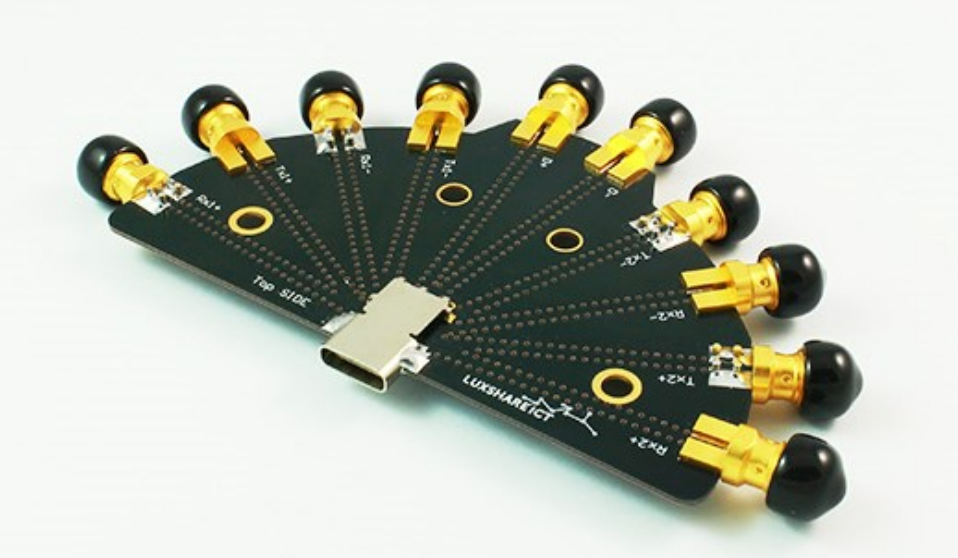


De-embedding fixture

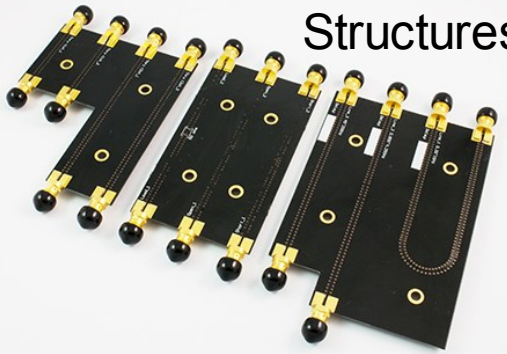


Calibration Board

USB Type-C High Speed Cable Fixture



TRL Calibration Calculator						
Inputs	Er	electrical Length (cm)	Propagation Velocity		Low Phase	High Phase
Line 1	3.55	6.634	1.5911E+08		30.02	150.11
Line 2		1.561			30.02	150.11
Line 3		0.332			30.02	150.11
Outputs	Start Frequency (GHz)	Stop Frequency (GHz)	Time Delay (ps)	Frequency Ratio f_2 / f_1 >8	Line Length (mm)	PCB line length (mm)
Short/ Open					37	37
Load		0.200			37	37
Thru(1x)					37	37
Thru(2x)					74	74
Line 1	0.200	1.000	416.96	5.00	66.343	140.343
Line 2	0.850	4.250	98.11	5.00	15.610	89.610
Line 3	4.000	20.000	20.85	5.00	3.317	77.317



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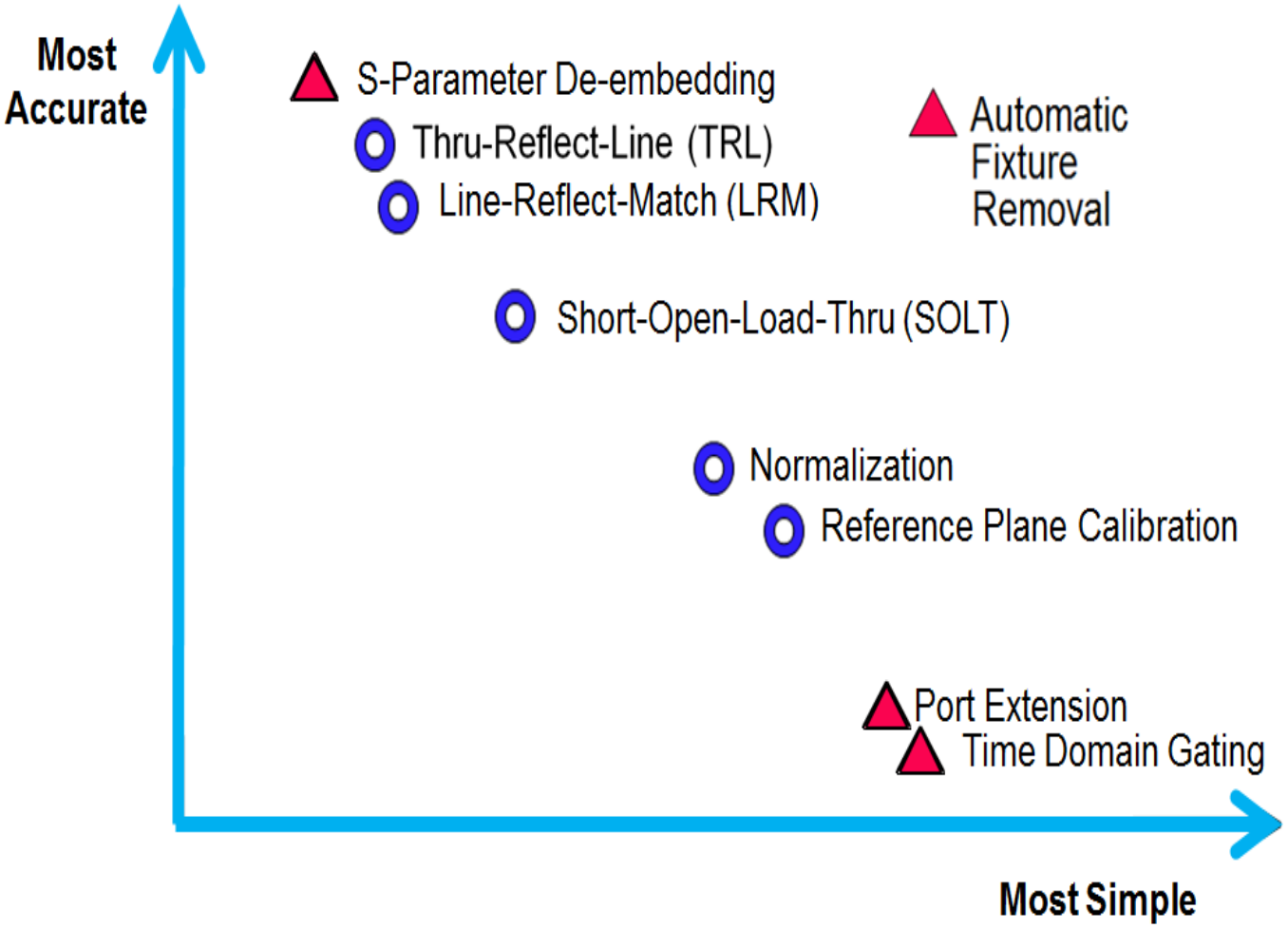
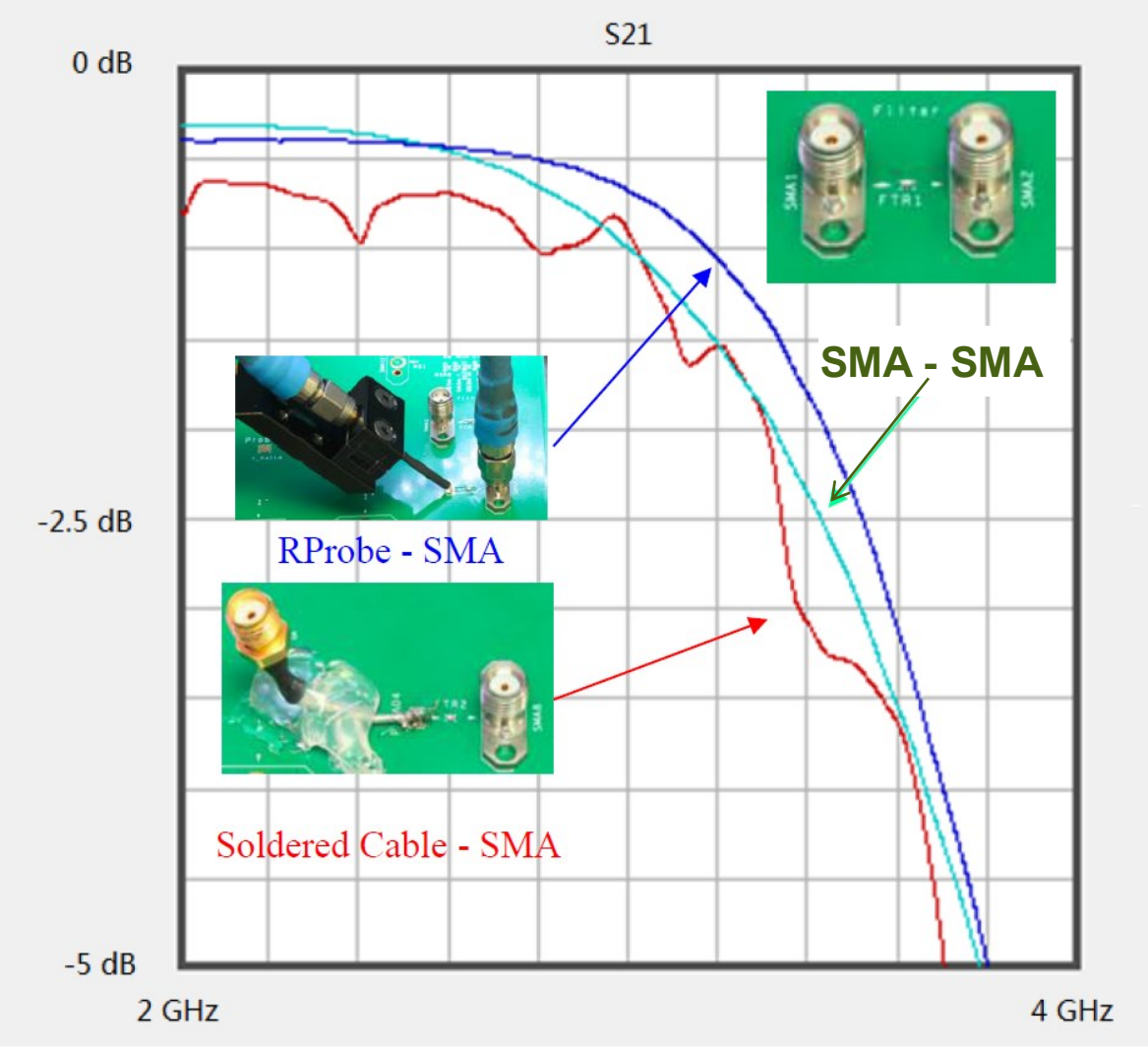
Error Correction Techniques



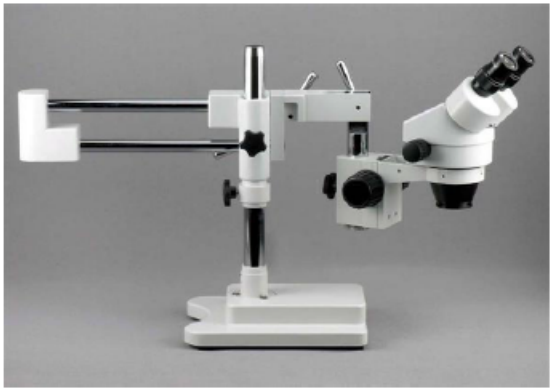
High Frequency Probing

When connectors are not an option…..

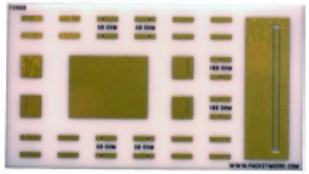
- PCB channel has no connectors: chip to chip.
- Direct measurement of the in-situ path is required.
- Reduced cost for repetitive production testing.



Tools and Accessories



Optical Microscope
(~ 90 x magnification)



TCS60
Calibration
Substrate

Mylar
Tape

Fine-tip
Sharpie pen

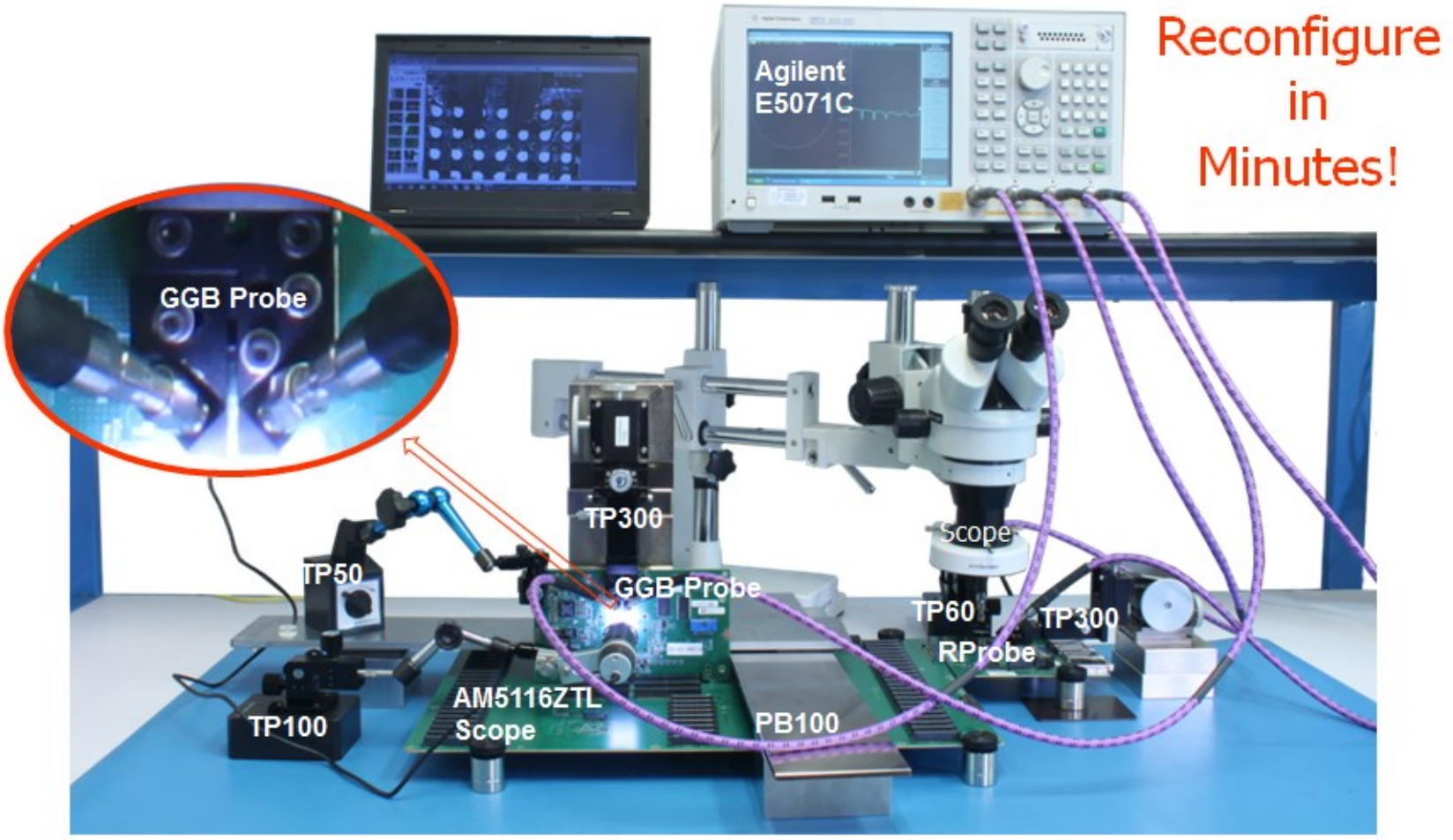
AM4113TL Dino-Lite Premier

USB Digital Microscope
(~ 90 x magnification)

- Using a good microscope is essential.
- You might damage the probe if you cannot see its tips well.

(Make sure to use a long working range (5 cm @ 90x) microscope!)

Example GHz Probes and Probe Stations



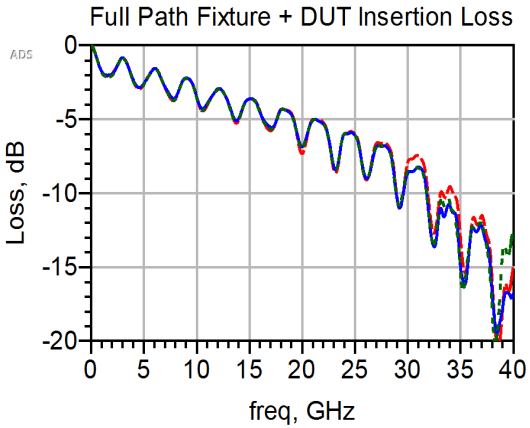
Simultaneous Horizontal/Vertical Probing

….in Summary

"A *theory* is something nobody believes, except the person who made it. An *experiment* is something everybody believes, except the person who made it." — Albert Einstein

"A *simulation* is something nobody believes, except the person who made it. A *measurement* is something everybody believes, except the person who made it." — Paul Huray

"Always verify simulation and measurements with standards"



Thank you Mr. Beatty!