Advances in Design, Modeling, Simulation and Measurement Validation of High Performance Board-to-Board 5 to10 Gbps Interconnects

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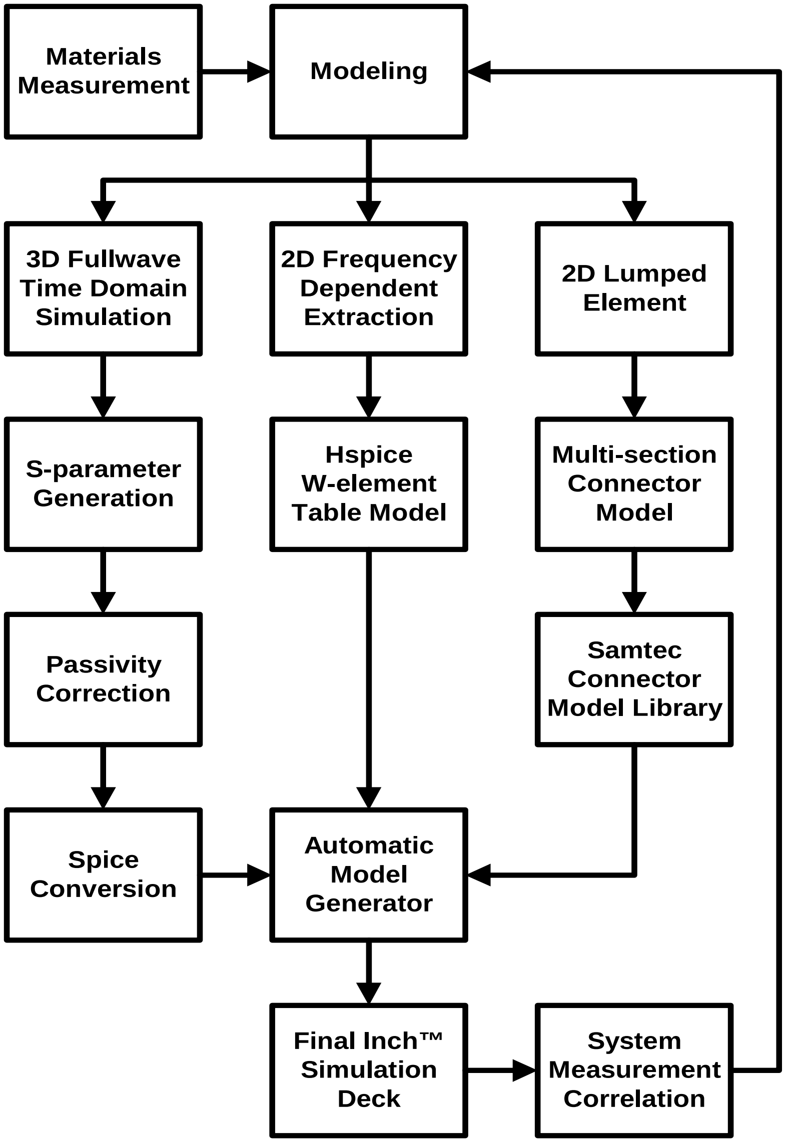
Introduction

- Final Inch^{TM}, a method for the design, modeling, simulation and evaluation of high performance board-to-board interconnects.
  - We will present a collection of methods which, when combined, provide a powerful framework for evaluation and correlating interconnect performance, where:
    - Everything matters
    - Everything is modeled
    - The results speak for themselves

Final Inch™ Modeling and Evaluation Process



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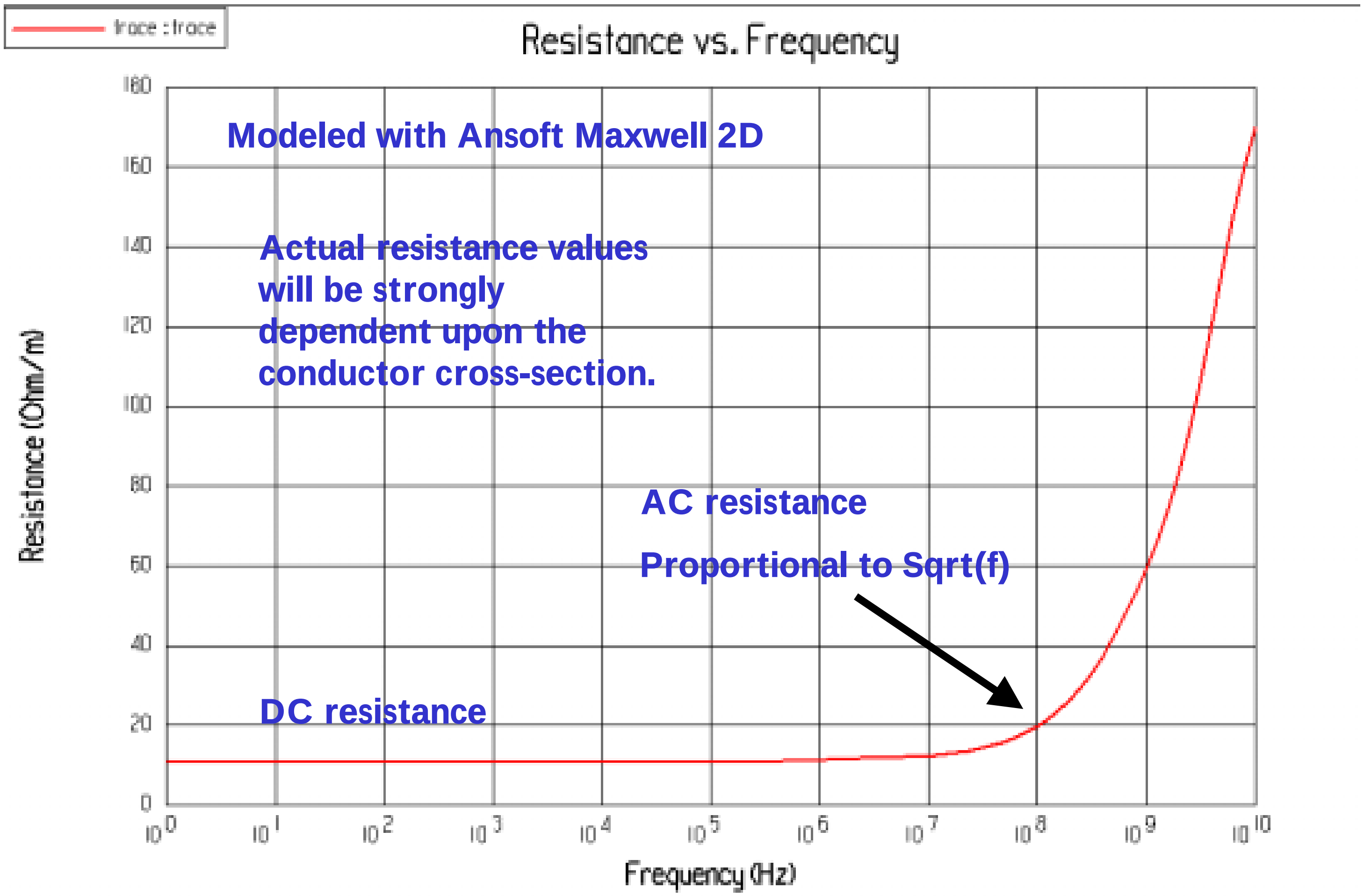
Frequency Dependent Modeling

- Frequency dependent modeling of significant interconnect elements is necessary for accurate simulation of systems.
  - Size matters
    - The longer an element is, the more important that accurate frequency dependent modeling is performed.
      - Traces, long connectors, flex, cables ….
        - » For short, well controlled elements, such as short board-to-board connectors, losses may be ignored with low error.
  - Irregularity matters
    - Irregular and 3-dimensional objects generally have non-TEM propagation modes and require modeling in the frequency domain.
      - Non-uniform traces, vias, SMA launches, connector transitions, cable transitions, connector breakout regions, antipads ….

TEM Modeling Of Uniform Structures

- Uniform long structures may generally be modeled using TEM or Quasi-TEM assumptions with 2-D field solvers.
  - Traces, coax, some connector cross sections ….
    - But error increases if the field solver does not model frequency dependent conductor and dielectric losses correctly.
      - Most do not!
      - Finite field penetration into conductors (skin effect) is often only partially modeled. Usually the resistive portion of skin effect is calculated, while the inductive portion is ignored
        - » Most solvers provide one value for inductance, which is incorrect!

Frequency Dependence of Resistance



Modeled with Ansoft Maxwell 2D

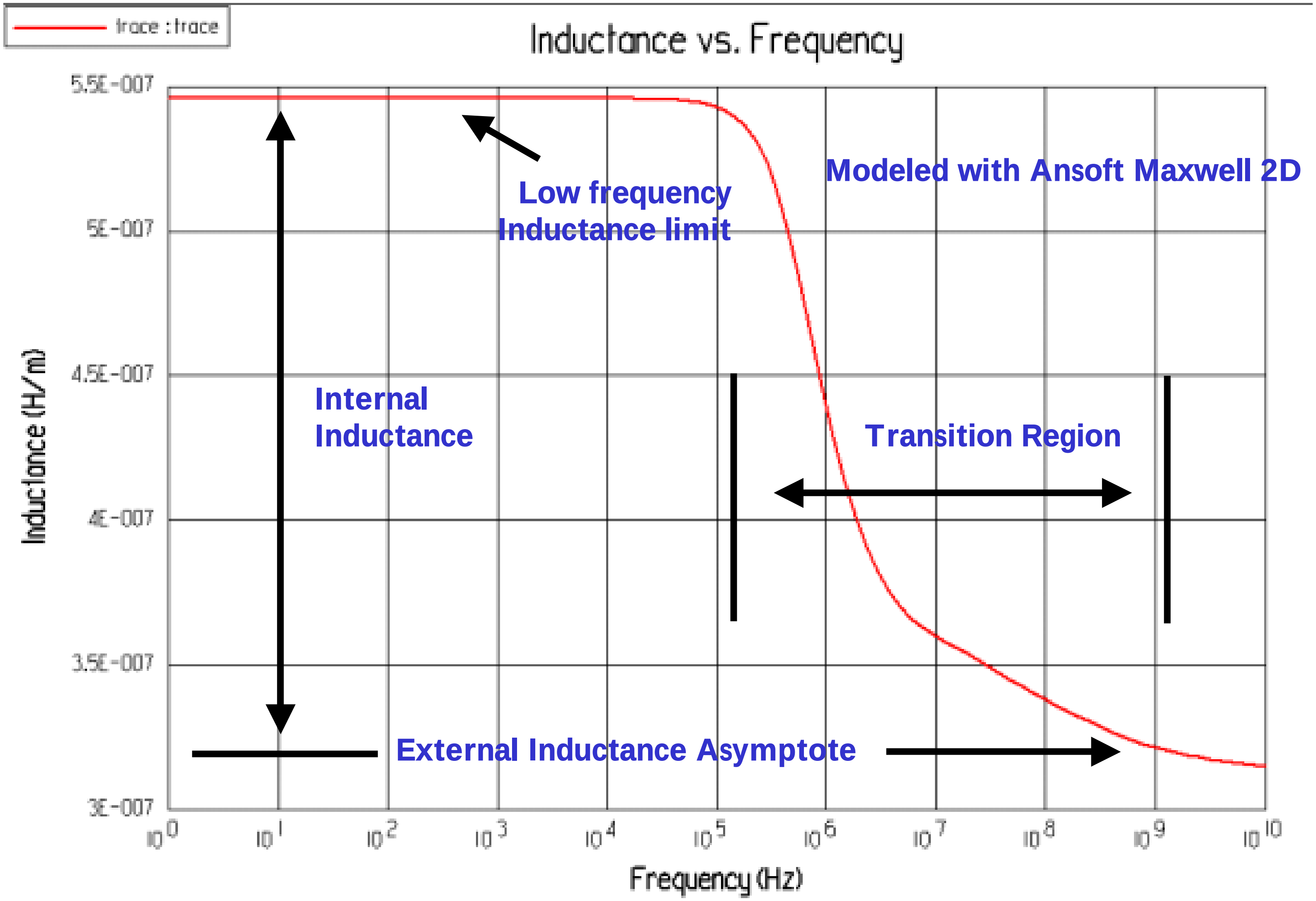
Actual resistance values will be strongly dependent upon the conductor cross-section.

AC resistance

Proportional to Sqrt(f)

DC resistance

Frequency Dependent Inductance



Low frequency Inductance limit

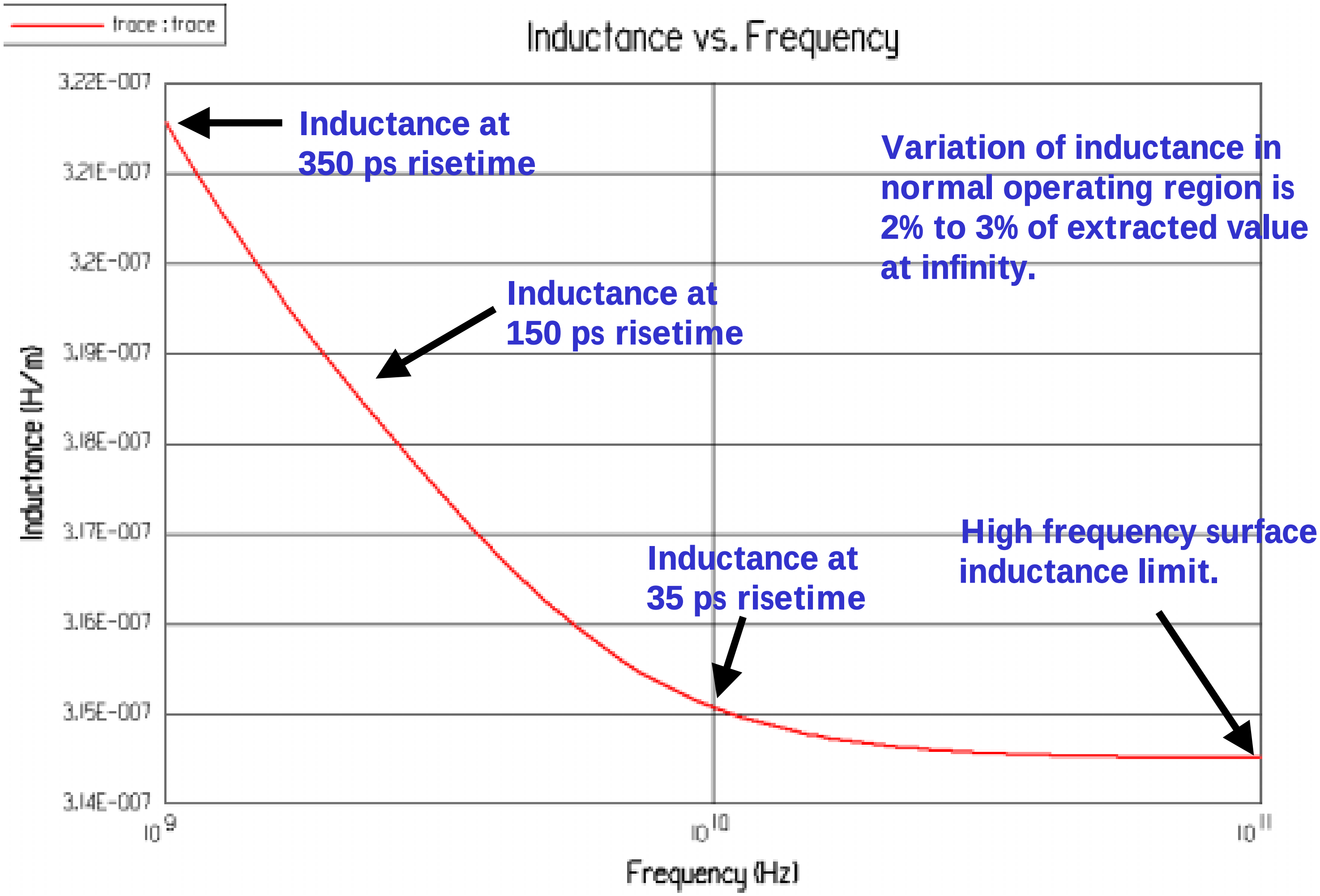
Modeled with Ansoft Maxwell 2D

Internal Inductance

Transition Region

External Inductance Asymptote

Frequency Dependence of Inductance



Inductance at 350 ps risetime

Inductance at 150 ps risetime

Inductance at 35 ps risetime

Variation of inductance in normal operating region is 2% to 3% of extracted value at infinity.

High frequency surface inductance limit.

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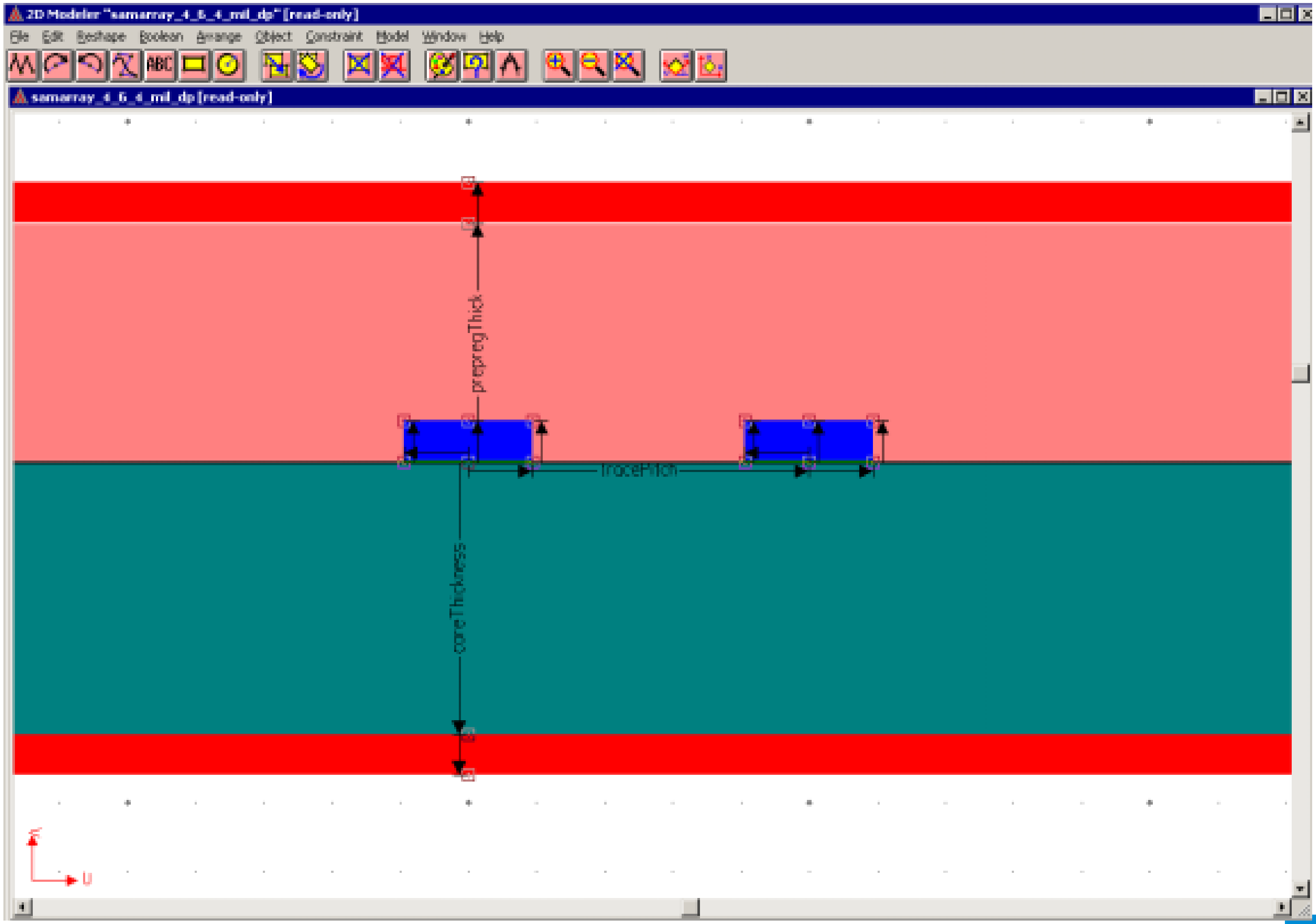
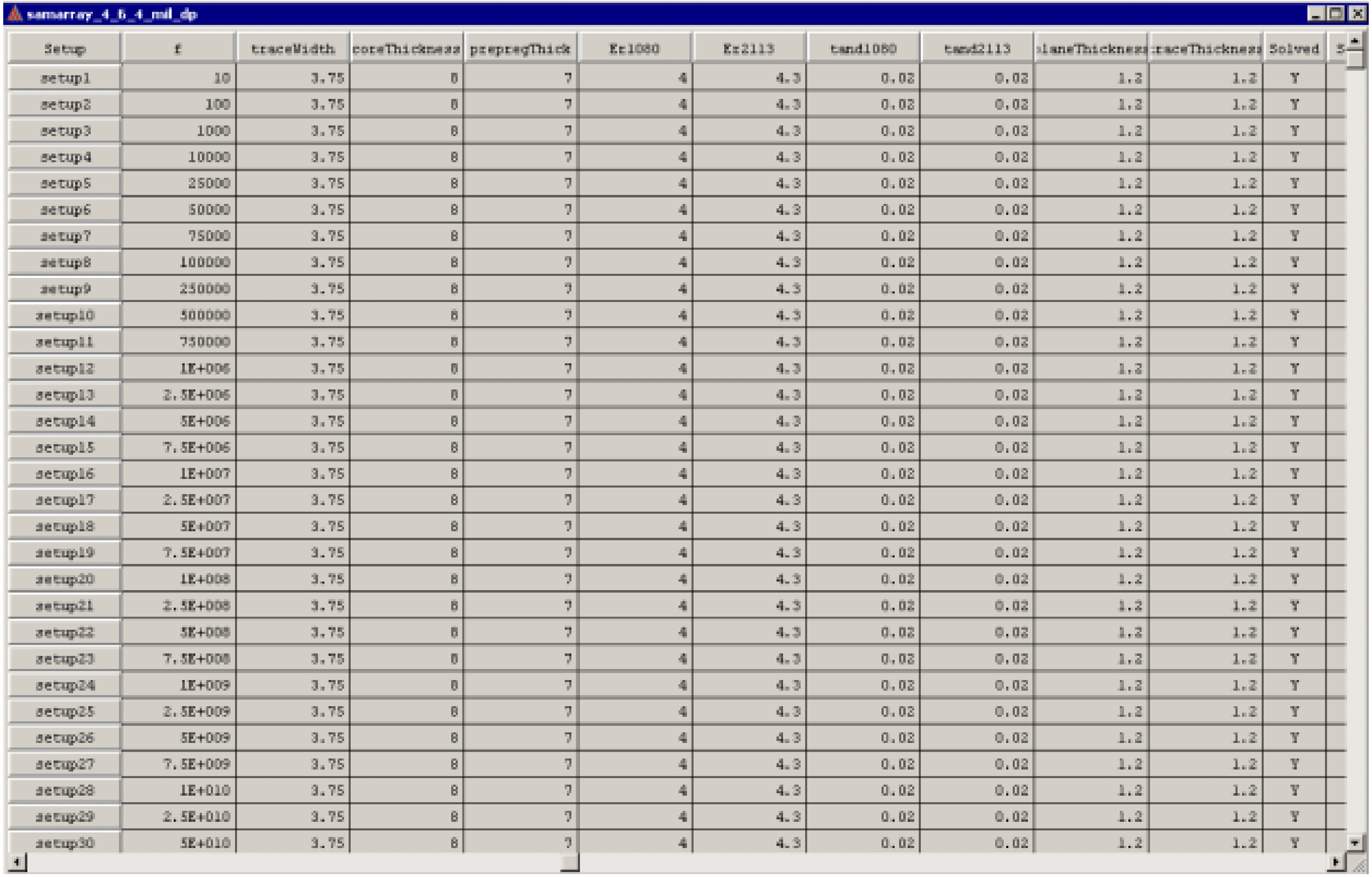
Final Inch^{TM} Trace Modeling

- Our approach to trace modeling.
  - Utilize Ansoft Maxwell 2D.
    - Finite element quasi-static field solver.
    - Capable of extracting frequency dependent R and L.
  - Measure (when possible) substrate material properties across frequency (Er and Loss tangent) and use during parameterization.
  - Extract trace parameters using a parametric sweep.
    - Sweep from 10 Hz to 50 GHz for accuracy across all frequency bands.
    - Utilize Z and Y matrices.
      - RLCG matrices do not include losses in Ansoft 2D.
  - Create HSPICE W-element table model.
    - Automated process to extract Z and Y matrices to create compatible table model.

2D Trace Modeling



Parametric Sweep



Setup	f	traceWidth	coreThickness	prepregThick	Er1080	Er2113	tand1080	tand2113	laneThickness	raceThickness	Solved	S
setup1	10	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup2	100	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup3	1000	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup4	10000	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup5	25000	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup6	50000	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup7	75000	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup8	100000	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup9	250000	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup10	500000	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup11	750000	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup12	1E+006	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup13	2.5E+006	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup14	5E+006	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup15	7.5E+006	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup16	1E+007	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup17	2.5E+007	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup18	5E+007	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup19	7.5E+007	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup20	1E+008	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup21	2.5E+008	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup22	5E+008	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup23	7.5E+008	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup24	1E+009	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup25	2.5E+009	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup26	5E+009	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup27	7.5E+009	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup28	1E+010	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup29	2.5E+010	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	
setup30	5E+010	3.75	8	7	4	4.3	0.02	0.02	1.2	1.2	Y	

Snippet of Final W-element Table Model

```
.MODEL final_inch_se W MODELTYPE=table N=1
+ RMODEL = final_inch_se_R LMODEL = final_inch_se_L
+ GMODEL = final_inch_se_G CMODEL = final_inch_se_C

* ###R-model###
* data type = * R-model
.MODEL final_inch_se_R SP N=1 SPACING=nonuniform
VALTYPE=real
+ INTERPOLATION=spline
+ DATA=32
* ============= ============= =============
* FREQUENCY:
+   0.0000000000000000e+000
* TABLE ELEMENTS:
* === row 1 ===
+   5.1907890527286469e+000
* ============= ============= =============
* FREQUENCY:
+   1.0000000000000000e+002
* TABLE ELEMENTS:
* === row 1 ===
+   5.1907890900627756e+000
```

Synopsys HSPICE W-element Fix

```
*********************************************
* code to force HSPICE W-element time step and bandwidth
algorithm
* work correctly for slow edge rate signals, and play well with
* other Laplacian and lumped element models
*
vfrog frog 0 pulse (1 0 0 25p 25p 75p 200p)
rfrog frog 0 50
```

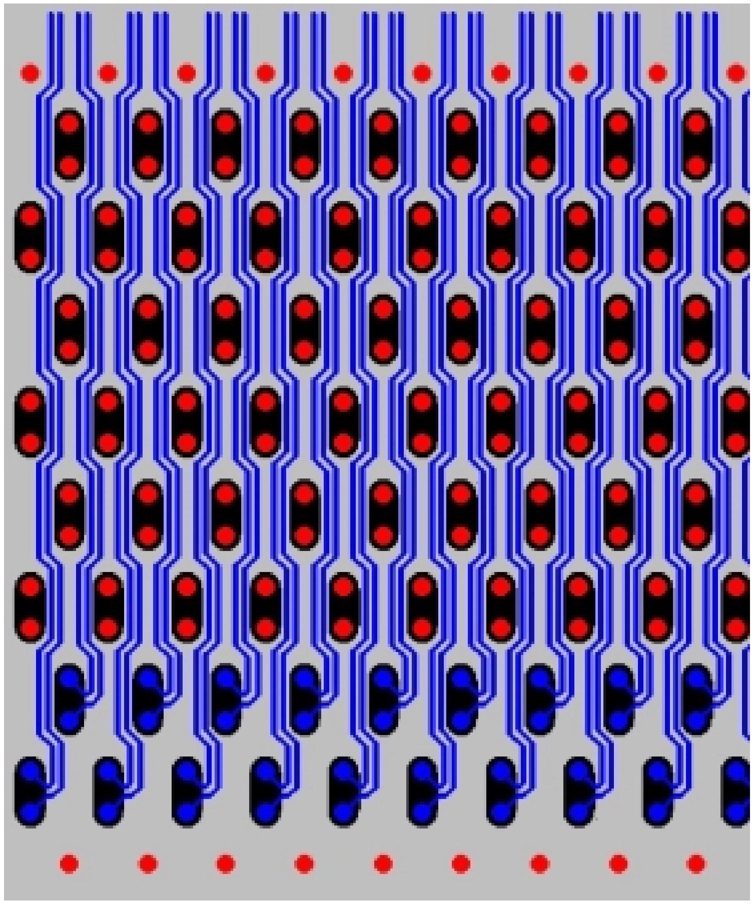
The above HSPICE code provides a “fix” for algorithmic problems with the w-element. In a nutshell, the HSPICE w-element automatically sets the bandwidth and time step for it’s internal inverse Laplace transformations using the rise time of signals in the system. For almost all normal excitations, this causes the bandwidth to be set too low, resulting in incorrect waveform results in the time domain, and oftentimes instability when interfaced with other elements.

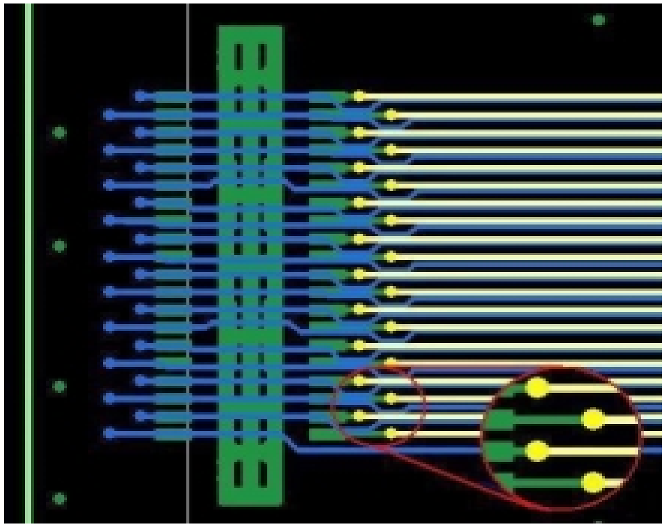
This code forces the w-element to adjust its bandwidth to accommodate 25 ps rise times and results in extraordinary waveform accuracy, as will be seen later in the presentation.

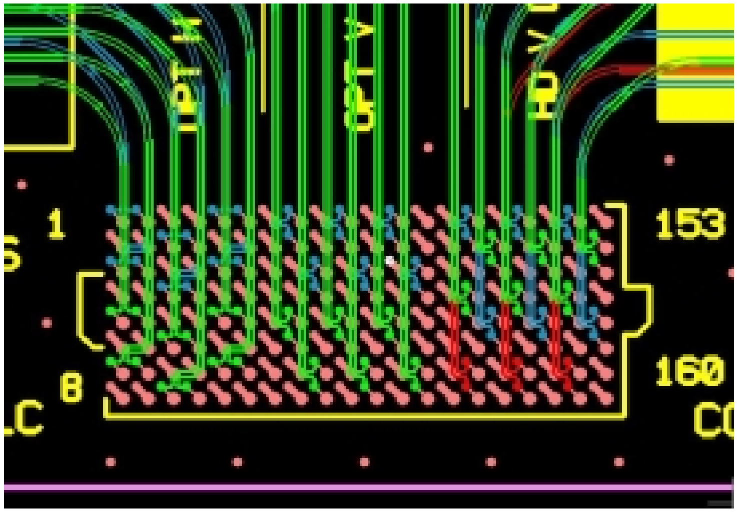
TEM vs. Non-TEM Modeling Of Non-Uniform Structures

- Non-uniform structures require modeling with a 2.5-D or 3-D full wave approach.
  - Fields generally do not meet TEM or Quasi-TEM assumptions.
    - Electric and Magnetic fields are not reasonably orthogonal.
    - Lumped and/or distributed model approximations are no longer accurate.
  - Network parameters (S-parameters) are generally the best way to model the broadband performance of these structures.
    - Full wave field solvers and simulators like CST Microwave Studio can be used for the extraction of these structures.

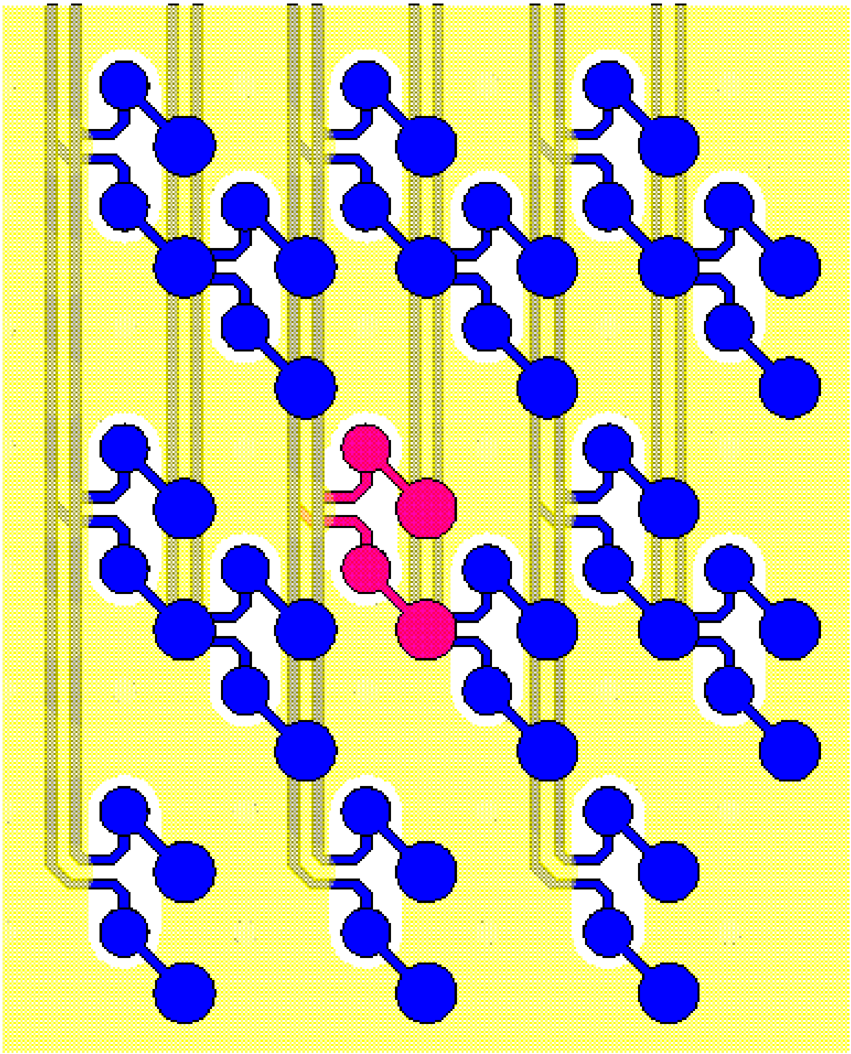
Connector Breakout Region (BOR)



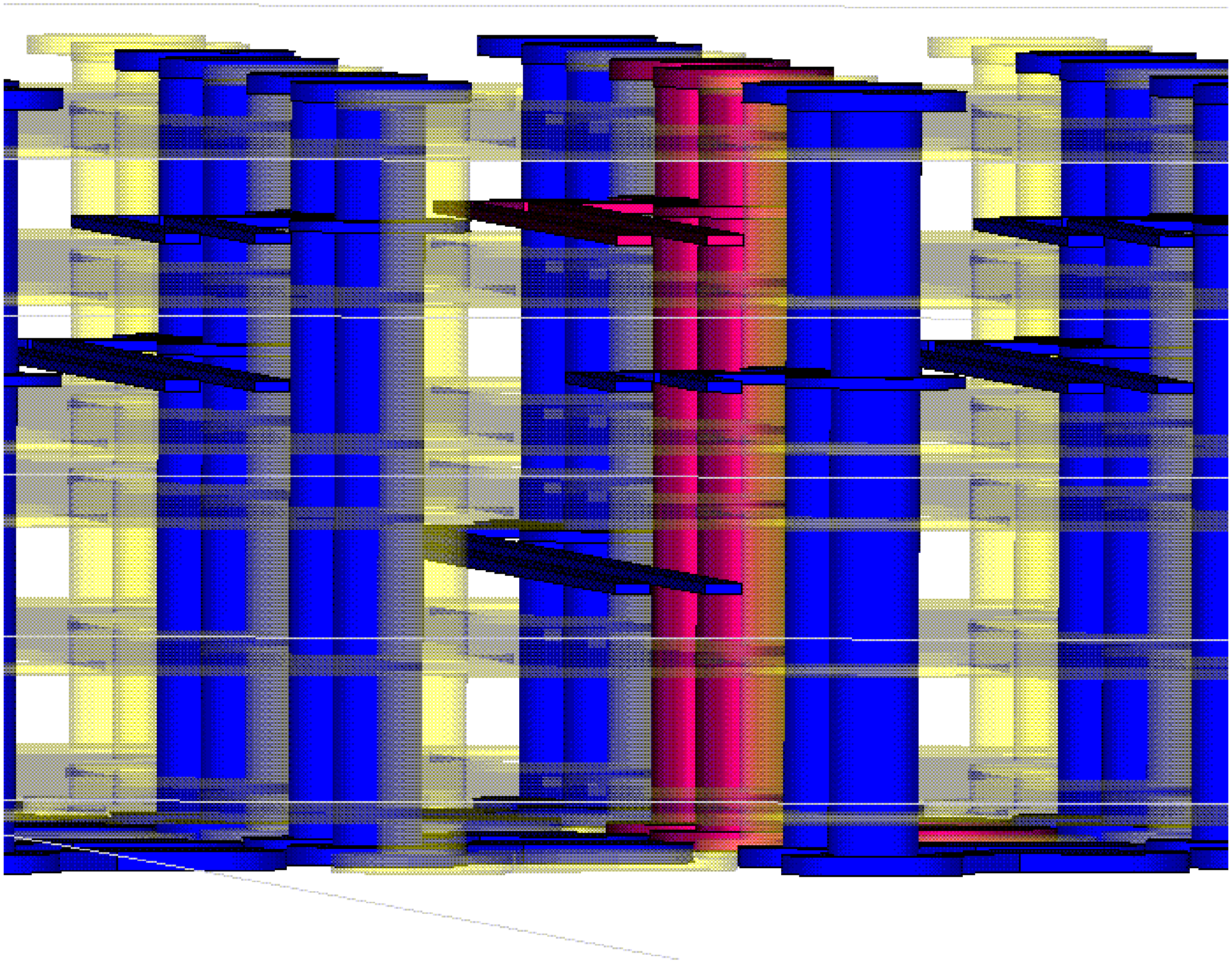




SamArray^{TM} 3-D Modeling Top View



SamArray^{TM} 3-D Modeling Via Stack Side View



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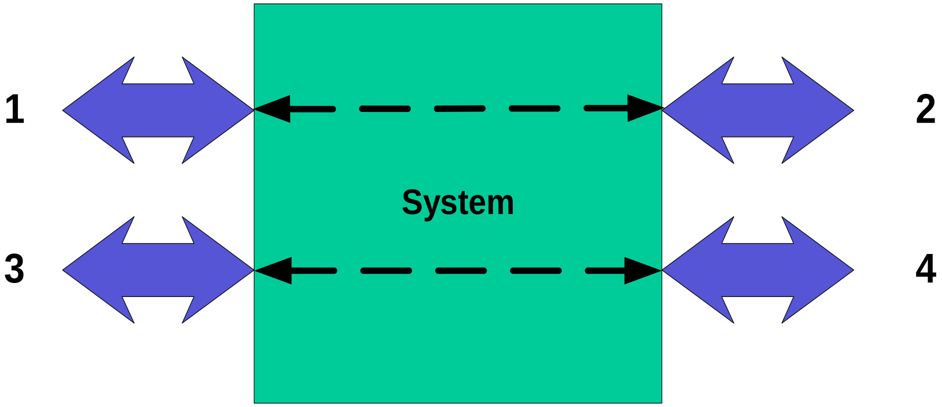
Single-ended S-parameters



S11, S22, S33, S44 = energy reflected back from ports (Return Loss)

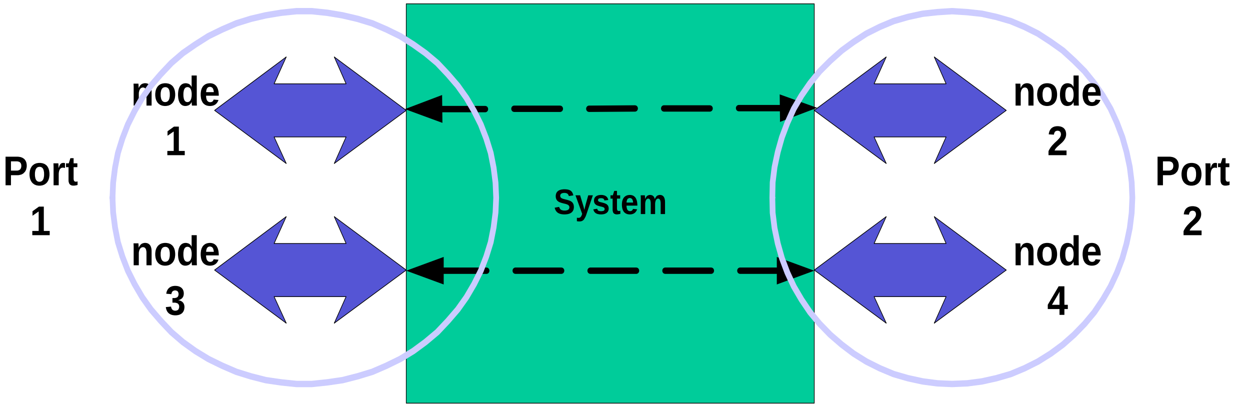
S31 = energy transferred from port 1 to port 3 (Near End Crosstalk)

S41 = energy transferred from port 1 to port 4 (Far End Crosstalk)

S21, S12, S34, S43 = energy transferred along through paths (Insertion Loss)

The paths that are defined to be insertion loss are the through paths from the inputs to the outputs of a system. The actual port combinations will change for each design, depending upon the numbering convention. When there is only one path, two ports, it is customary to label them 1 and 2. But for multi-path systems, this is not always the case.

Differential Mixed Mode S-parameters



Single-ended ports may be grouped together logically to represent differentially excited ports. Four single-ended ports may be combined into two differential ports, as a simple linear mapping operation.

Since each port contains two nodes, two modes of excitation may be described: Differential Mode and Common Mode. These are normally annotated using "D" for differential and "C" for common.

Sdd11 – port 1 differential mode return loss

Scc11 – port 1 common mode return loss

Sdd21 – port 1 to port 2 differential mode insertion loss

Differential Mixed Mode S-parameters

Excitation of a differential port can be completely described by linear combinations of even and odd mode excitation of the pair elements. Formally this means that the excitation is a linear combination of the excitation vectors:

$$\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \times \begin{bmatrix} v1p & v2p \\ v1m & v2m \end{bmatrix} = \begin{bmatrix} v1d & v2d \\ v1c & v2c \end{bmatrix}$$

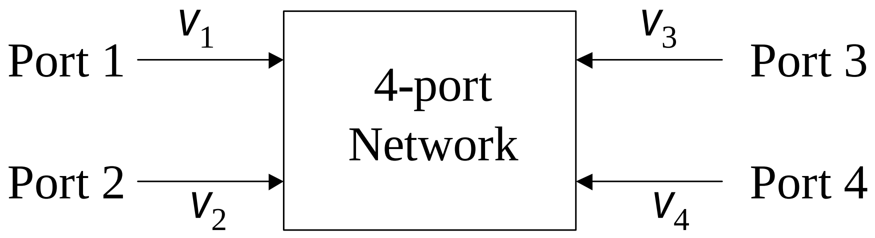
where subscripts *p* and *m* are plus and minus terminal voltages for the differential pair, and subscripts *d* and *c* are differential and common mode voltages.

Differential Mixed Mode S-parameters

The formulation of mixed mode S-parameters involves a linear transformation of the natural S-parameters:

$$S_{mm} = MS_{nat}M^{-1}$$

$\boldsymbol{S_{mm}}$ and $\boldsymbol{S_{nat}}$ are the mixed mode and natural S-parameter matrices respectively. The work of the linear transformation is done with the matrix ***M***. Let's consider for a moment a 4-port single-ended network:



Differential Mixed Mode S-parameters

To convert the natural S-parameters of this network to mixed mode, matrix ***M*** is constructed as follows:

$$M = \frac{1}{\sqrt{2}} \times \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

S_{mm} then becomes:

$$S_{mm} = MS_{nat}M^{-1} = \begin{bmatrix} S^{dd} & S^{dc} \\ S^{cd} & S^{cc} \end{bmatrix}$$

Differential Mixed Mode S-parameters

S^{dd} and S^{cc} are the pure differential and common mode S-parameters, and S^{dc} and S^{cd} are the mixed mode differential to common and common to differential S-parameters respectively.

$$S_{dd} = \begin{bmatrix} S_{11}^{dd} & S_{12}^{dd} \\ S_{21}^{dd} & S_{22}^{dd} \end{bmatrix}$$

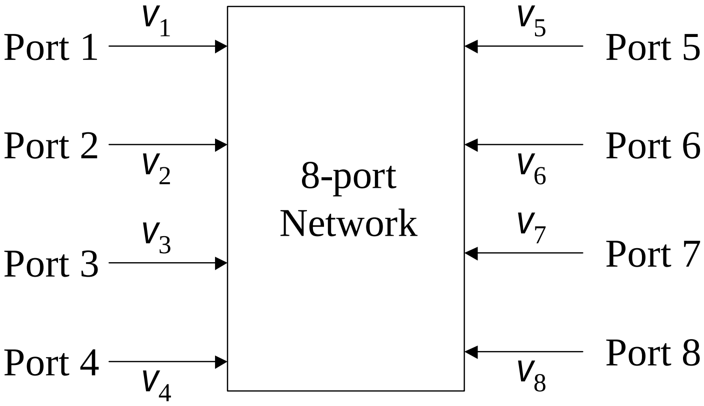
$$S_{dc} = \begin{bmatrix} S_{11}^{dc} & S_{12}^{dc} \\ S_{21}^{dc} & S_{22}^{dc} \end{bmatrix}$$

$$S_{cd} = \begin{bmatrix} S_{11}^{cd} & S_{12}^{cd} \\ S_{21}^{cd} & S_{22}^{cd} \end{bmatrix}$$

$$S_{cc} = \begin{bmatrix} S_{11}^{cc} & S_{12}^{cc} \\ S_{21}^{cc} & S_{22}^{cc} \end{bmatrix}$$

Differential Mixed Mode S-parameters

Extending the M matrix to N ports is simply a matter of adding the necessary even and odd mode excitations. For example the network below:



The M matrix to combine ports 1 and 2, 3 and 4, 5 and 6, and 7 and 8 into differential pairs will be:

$$M = \frac{1}{\sqrt{2}} \times \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

Differential Mixed Mode S-parameters

Like the 4-port example, $\boldsymbol{S_{mm}}$ is:

$$S_{mm} = MS_{nat}M^{-1} = \begin{bmatrix} S^{dd} & S^{dc} \\ S^{cd} & S^{cc} \end{bmatrix}$$

but now:

$$S_{dd} = \begin{bmatrix} S_{11}^{dd} & S_{12}^{dd} & S_{13}^{dd} & S_{14}^{dd} \\ S_{21}^{dd} & S_{22}^{dd} & S_{23}^{dd} & S_{24}^{dd} \\ S_{31}^{dd} & S_{32}^{dd} & S_{33}^{dd} & S_{34}^{dd} \\ S_{41}^{dd} & S_{42}^{dd} & S_{43}^{dd} & S_{44}^{dd} \end{bmatrix} \qquad S_{dc} = \begin{bmatrix} S_{11}^{dc} & S_{12}^{dc} & S_{13}^{dc} & S_{14}^{dc} \\ S_{21}^{dc} & S_{22}^{dc} & S_{23}^{dc} & S_{24}^{dc} \\ S_{31}^{dc} & S_{32}^{dc} & S_{33}^{dc} & S_{34}^{dc} \\ S_{41}^{dc} & S_{42}^{dc} & S_{43}^{dc} & S_{44}^{dc} \end{bmatrix}$$

$$S_{cd} = \begin{bmatrix} S_{11}^{cd} & S_{12}^{cd} & S_{13}^{cd} & S_{14}^{cd} \\ S_{21}^{cd} & S_{22}^{cd} & S_{23}^{cd} & S_{24}^{cd} \\ S_{31}^{cd} & S_{32}^{cd} & S_{33}^{cd} & S_{34}^{cd} \\ S_{41}^{cd} & S_{42}^{cd} & S_{43}^{cd} & S_{44}^{cd} \end{bmatrix} \qquad S_{cc} = \begin{bmatrix} S_{11}^{cc} & S_{12}^{cc} & S_{13}^{cc} & S_{14}^{cc} \\ S_{21}^{cc} & S_{22}^{cc} & S_{23}^{cc} & S_{24}^{cc} \\ S_{31}^{cc} & S_{32}^{cc} & S_{33}^{cc} & S_{34}^{cc} \\ S_{41}^{cc} & S_{42}^{cc} & S_{43}^{cc} & S_{44}^{cc} \end{bmatrix}$$

Differential Mixed Mode S-parameters

$$S_{dd} = \frac{1}{2}\begin{bmatrix} S_{11}-S_{21}-S_{12}+S_{22} & S_{13}-S_{23}-S_{14}+S_{24} & S_{15}-S_{25}-S_{16}+S_{26} & S_{17}-S_{27}-S_{18}+S_{28} \\ S_{31}-S_{41}-S_{32}+S_{42} & S_{33}-S_{43}-S_{34}+S_{44} & S_{35}-S_{45}-S_{36}+S_{46} & S_{37}-S_{47}-S_{38}+S_{48} \\ S_{51}-S_{61}-S_{52}+S_{62} & S_{53}-S_{63}-S_{54}+S_{64} & S_{55}-S_{65}-S_{56}+S_{66} & S_{57}-S_{67}-S_{58}+S_{68} \\ S_{71}-S_{81}-S_{72}+S_{82} & S_{73}-S_{83}-S_{74}+S_{84} & S_{75}-S_{85}-S_{76}+S_{86} & S_{77}-S_{87}-S_{78}+S_{88} \end{bmatrix}$$

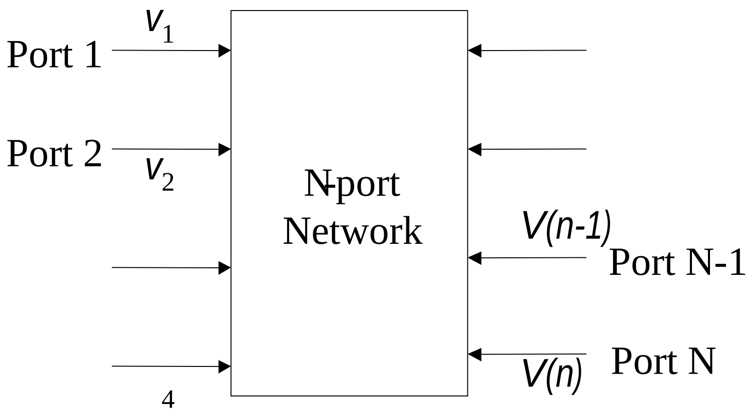
$$S_{cc} = \frac{1}{2}\begin{bmatrix} S_{11}+S_{21}+S_{12}+S_{22} & S_{13}+S_{23}+S_{14}+S_{24} & S_{15}+S_{25}+S_{16}+S_{26} & S_{17}+S_{27}+S_{18}+S_{28} \\ S_{31}+S_{41}+S_{32}+S_{42} & S_{33}+S_{43}+S_{34}+S_{44} & S_{35}+S_{45}+S_{36}+S_{46} & S_{37}+S_{47}+S_{38}+S_{48} \\ S_{51}+S_{61}+S_{52}+S_{62} & S_{53}+S_{63}+S_{54}+S_{64} & S_{55}+S_{65}+S_{56}+S_{66} & S_{57}+S_{67}+S_{58}+S_{68} \\ S_{71}+S_{81}+S_{72}+S_{82} & S_{73}+S_{83}+S_{74}+S_{84} & S_{75}+S_{85}+S_{76}+S_{86} & S_{77}+S_{87}+S_{78}+S_{88} \end{bmatrix}$$

$$S_{dc} = \frac{1}{2}\begin{bmatrix} S_{11}-S_{21}+S_{12}-S_{22} & S_{13}-S_{23}+S_{14}-S_{24} & S_{15}-S_{25}+S_{16}-S_{26} & S_{17}-S_{27}+S_{18}-S_{28} \\ S_{31}-S_{41}+S_{32}-S_{42} & S_{33}-S_{43}+S_{34}-S_{44} & S_{35}-S_{45}+S_{36}-S_{46} & S_{37}-S_{47}+S_{38}-S_{48} \\ S_{51}-S_{61}+S_{52}-S_{62} & S_{53}-S_{63}+S_{54}-S_{64} & S_{55}-S_{65}+S_{56}-S_{66} & S_{57}-S_{67}+S_{58}-S_{68} \\ S_{71}-S_{81}+S_{72}-S_{82} & S_{73}-S_{83}+S_{74}-S_{84} & S_{75}-S_{85}+S_{76}-S_{86} & S_{77}-S_{87}+S_{78}-S_{88} \end{bmatrix}$$

$$S_{cd} = \frac{1}{2}\begin{bmatrix} S_{11}+S_{21}-S_{12}-S_{22} & S_{13}+S_{23}-S_{14}-S_{24} & S_{15}+S_{25}-S_{16}-S_{26} & S_{17}+S_{27}-S_{18}-S_{28} \\ S_{31}+S_{41}-S_{32}-S_{42} & S_{33}+S_{43}-S_{34}-S_{44} & S_{35}+S_{45}-S_{36}-S_{46} & S_{37}+S_{47}-S_{38}-S_{48} \\ S_{51}+S_{61}-S_{52}-S_{62} & S_{53}+S_{63}-S_{54}-S_{64} & S_{55}+S_{65}-S_{56}-S_{66} & S_{57}+S_{67}-S_{58}-S_{68} \\ S_{71}+S_{81}-S_{72}-S_{82} & S_{73}+S_{83}-S_{74}-S_{84} & S_{75}+S_{85}-S_{76}-S_{86} & S_{77}+S_{87}-S_{78}-S_{88} \end{bmatrix}$$

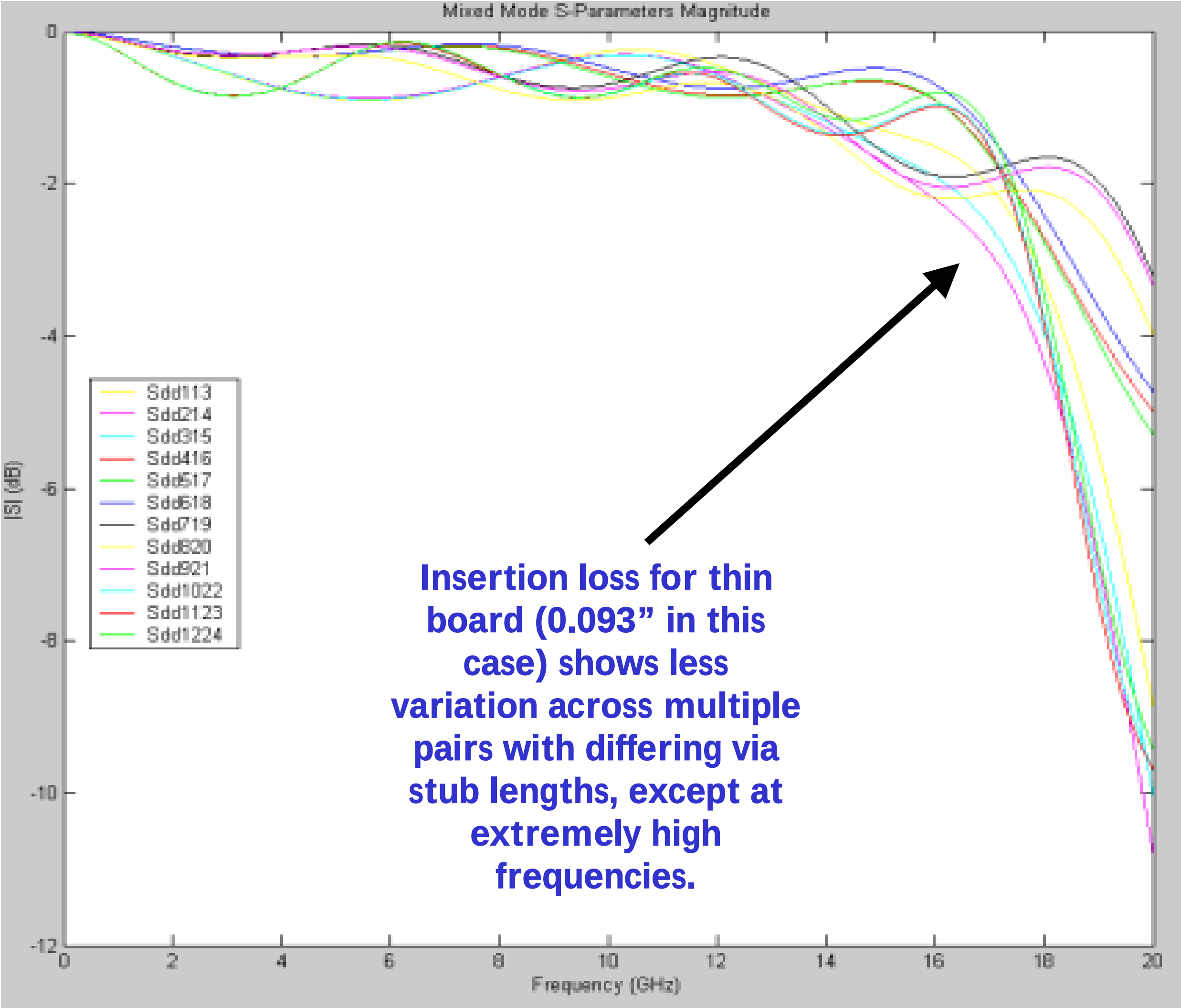
Differential Mixed Mode S-parameters

The mixed-mode formulation can be extended to any number of ports, limited only by memory and processing power.



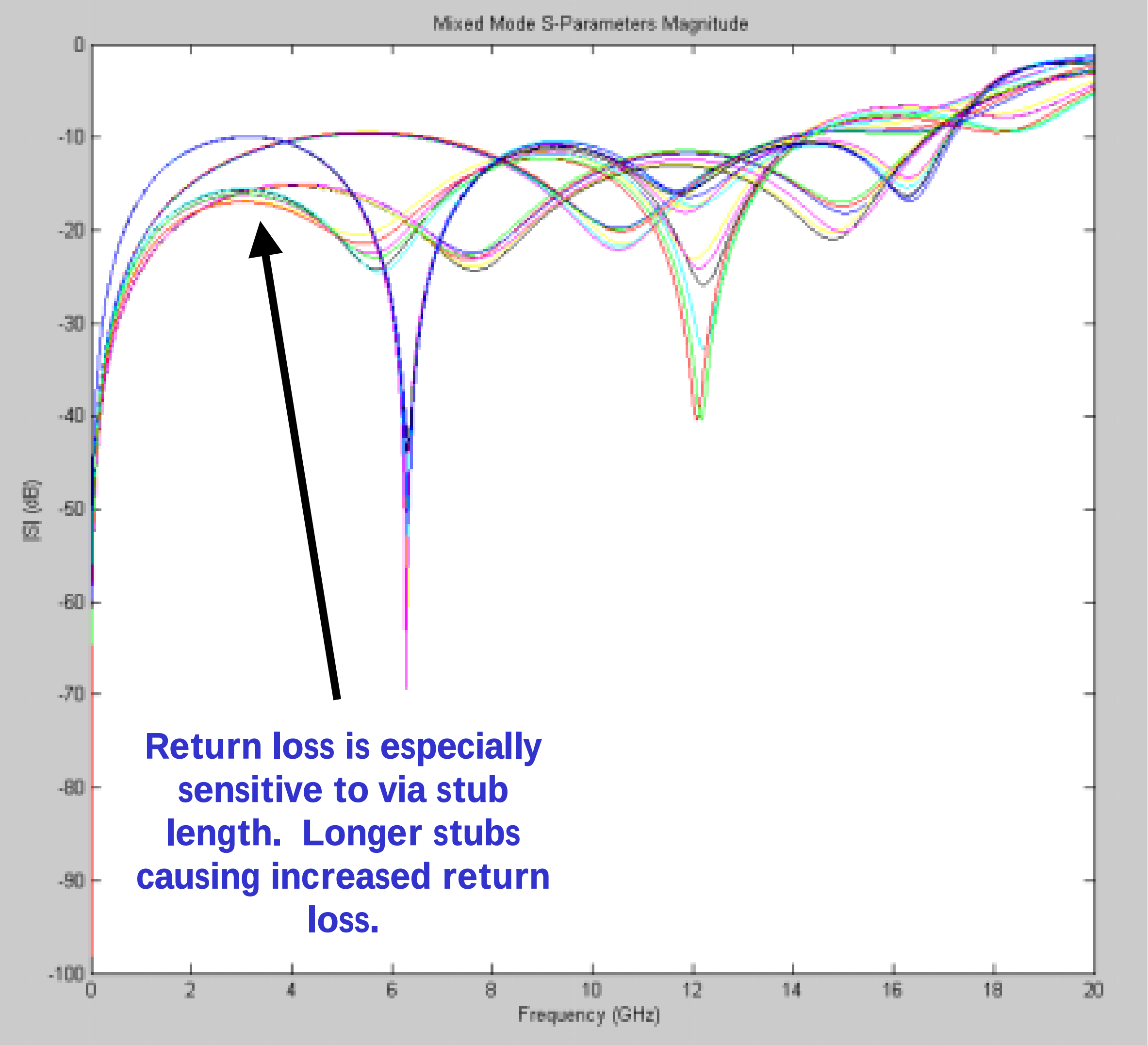
For Final Inch™ S-parameter processing, 48-port single-ended S-parameter files are commonly processed to produce the necessary mixed-mode S-parameters. The following slides show the resulting output plots for the previous SamArray™ Final Inch™ breakout region (BOR).

Differential Insertion Loss



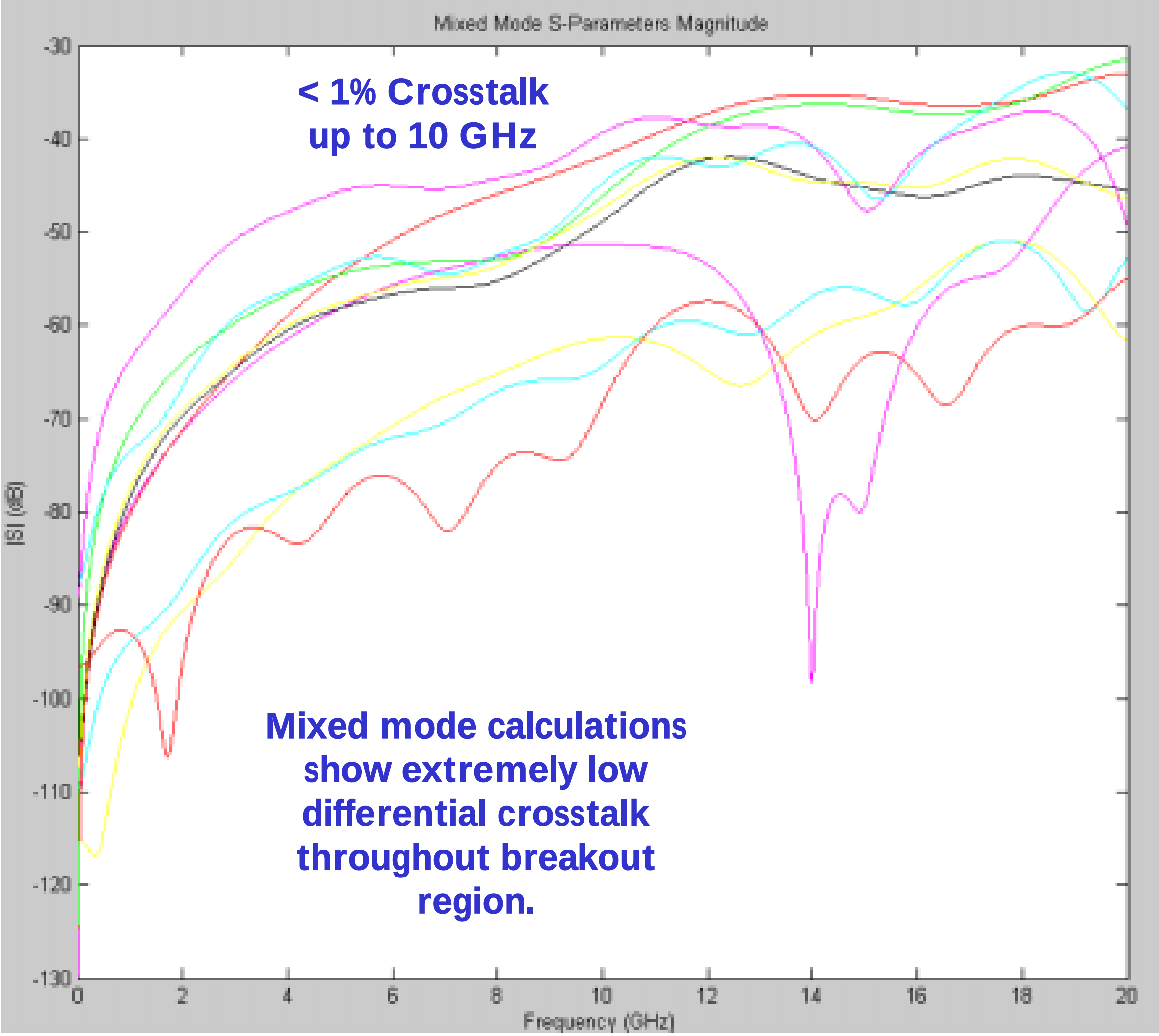
Insertion loss for thin board (0.093" in this case) shows less variation across multiple pairs with differing via stub lengths, except at extremely high frequencies.

Differential Return Loss



Return loss is especially sensitive to via stub length. Longer stubs causing increased return loss.

Differential Crosstalk



< 1% Crosstalk
up to 10 GHz

Mixed mode calculations
show extremely low
differential crosstalk
throughout breakout
region.

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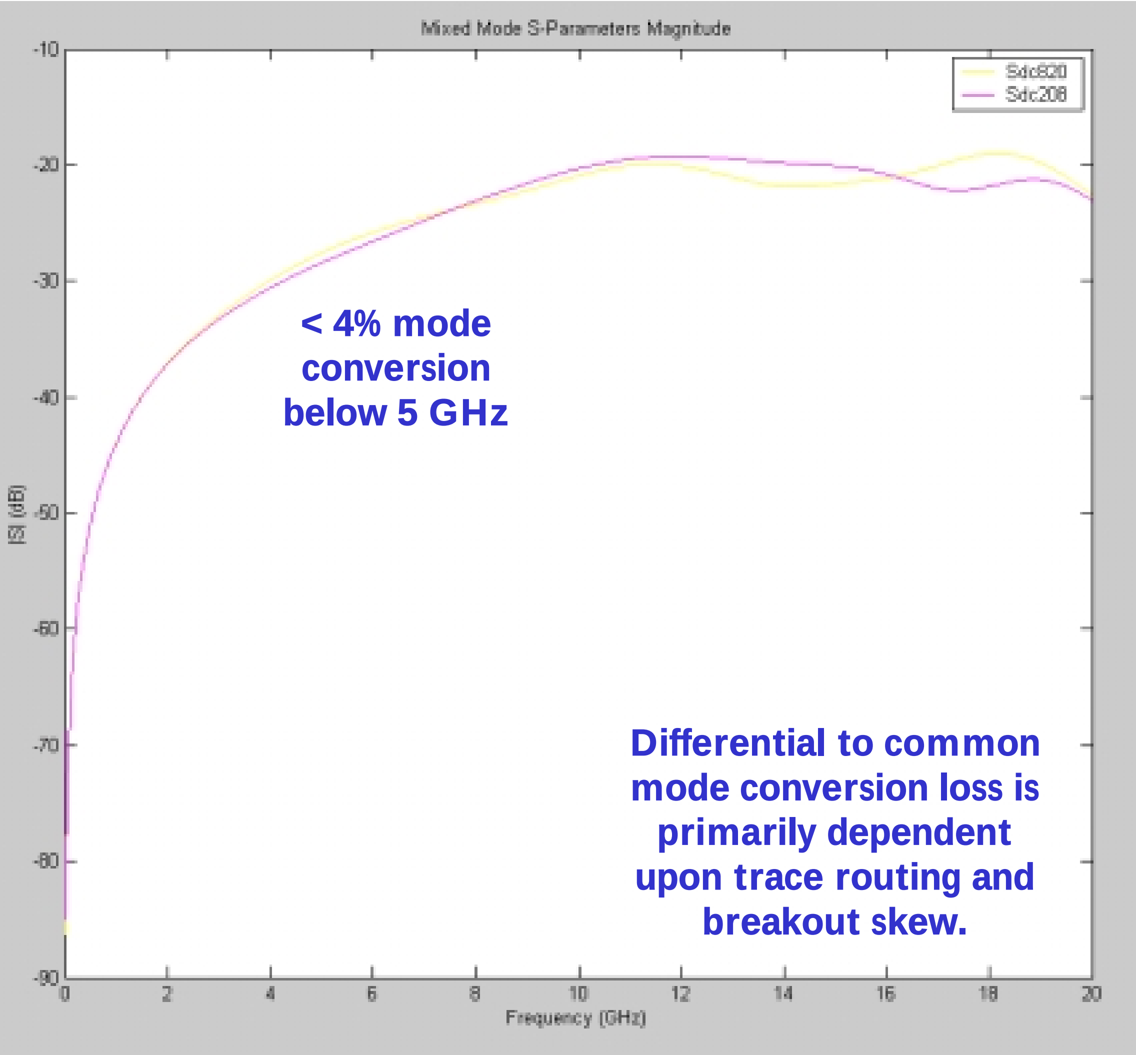
Differential to Common Mode Conversion



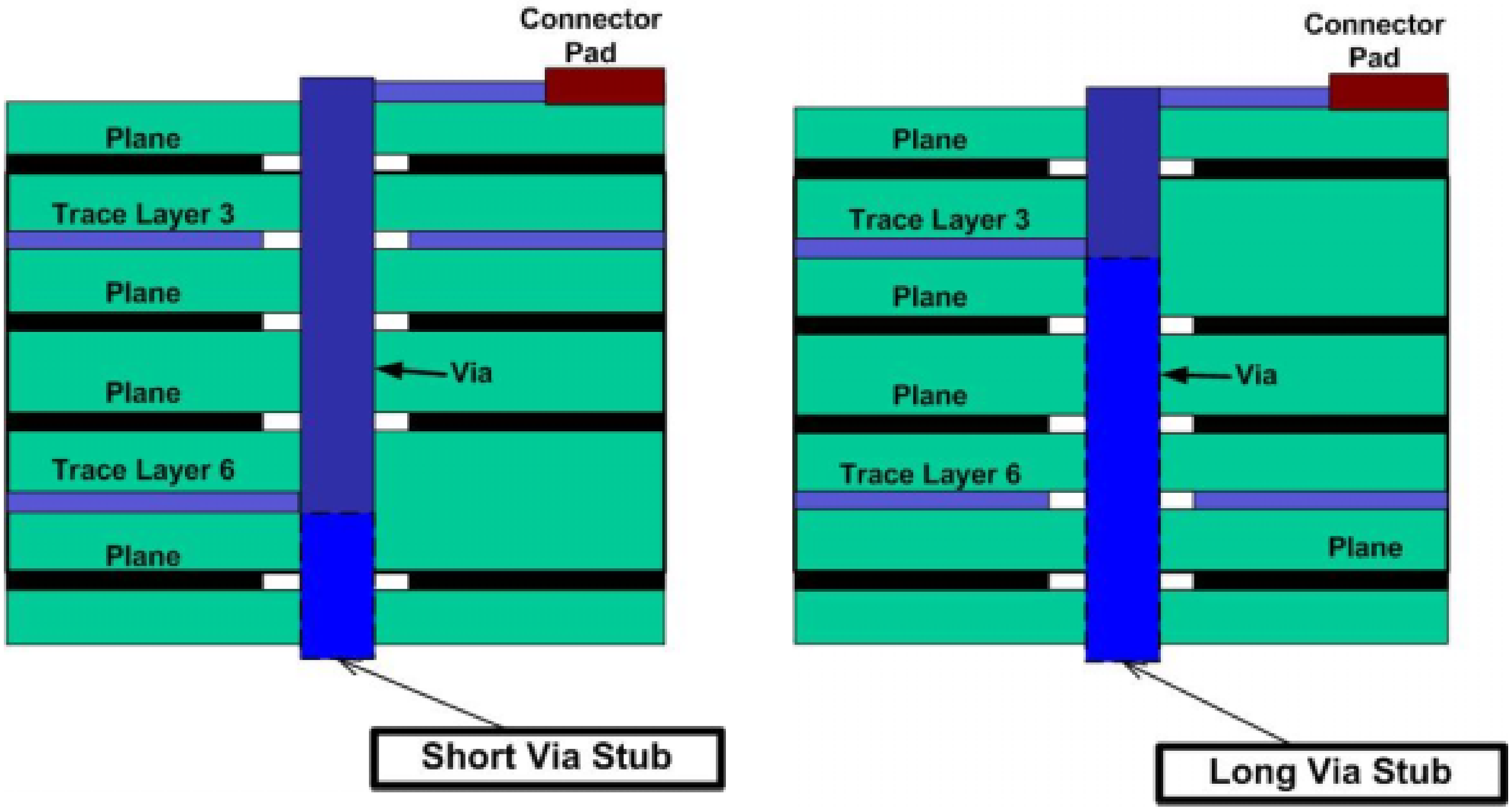
< 4% mode conversion below 5 GHz

Differential to common mode conversion loss is primarily dependent upon trace routing and breakout skew.

Non-TEM Modeling
Of Vias

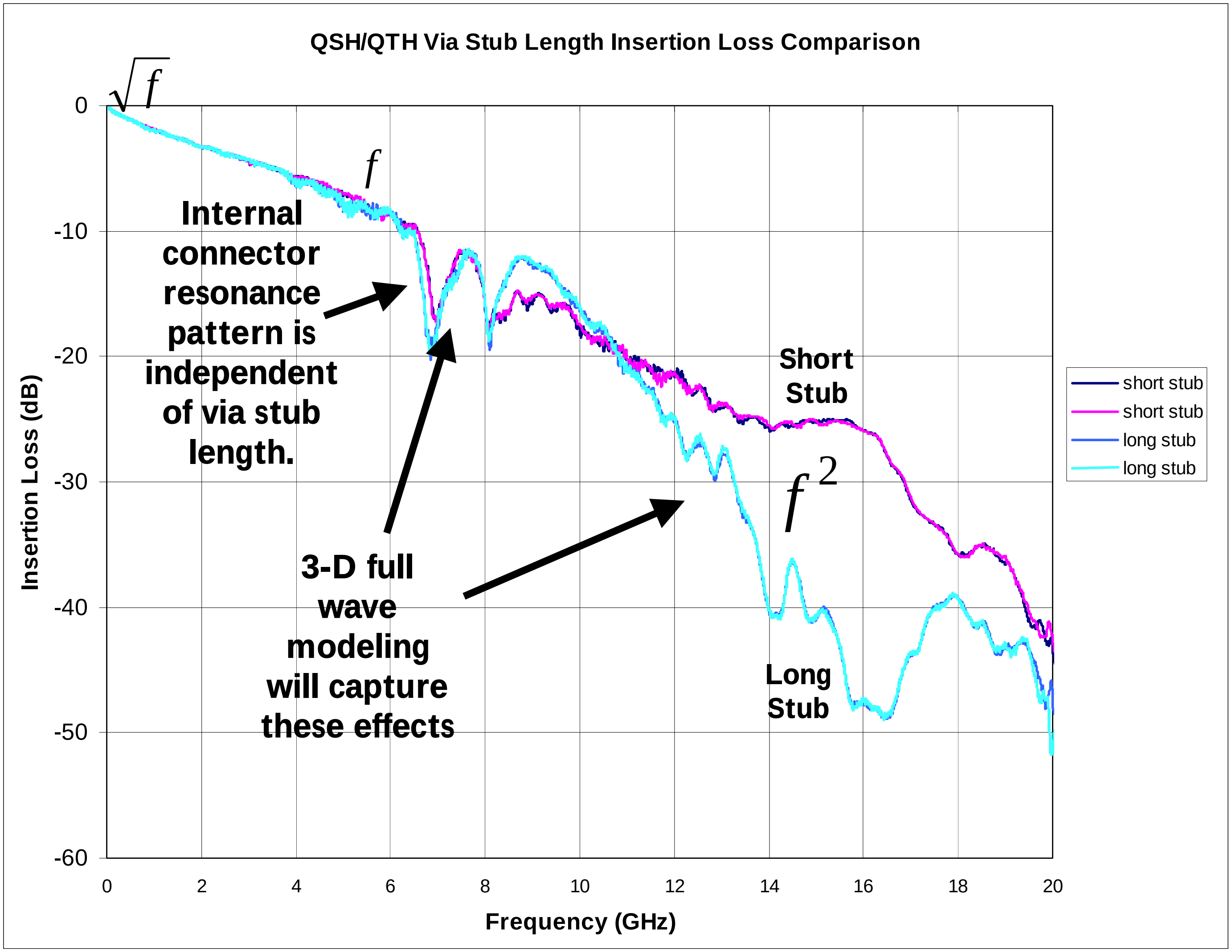
- Via structures, inherent in breakout out regions (BOR) of connector pin fields, can have a significant impact on signal quality.
  - These structures can be extracted in a complete BOR full-wave extraction.
  - The via stub effect can be easily seen through measurements, and its affect on insertion loss can be easily ascertained.
    - For thin boards (.063” for example) via stub signal degradation is generally limited to extremely high frequencies and should not be confused with other possible sources of resonance.
  - The via stub effect is the most likely cause for documents erroneously stating that trace loss follows a 2rd order polynomial curve, rather than a 1st order polynomial.
    - We have found no material loss mechanisms responsible for any loss that is proportional to f^2.
      - » Most probable cause for erroneous loss equations are quarter and half-wave resonance phenomena in structures, whether in connectors, vias, or cables.

Via Stubs


Connector Pad
Plane
Trace Layer 3
Plane
Via
Plane
Trace Layer 6
Plane
Short Via Stub
Connector Pad
Plane
Trace Layer 3
Plane
Via
Plane
Trace Layer 6
Plane
Long Via Stub

Insertion Loss of Small Connector Stubs and Vias

0.063” PCB with .010” and .050” stubs



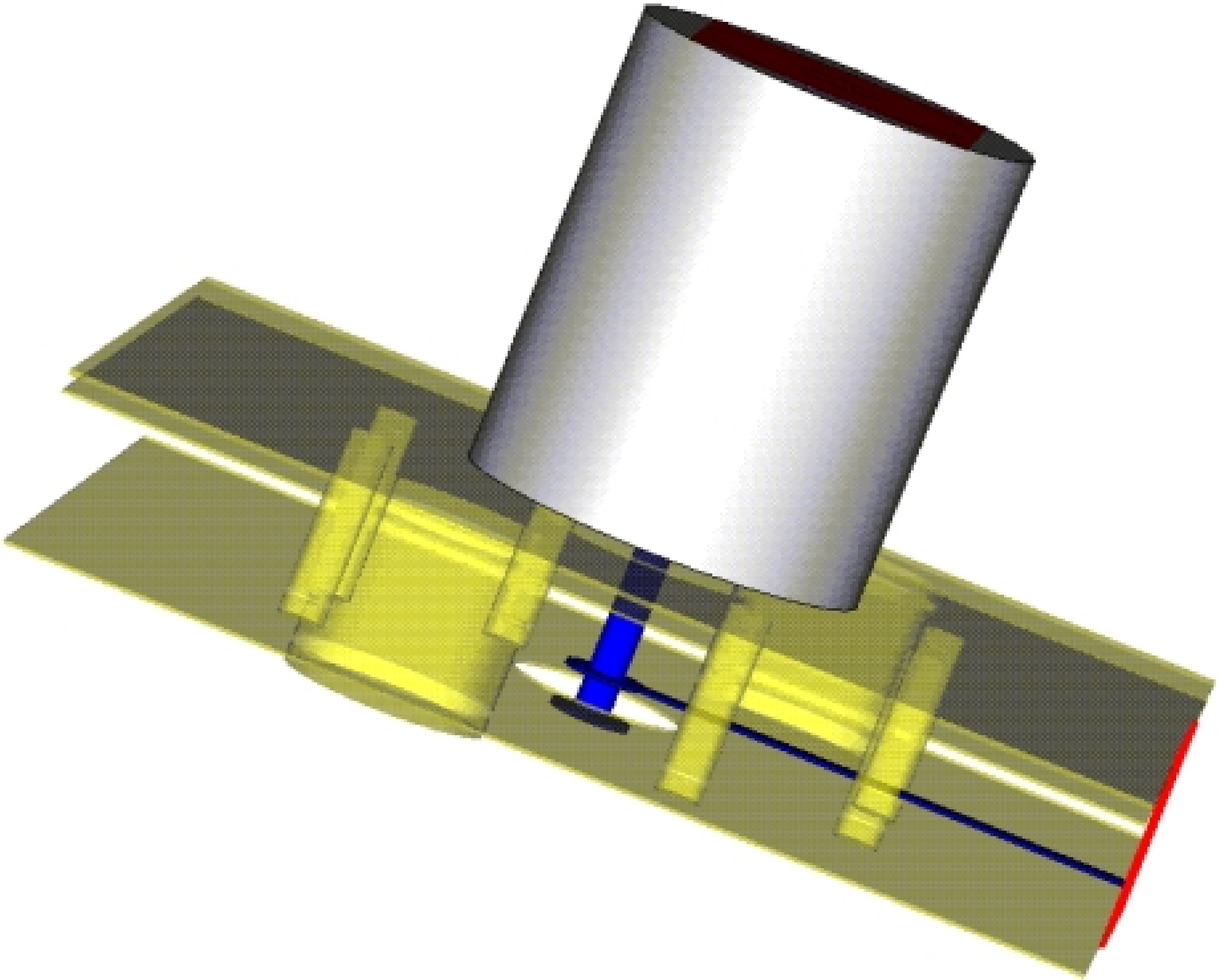
Internal connector resonance pattern is independent of via stub length.

3-D full wave modeling will capture these effects

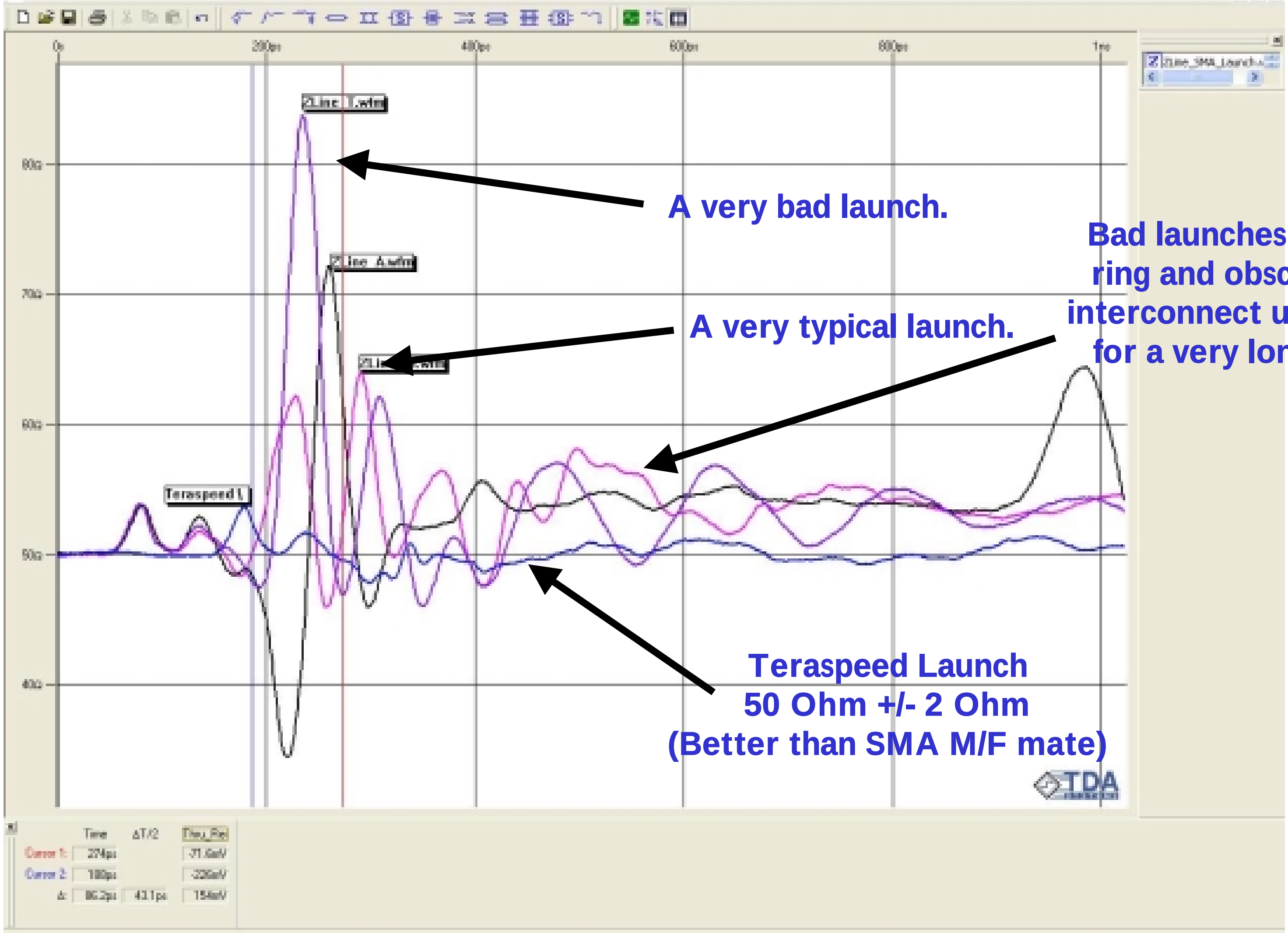
SMA Launches

- Test and evaluation boards require methods to accurately measure material and interconnect.
  - Off the shelf SMA connectors are attractive.
    - Easy to interface to.
    - Deceptively simple to place on boards.
    - But do they work well?
      - Generally the answer is no, without detailed transition development.
  - SMA connector launches are extremely complex 3-D non-TEM structures, which lend themselves to full-wave analysis and optimization.
    - If not optimized, SMAs will obscure measurement of real system performance.
      - The goal is to make the connection to instrumentation as transparent as possible.

SMA Launch



There’s No Such Thing As A Free Launch



80 Ohms

70 Ohms

60 Ohms

50 Ohms

40 Ohms

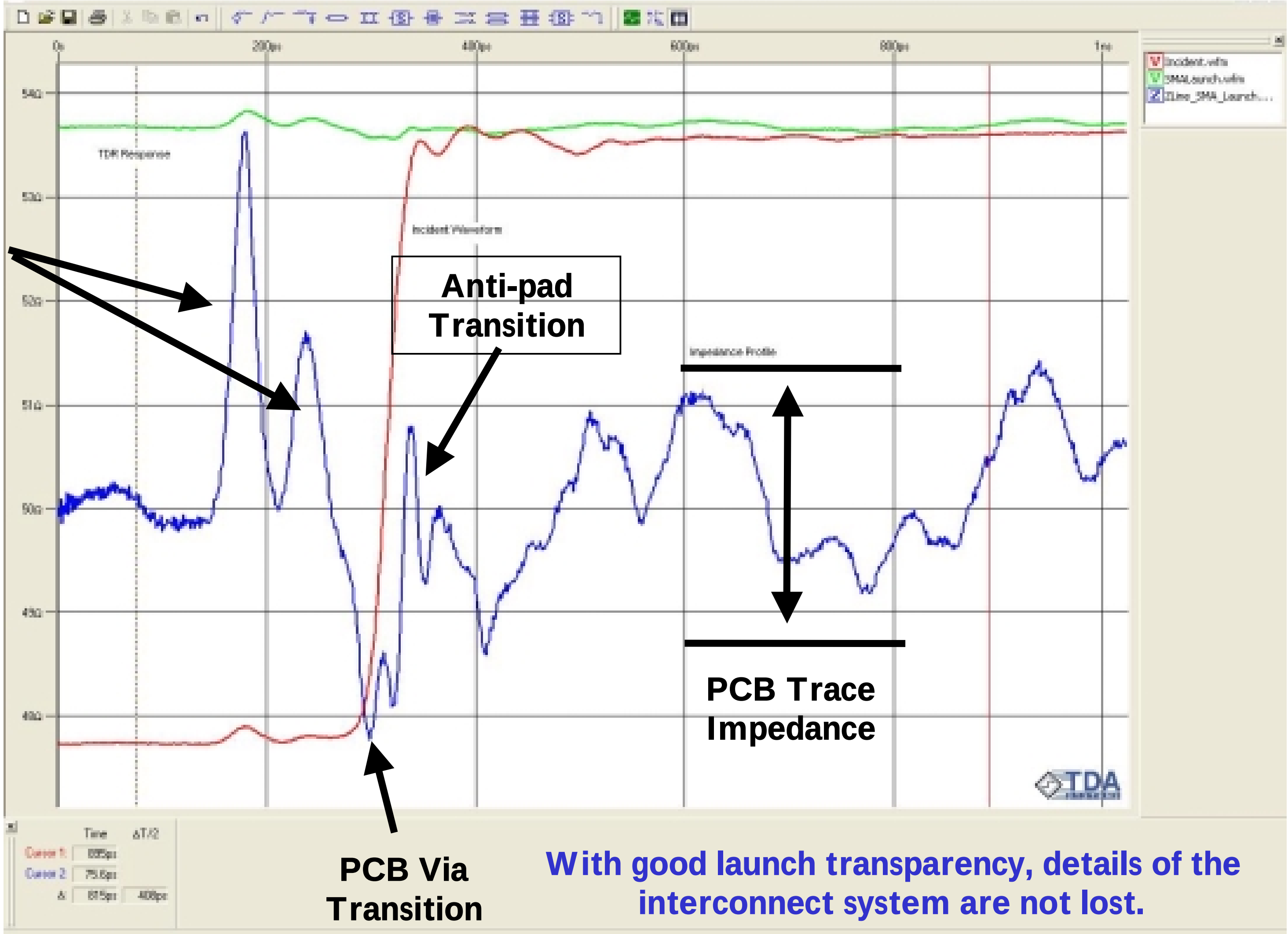
A very bad launch.

A very typical launch.

Bad launches tend to ring and obscure the interconnect under test for a very long time.

Teraspeed Launch
50 Ohm +/- 2 Ohm
(Better than SMA M/F mate)

Optimized SMA Launch



SMA M/F Connection

51 Ohms

48 Ohms

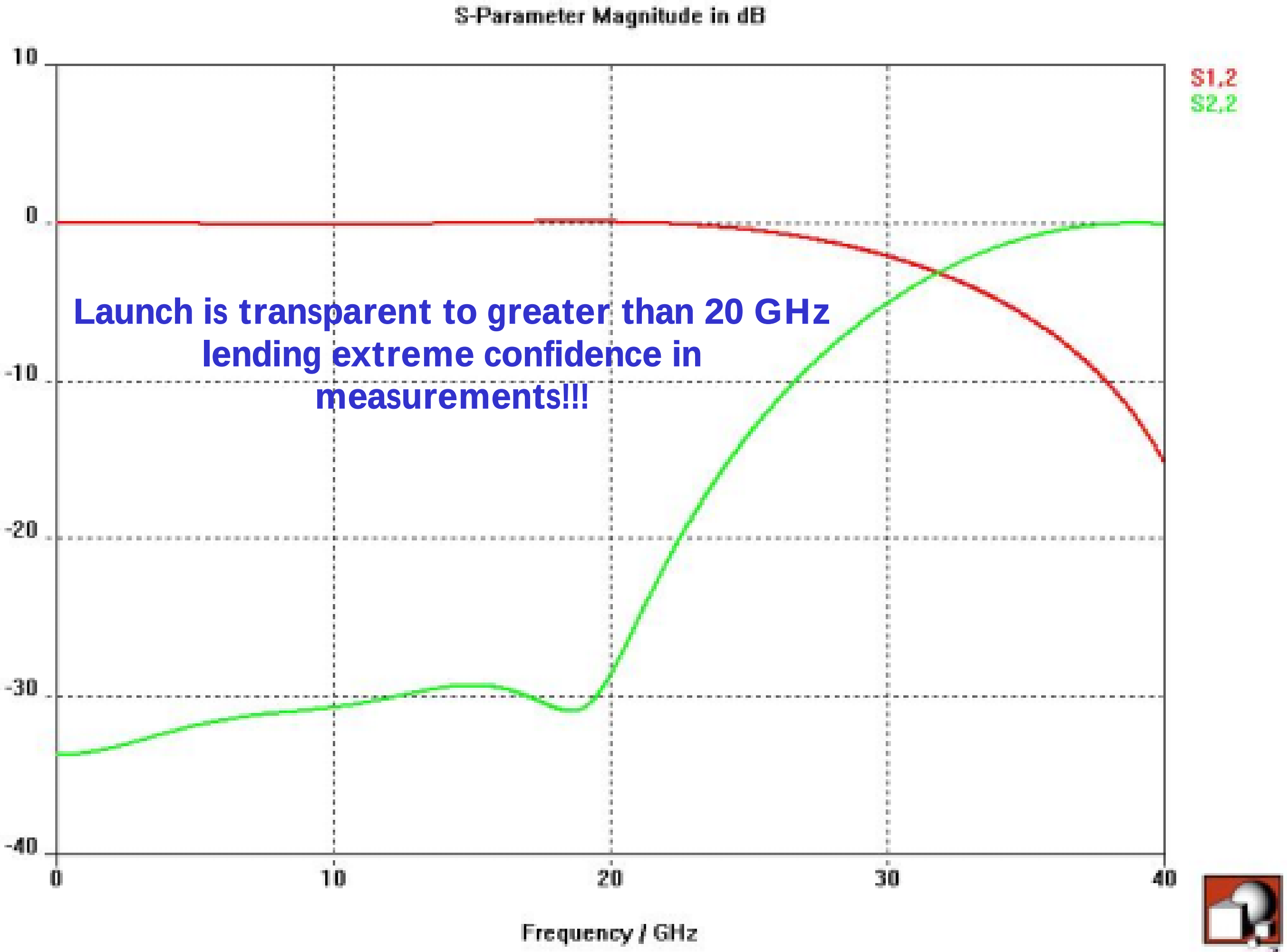
Anti-pad Transition

PCB Trace Impedance

PCB Via Transition

With good launch transparency, details of the interconnect system are not lost.

Optimized SMA Launch S-parameters



Launch is transparent to greater than 20 GHz lending extreme confidence in measurements!!!

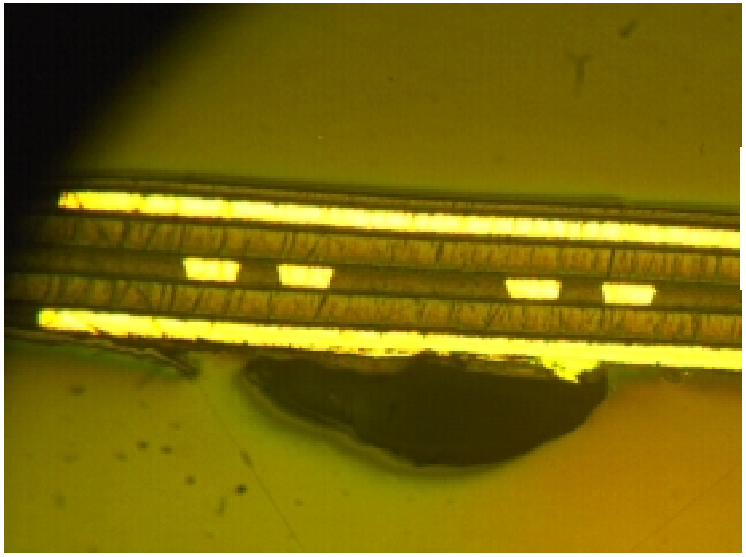
Material Characterization

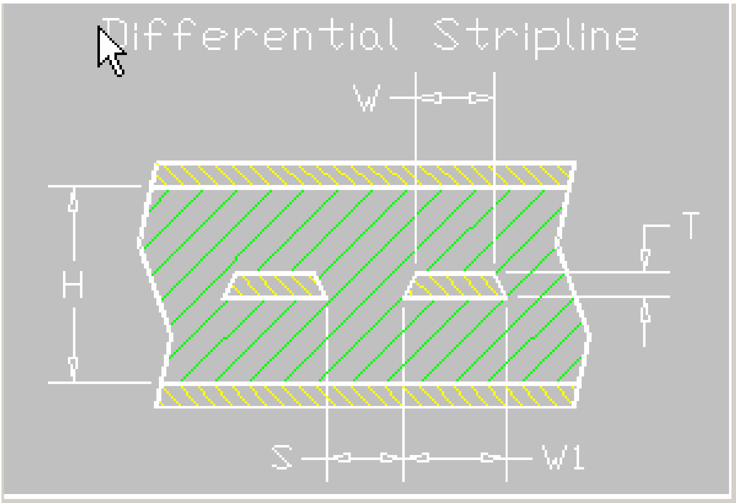
- Accurate modeling and simulation of an interconnect requires reliable modeling of materials.
  - FR4, Polyimide, BT …
  - Most materials are specified at the blazing fast frequency of 1 MHz
    - Useless for high performance modeling.
  - Methods for accurate modeling of materials vary.
    - Measurement of capacitance.
    - Measurement of perturbation of microwave cavity.
    - Measurement of resonance.
    - Measurement of delay and attenuation.
- What is the easiest and most accurate method for measurement of normal PCB and flex laminates?

IPC-TM-650 Test Methods Manual

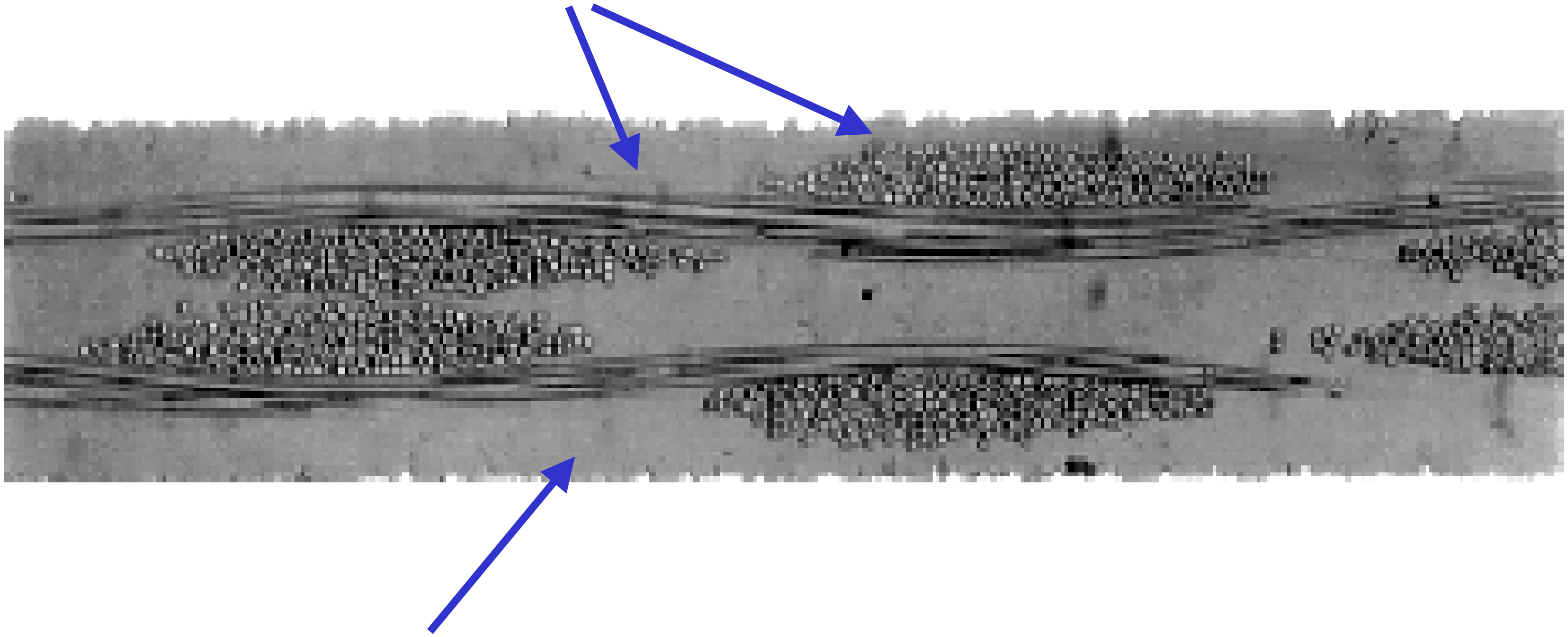
- Number 2.5.5.3, “Permittivity (Dielectric Constant and Loss Tangent (Dissipation Factor) of Materials (Two Fluid Cell Method)”
- Number 2.5.5.5.1, “Stripline Test for Complex Relative Permittivity of Circuit Board Materials to 14 GHz”
- Number 2.5.5.7, “Characteristic Impedance and Time Delay of Line on Printed Boards by TDR” describes a time domain measurement technique on a long microstrip.

Flex Material Cross Section





FR4 Material Cross Section



Fiberglass Bundles Er = 6.6

Epoxy Er 3.6

Non-homogeneous material has dielectric constant variation due to ratio of glass to epoxy

Dupont™ Pyralux® FR
Material Specifications vs. Measurement

- Specified
  - Er = 3.5 @ 1 MHz
  - Loss Tangent 0.020
- Measured
  - Effective Er ranges from 3.05 to 3.5
  - Loss Tangent .0127 to .0163
- The difference is left on the table during design modeling, simulation and design trade-off!

Trace Width Etch Factor Determination by DC Measurement

In order to accurately create models of substrate traces, it is necessary to know the actual trace width of traces produced. When cross sectional data is not readily available, a method using the ratio of DC resistances may be used within reasonable error.

$$(w_1 - x) R_1 = (w_2 - x) R_2$$

Or

$$x = (w_1 R_1 - w_2 R_2) / (R_1 - R_2)$$

Where

R_1 and R_2 = measured resistances for different widths
w_1 and w_2 = corresponding specified widths.

By utilizing several different length and width of traces on the same substrate, it is possible to determine the average trace reduction (etch factor) used during the etching process. Accurate determination of the etch factor allows for much more accurate determination of target trace widths, for impedance control and modeling purposes.

Trace Width Etch Factor Determination by DC Resistance Measurement

Drawn Design Width (mils)	**5 mil**	**10 mil**	**15 mil**
Length (inches)			
1 inch	0.15 ohms	0.06 ohms	0.04 ohms (adjusted to 0.0375 ohms)
2 inches	0.30 ohms	0.12 ohms	0.08 ohms (adjusted to 0.075 ohms)
4 inches	0.60 ohms	0.24 ohms	0.15 ohms
Calculated Etching Adjusted Widths	**3.33 mils**	**8.33 mils**	**13.33 mil**

Etch factor for this process was 1.67 mils. Longer trace lengths will allow for more accurate determination of R

Characteristic Impedance and Delay

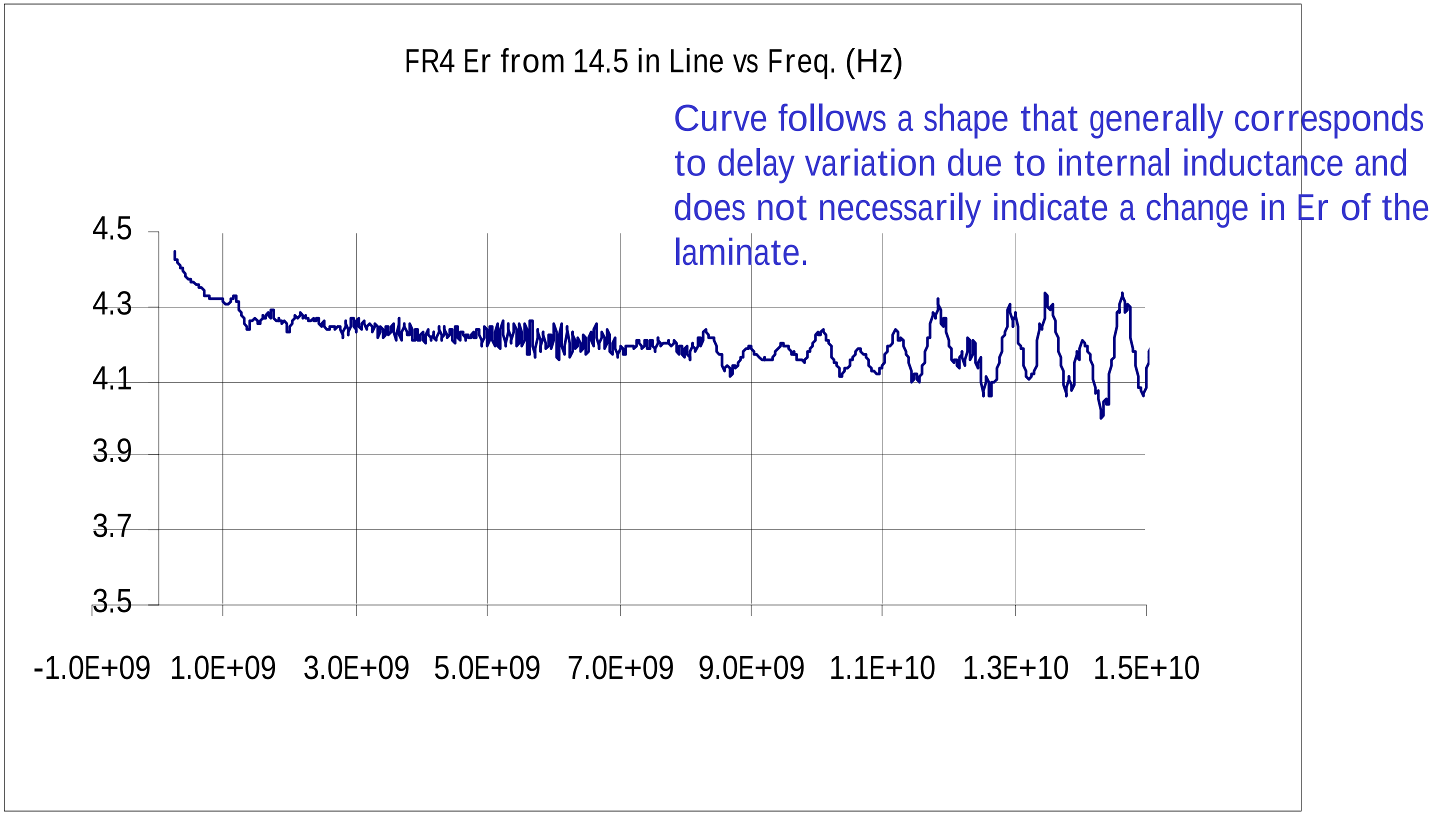
Design Width (mils)	**5 mil drawn** **3.33 mil etched**	**10 mil drawn** **8.33 mil etched**	**15 mil drawn** **13.33 mil etched**
Length (inches)			
1 inch	53.5 ohms	36.6 ohms	28.9 ohms
2 inches	53.4 ohms	36.7 ohms	29.2 ohms
4 inches	53.1 ohms	36.9 ohms	29.3 ohms
Field Solver Impedance	54.46 ohms	34.65 ohms	25.46 ohms

Error in Z with wide traces most likely due to variation in dielectric thickness. Adhesive “squish” is proportional to the area void of copper. In the area of wider or more tightly packed traces, dielectric is thicker, causing increased Z.

Effective Relative Dielectric Constant and Loss Measurement

- Two basic measurement methods were used and evaluated for dielectric constant and loss measurements.
  - Resonator method with multiple resonator types.
    - Found to be extremely sensitive but noisy.
    - Not reliable for broadband measurements and lossy substrates like Polyimide and FR4.
  - Trace delay method.
    - Found to be easy to use and accurate.
    - Will be presented here.

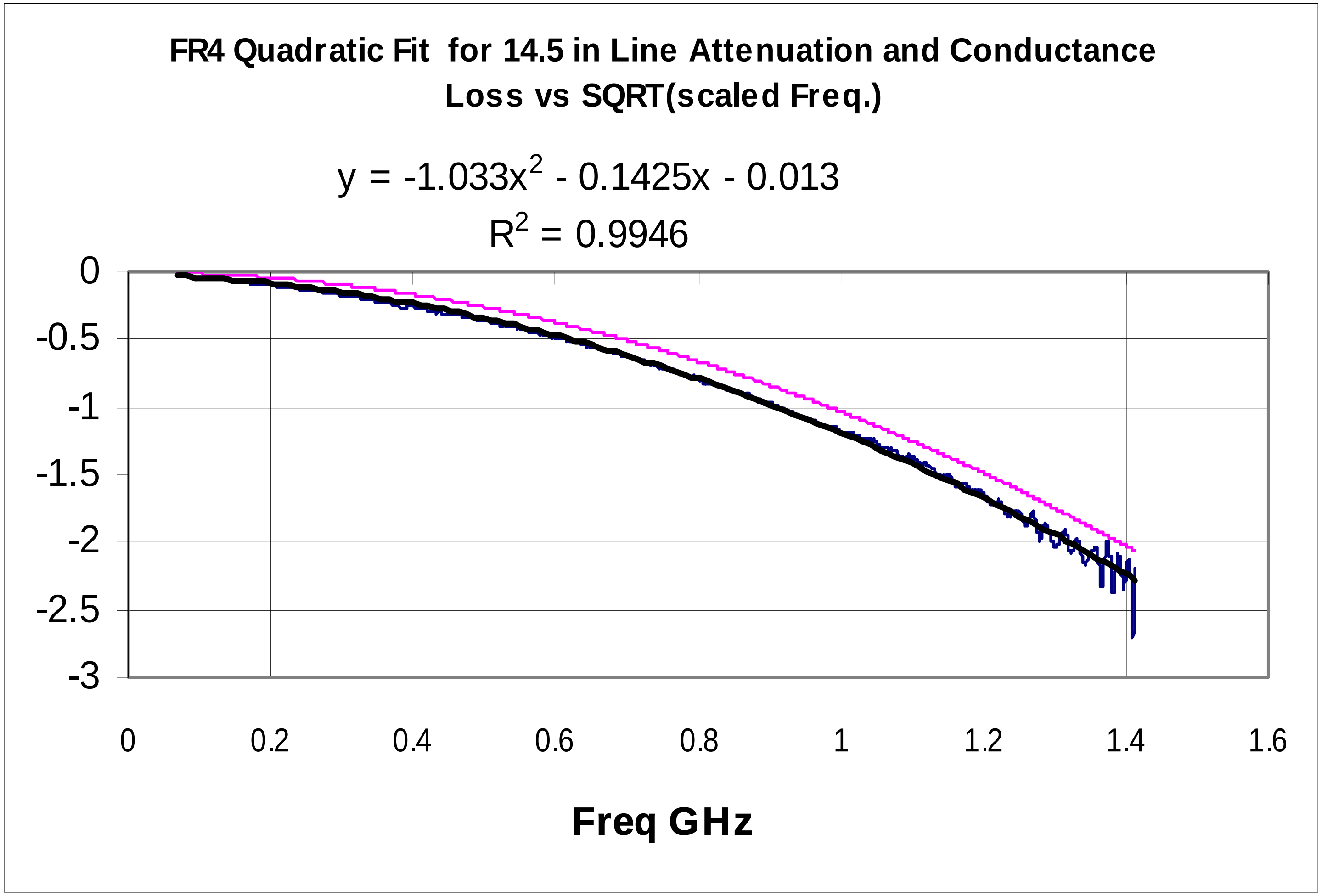
FR4 Effective Er Measurement Delay Method



Curve follows a shape that generally corresponds to delay variation due to internal inductance and does not necessarily indicate a change in Er of the laminate.

Trace delay vs. frequency is measured by de-embedding the cables and SMAs with a VNA but does not measure Er directly. Trace delay is a function of Er and a function of the internal inductance of the conductors. Thus we call this the effective relative dielectric constant.

FR4 Quadratic Fit Loss Extraction



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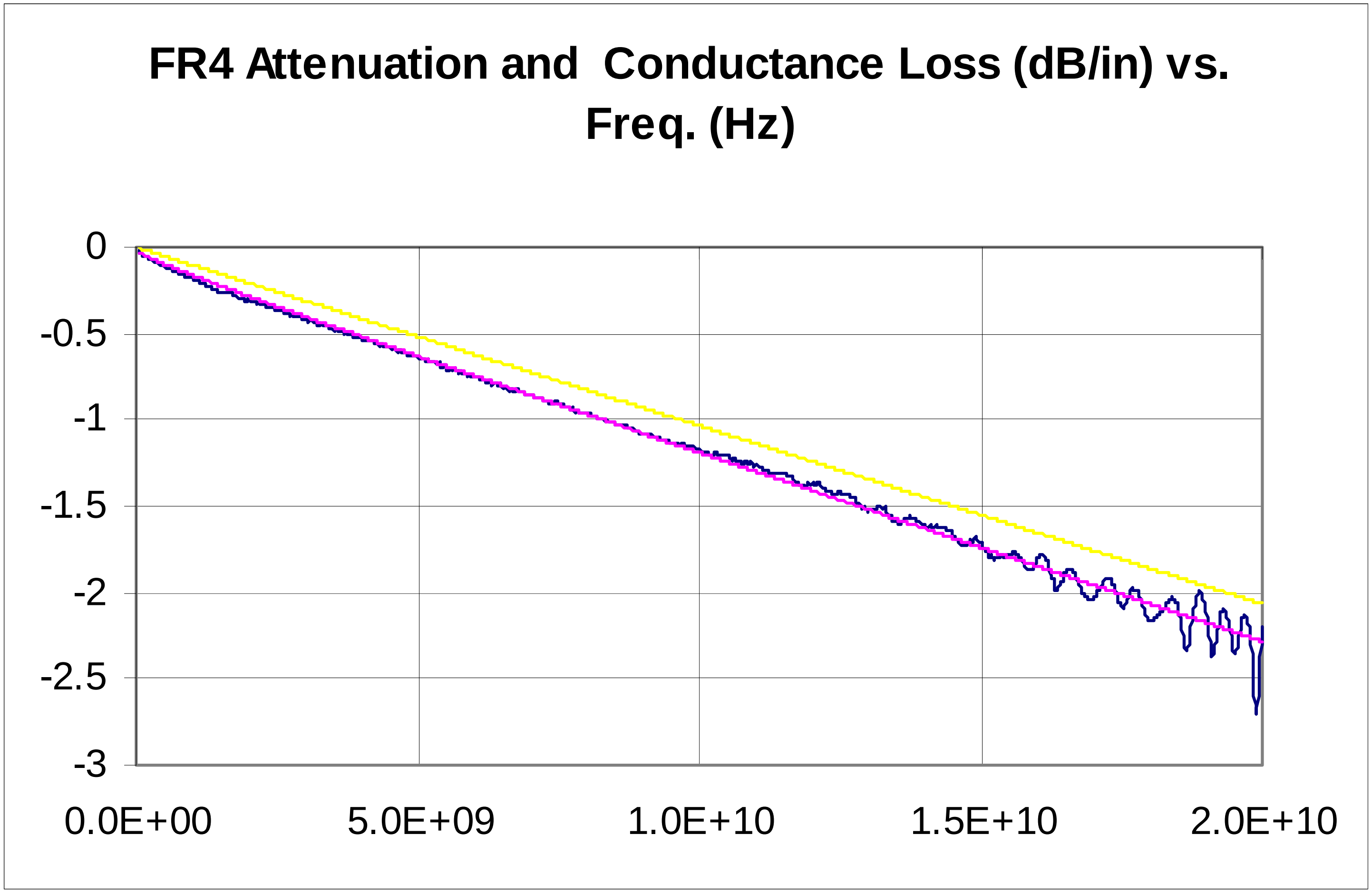
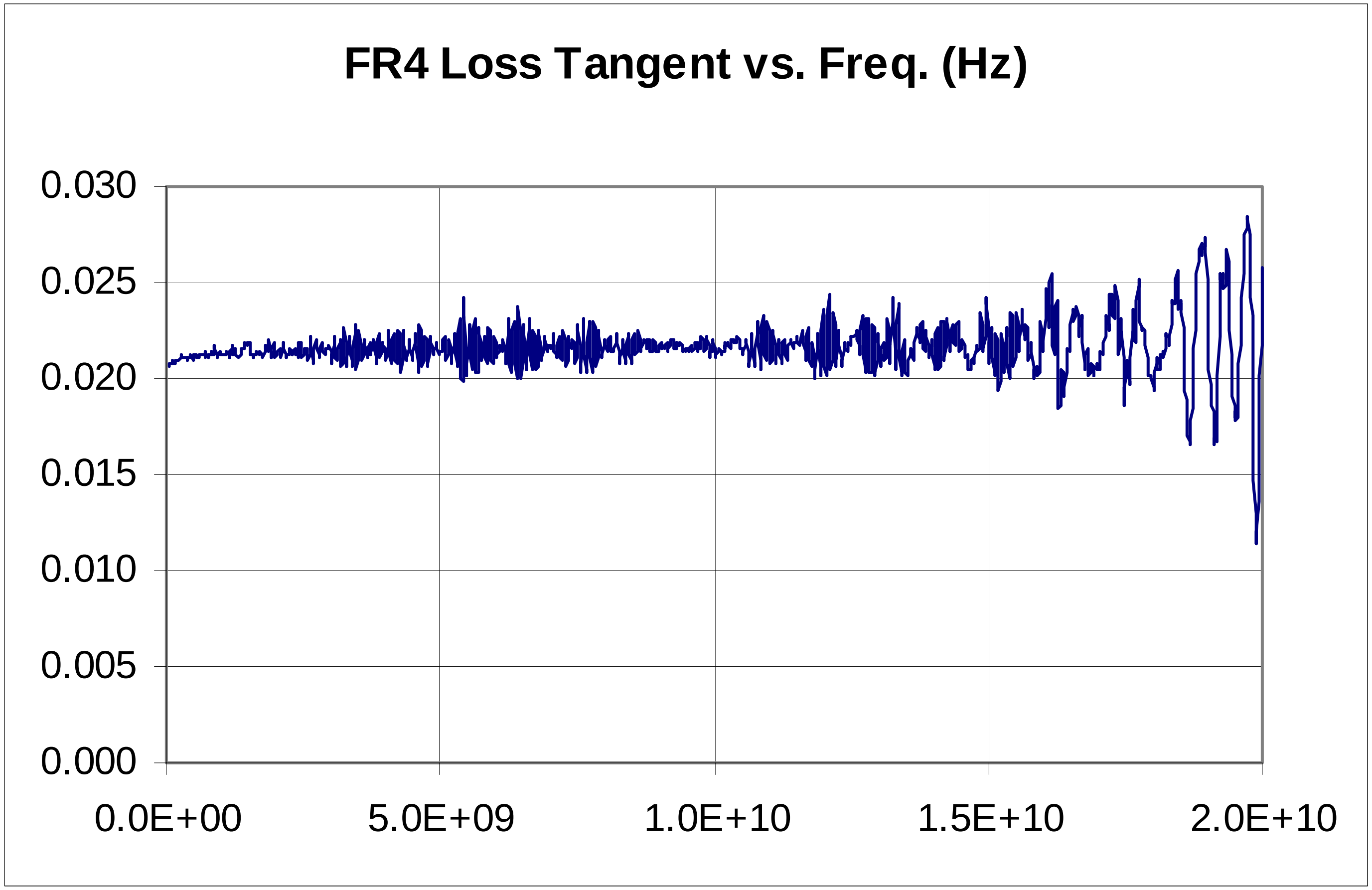
FR4 Total Attenuation & Conductance Loss (dB/in.) vs. Freq. (Hz)



FR4 Loss Tangent vs. Freq. (Hz)



Time and Frequency Domain Transformation

Fourier Transform

$$F(j\omega)=\int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt$$

The value of $f(t)$ at each instance in time has implications for all frequencies.

The value of $F\ (j\omega)$ at each instance in time has implications for all frequencies.

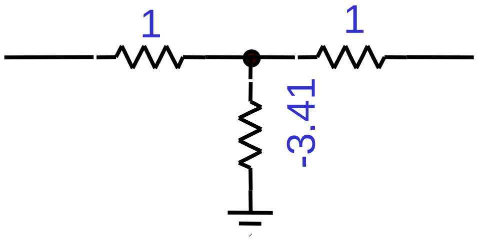
Inverse Fourier Transform

$$f(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty} F(j\omega)e^{j\omega t}d\omega$$

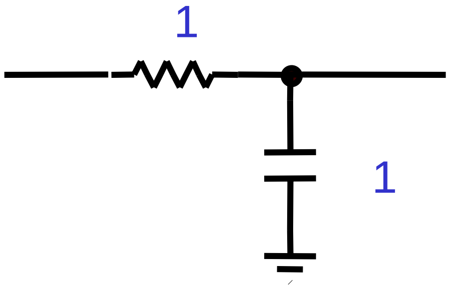
Passivity

$$S = \begin{bmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix}$$

$$Z = \begin{bmatrix} \frac{-1}{\sqrt{2}-1} & \frac{-\sqrt{2}}{\sqrt{2}-1} \\ \frac{-\sqrt{2}}{\sqrt{2}-1} & \frac{-1}{\sqrt{2}-1} \end{bmatrix} = \begin{bmatrix} -2.414 & -3.414 \\ -3.414 & -2.414 \end{bmatrix}$$



Passivity



$$Z = \begin{bmatrix} 1+j & -j \\ -j & j \end{bmatrix}$$

$$S = \frac{1}{13}\begin{bmatrix} 3+2j & -6-4j \\ -6-4j & -1+8j \end{bmatrix}$$

Passivity

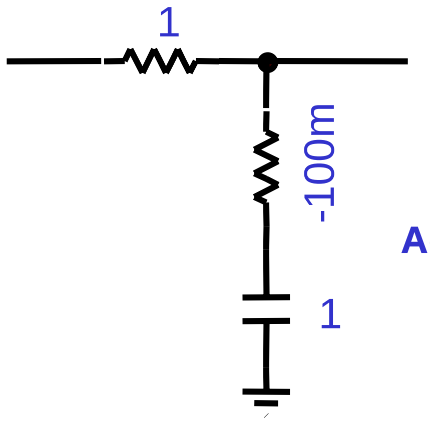
$$S = \frac{1}{13}\begin{bmatrix} 3+2j & -6-4j \\ -6-4j & -1+8j \end{bmatrix}$$

Original S-parameters

$$S_{error} = \frac{1}{13}\begin{bmatrix} 2.9+1.8j & -5.9-3.6j \\ -5.9-3.6j & -1.2+7.3j \end{bmatrix}$$

Measurement or Extraction Error

$$Z = \begin{bmatrix} 1.1+j & -0.1-j \\ -0.1-j & 0.1+j \end{bmatrix}$$



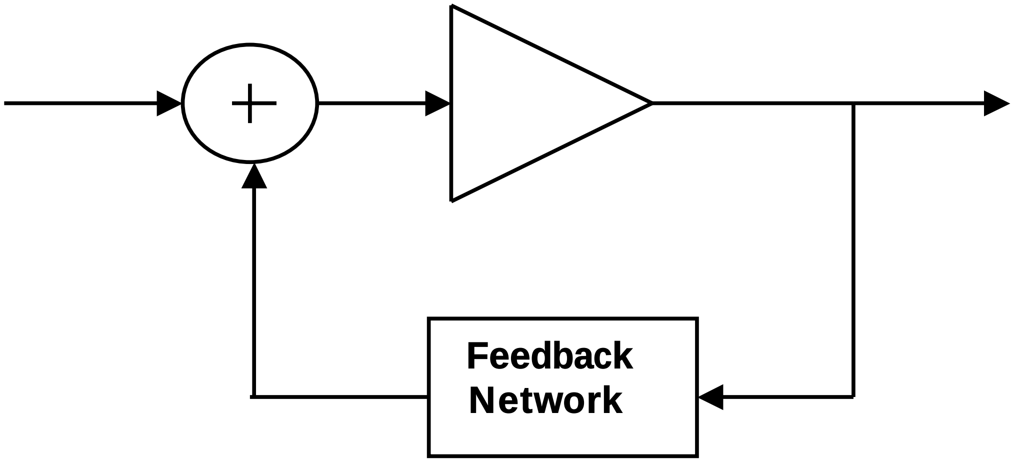
Active Circuit

Formal Condition for Passivity

$$I - S * S'$$

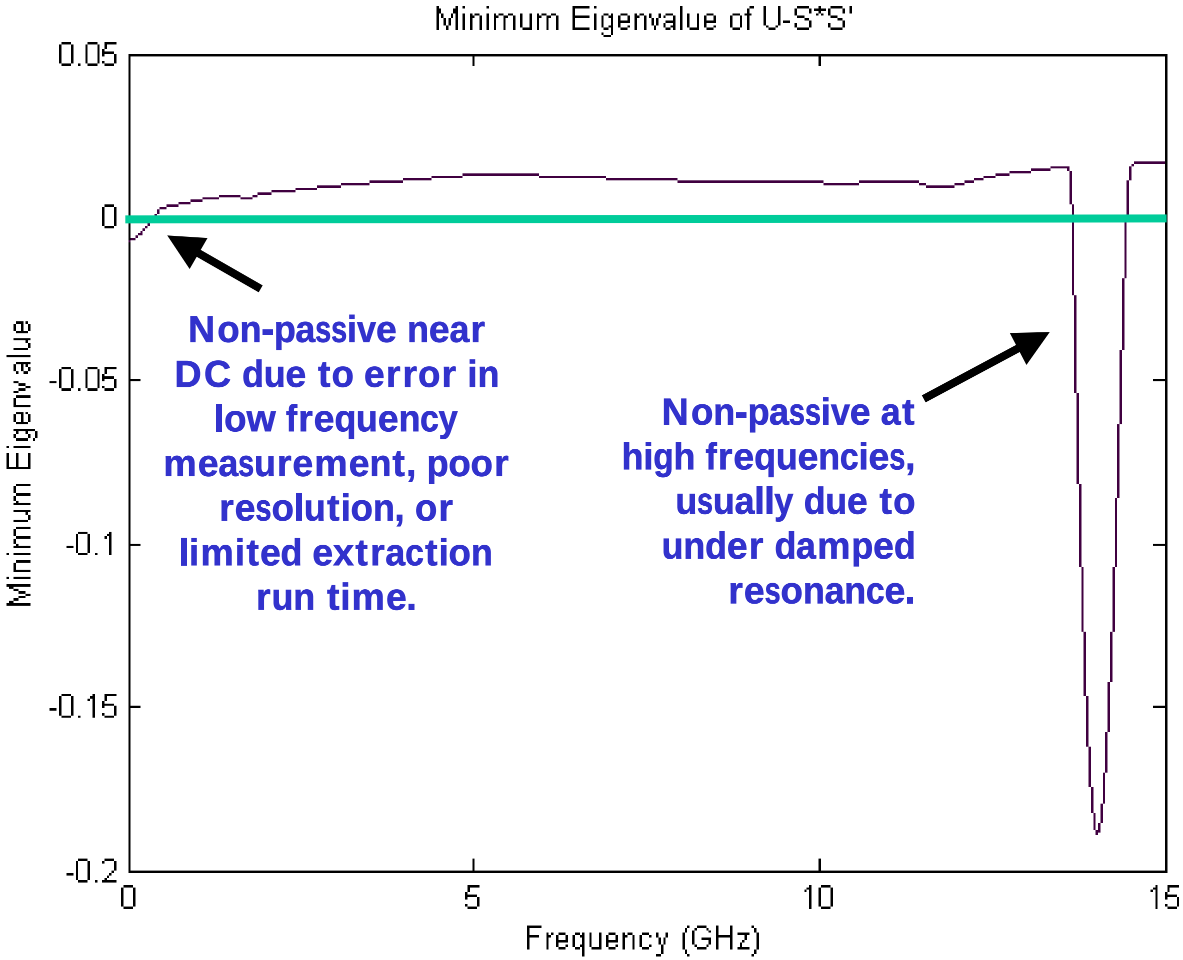
Has Eigenvalues
with non-negative
real parts

Simple Linear Network Model of Simulation Stability



Oscillation in simulation occurs whenever loop gain is greater than one. (negative eigenmodes)

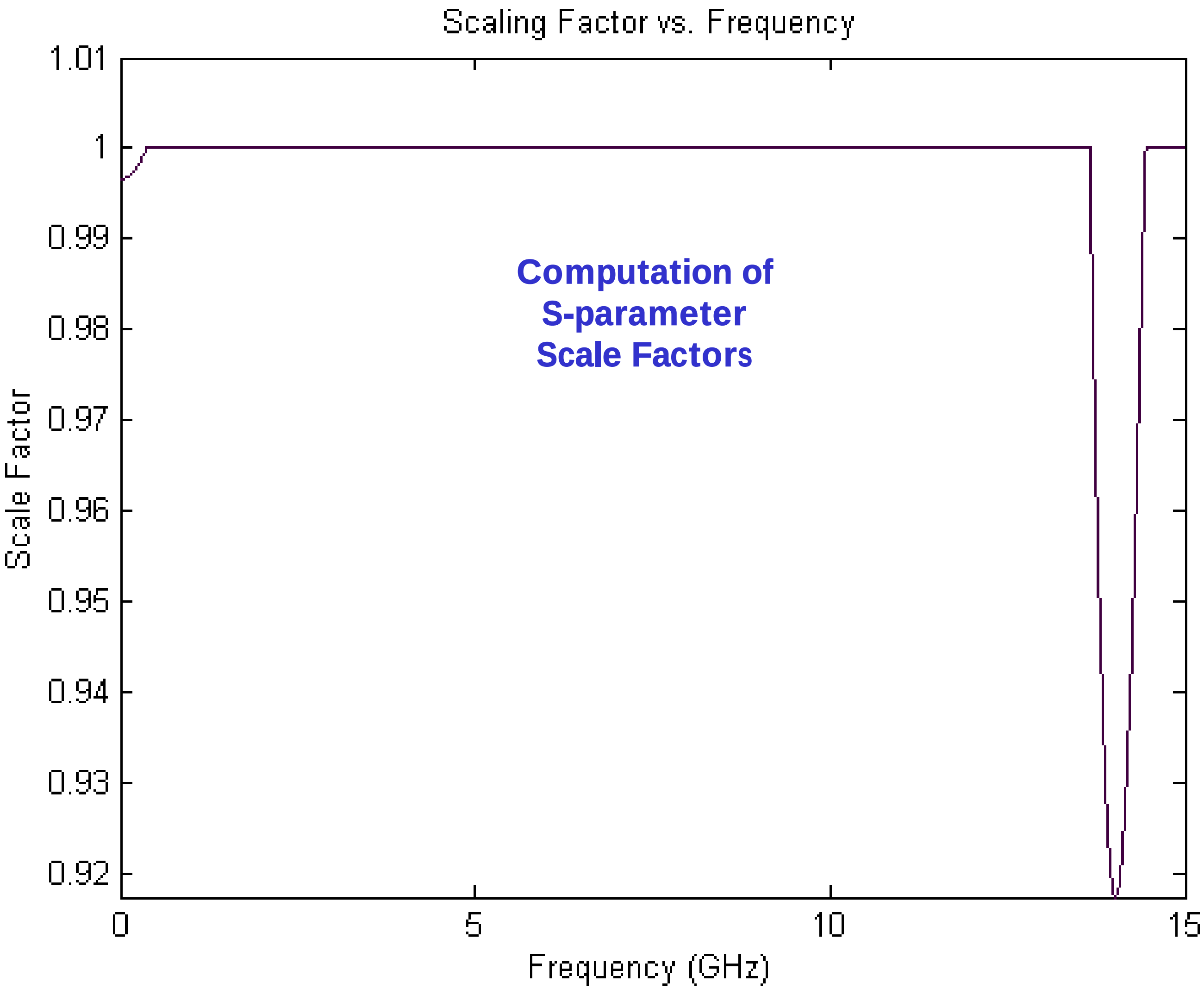
Eigenvalue Display



Non-passive near DC due to error in low frequency measurement, poor resolution, or limited extraction run time.

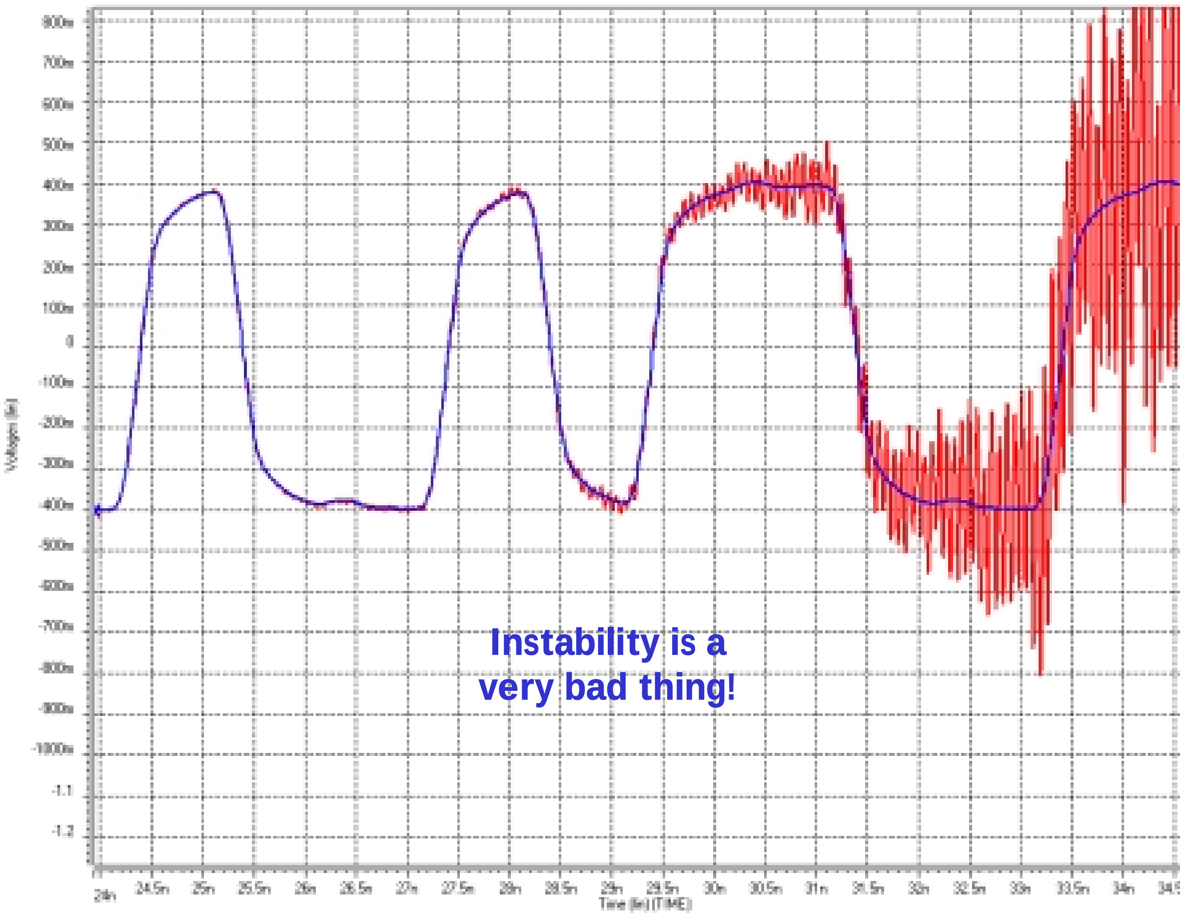
Non-passive at high frequencies, usually due to under damped resonance.

S-parameter Scaling



Computation of S-parameter Scale Factors

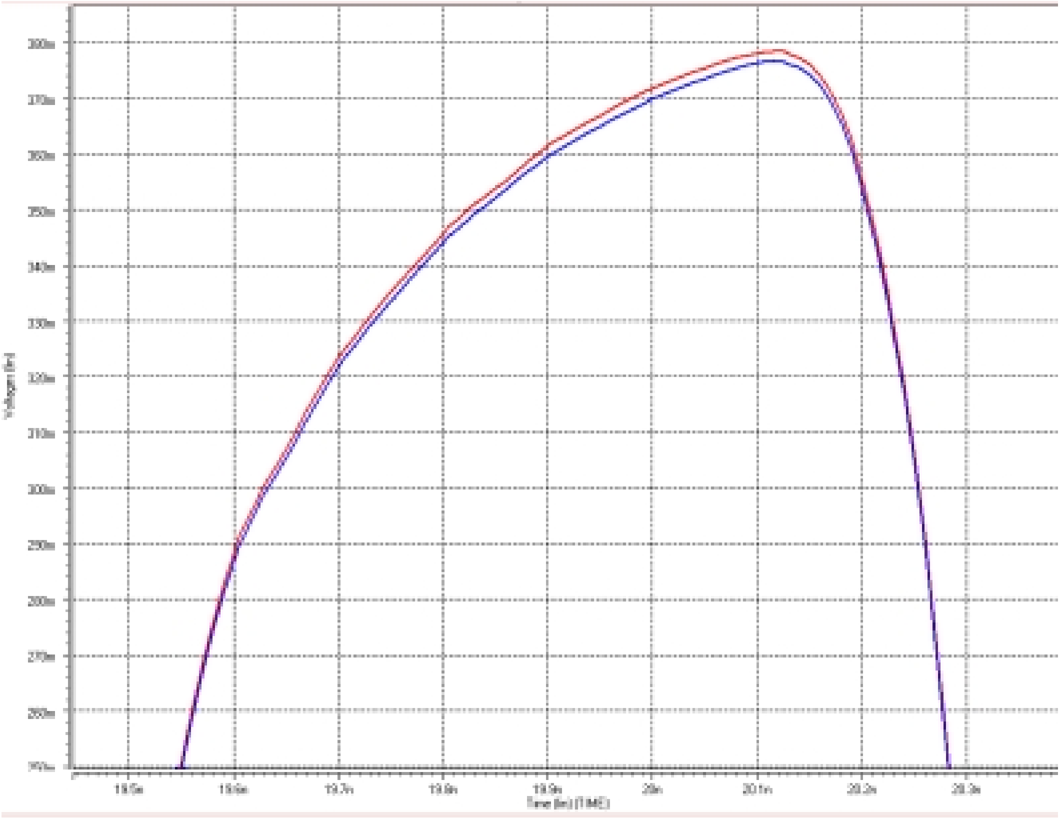
Simulation of Original vs. Passivity Corrected and Nudged Model



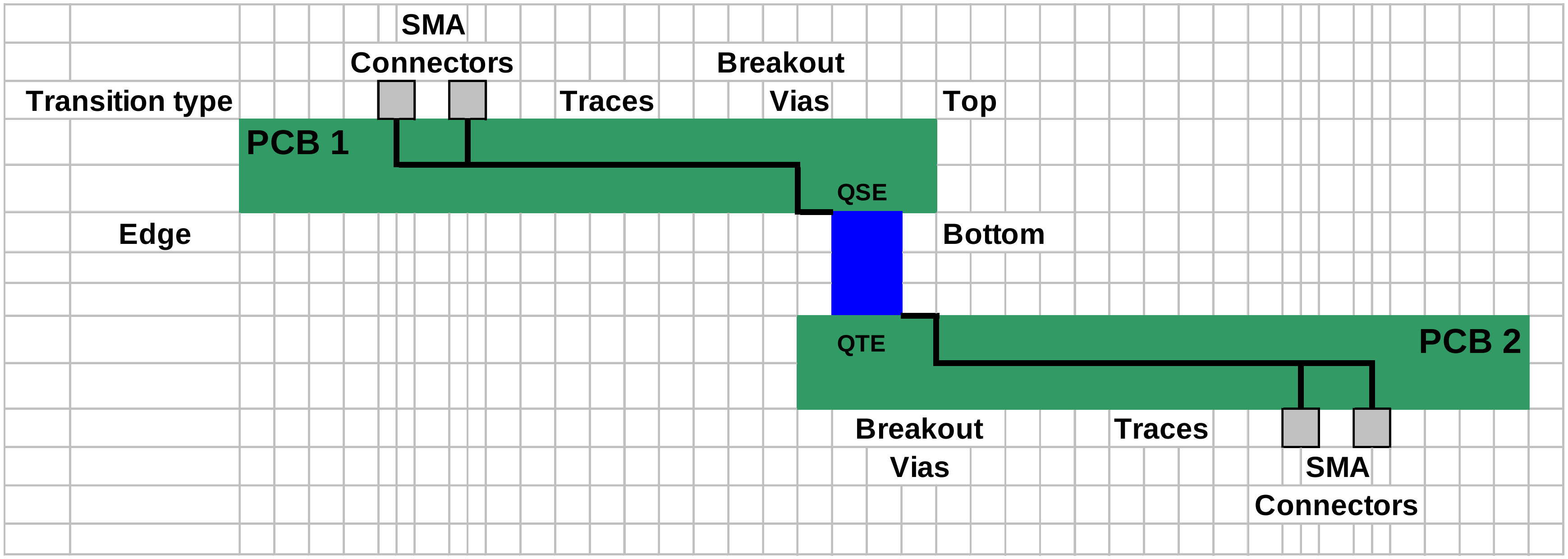
Instability is a very bad thing!

Simulation of Original vs. Passivity Corrected and Nudged Model

Simulation of Original vs. Passivity Corrected and Nudged Model



Putting the Final Inch^{TM} Together

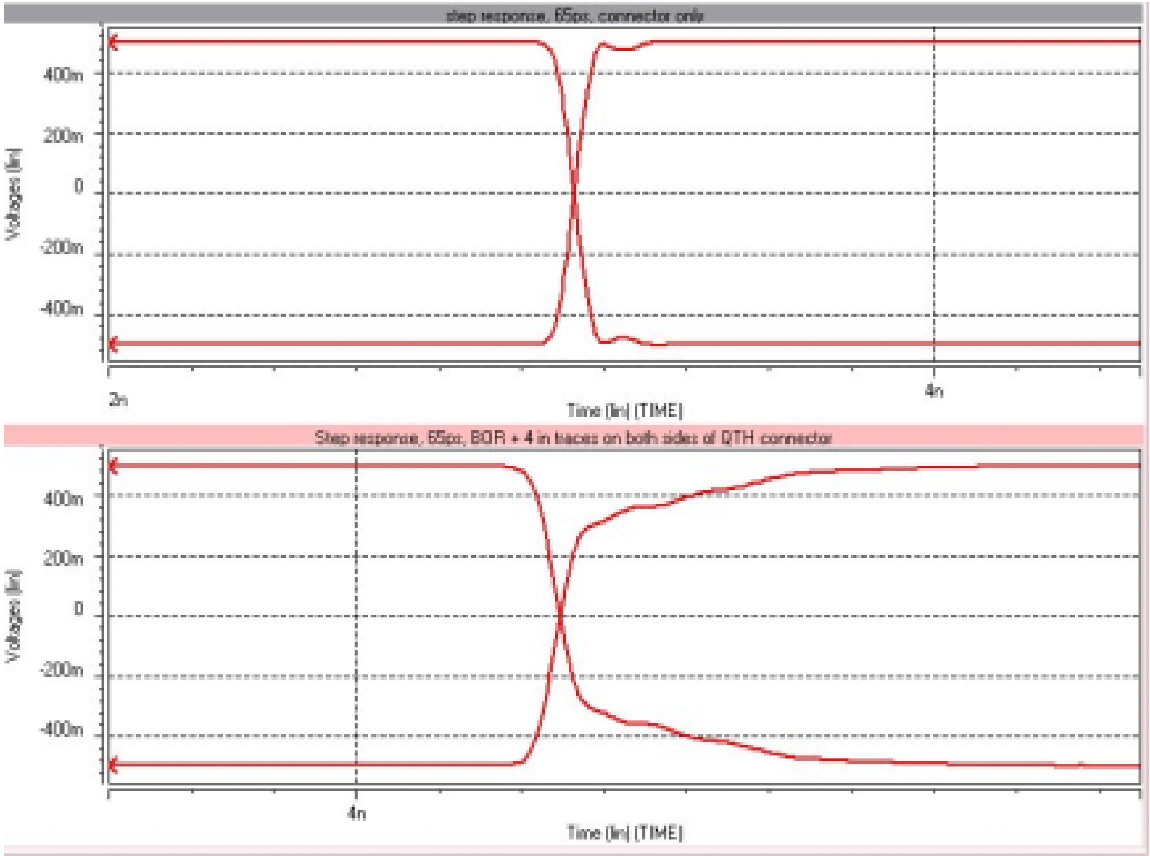


Final Inch^{TM} test and simulation environment

QTE/QSE Final Inch^{TM} Connector Only vs. Connector + BOR

Connector only

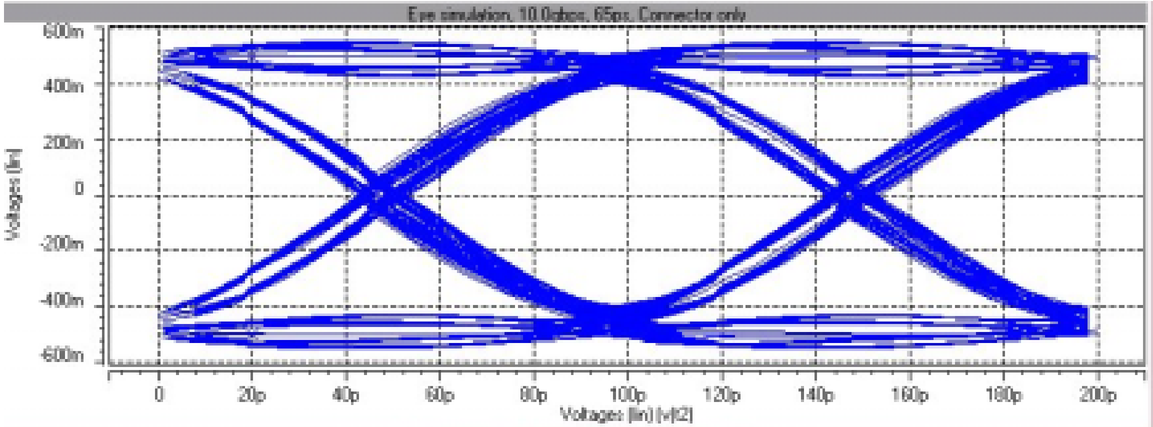
Connector + BOR



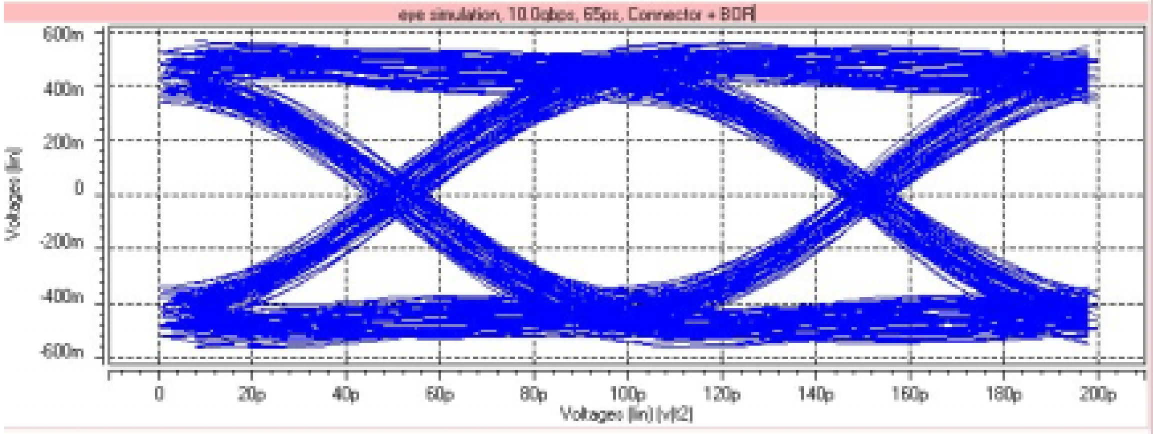
Pulse Response

QTE/QSE Final Inch^{TM} Connector Only vs. Connector + BOR

Connector only



Connector + BOR

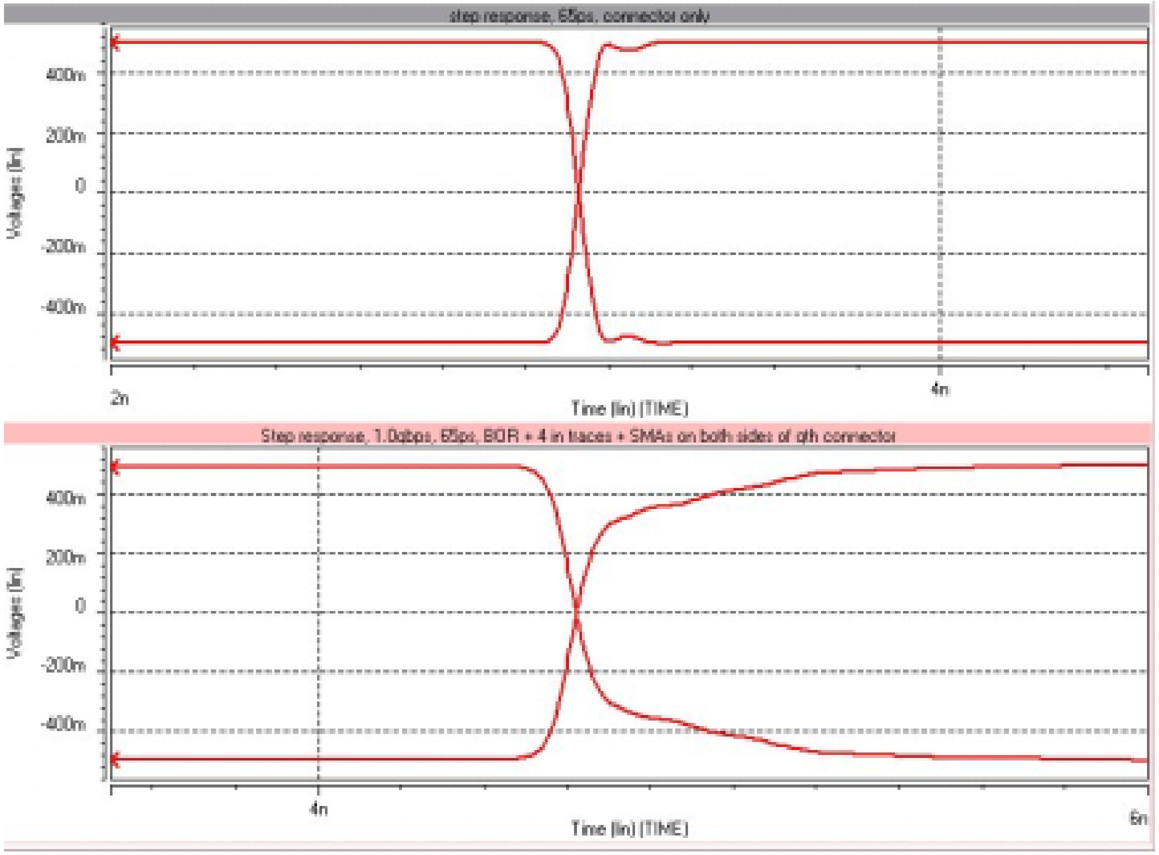


10 Gbps

QTE/QSE Final InchTM Connector Only vs. Connector + BOR + 8” Total Trace Length

Connector only

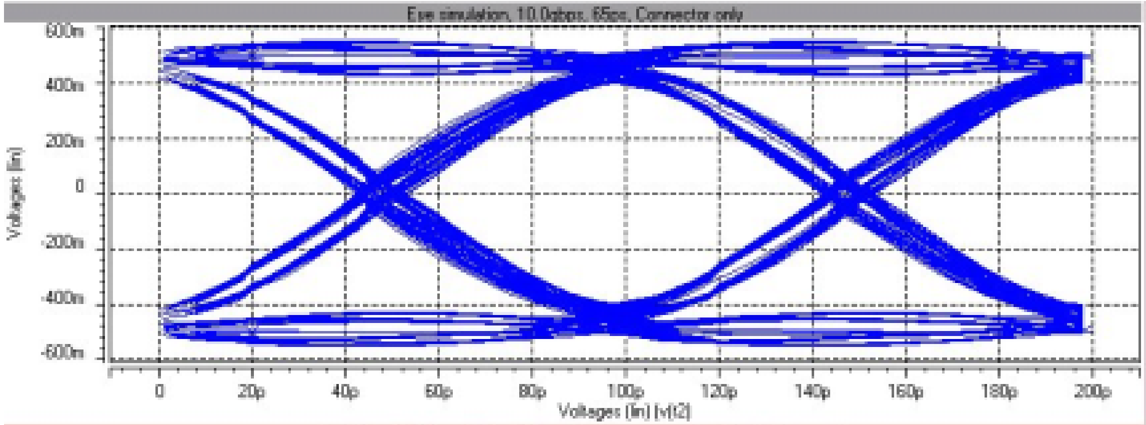
Connector + BOR + 8” Trace



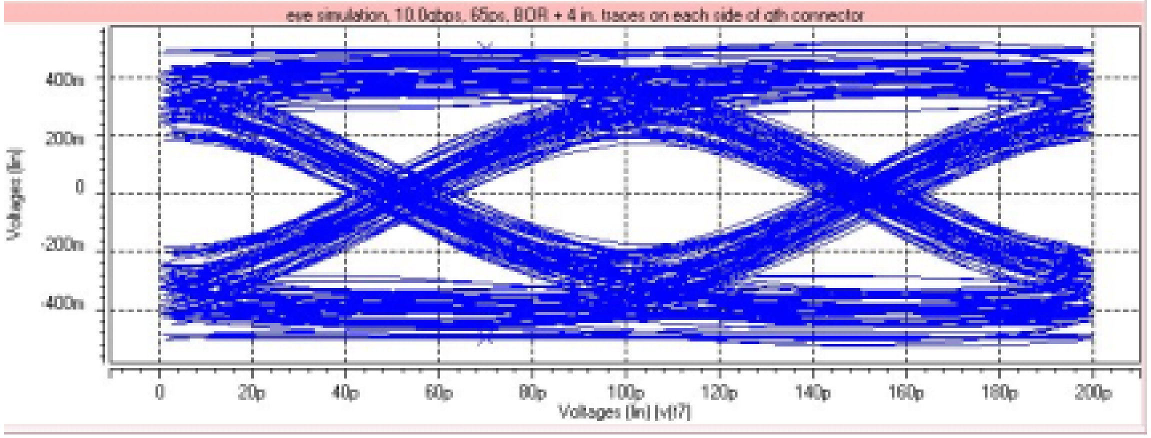
Pulse Response

QTE/QSE Final Inch™ Connector Only vs. Connector + BOR + 8” Total Trace Length

Connector only



Connector + BOR + 8” Trace



10 Gbps

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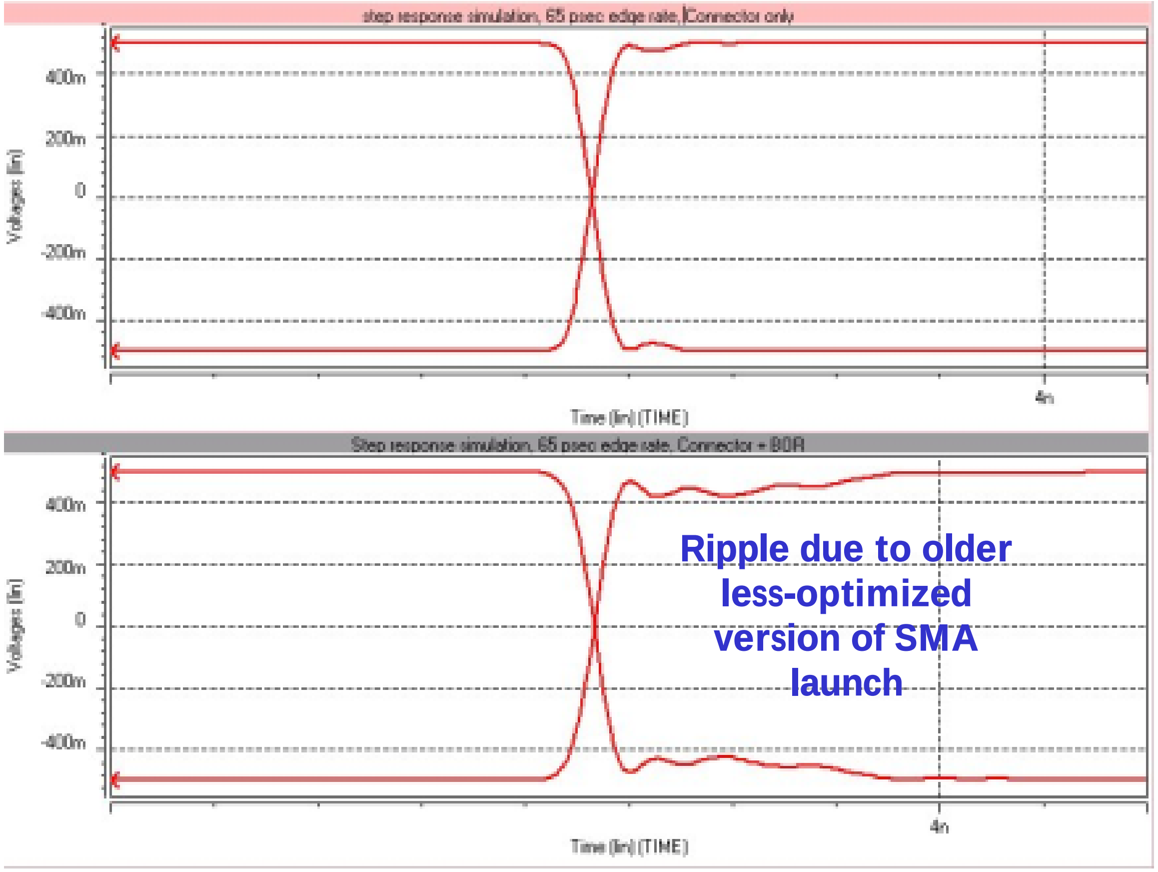
QTE/QSE Final Inch™ Connector Only vs. Connector + BOR + 8” Total Trace Length + SMAs

Connector only

Connector + BOR + 8” Trace + SMAs

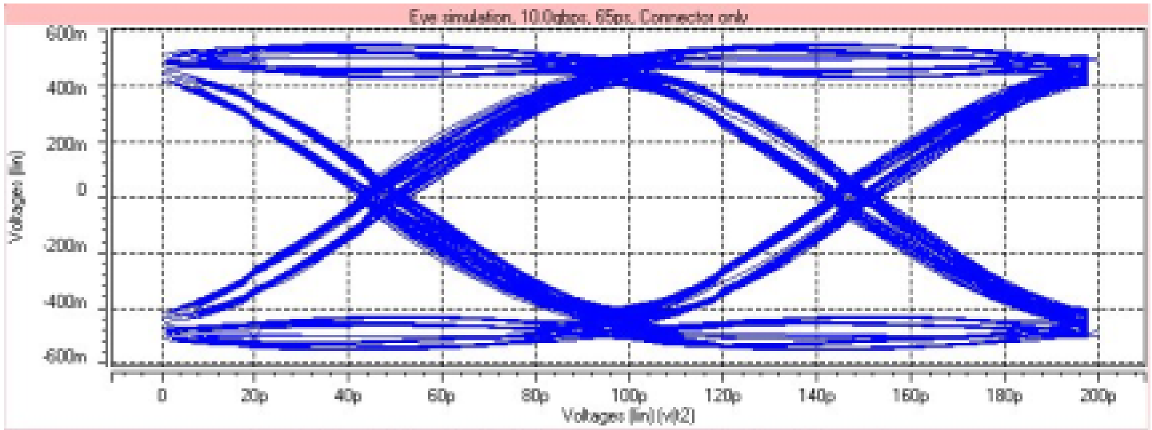


Ripple due to older less-optimized version of SMA launch

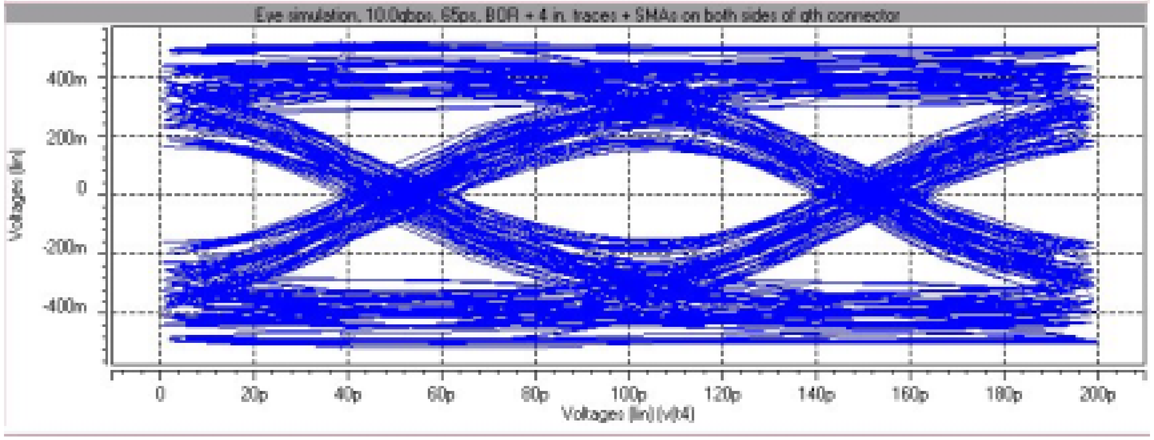
Pulse Response

QTE/QSE Final Inch™ Connector Only vs. Connector + BOR + 8” Total Trace Length + SMAs

Connector only



Connector + BOR + 8” Trace + SMAs

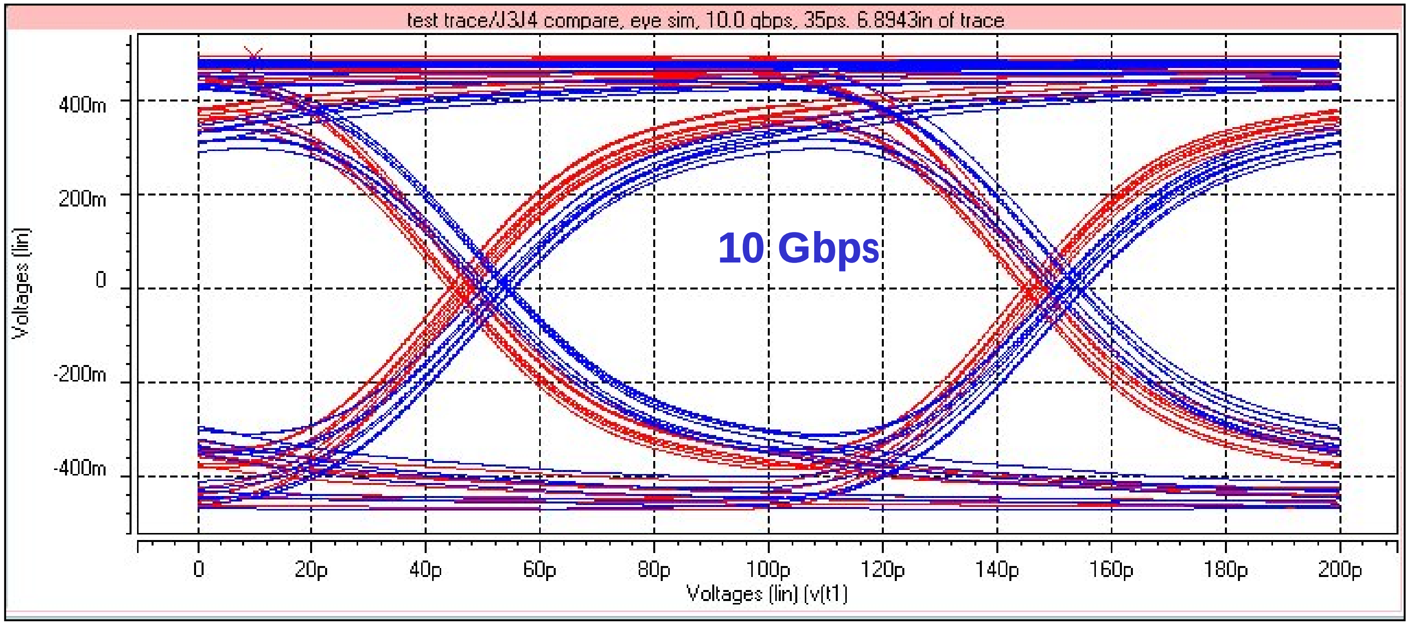


10 Gbps

QTE/QSE Final Inch™
Field Solver Modeled vs. VNA Measured Model Simulation of a Trace

Red – Field solver modeled

Blue – VNA measurement based model

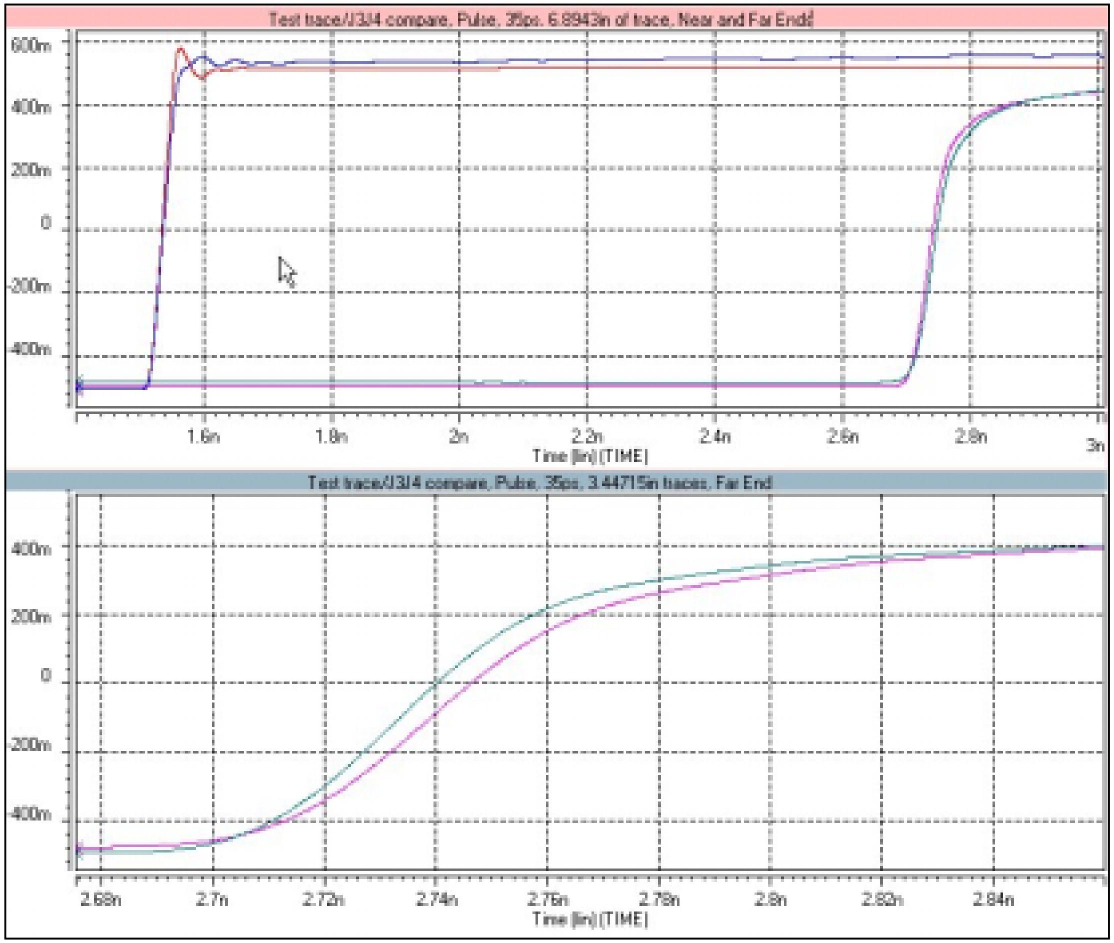


QTE/QSE Final Inch™ Field Solver Modeled vs. VNA Measured Model Simulation of a Trace

Red – Field solver modeled

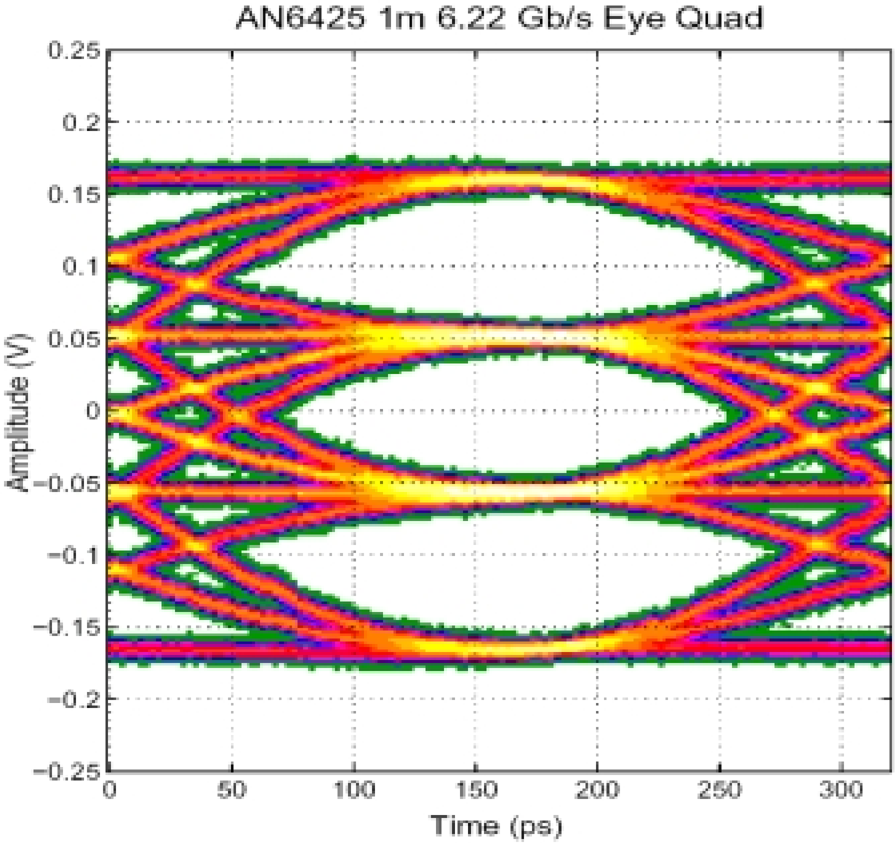
Blue – VNA measurement based model

Total delay error less than 0.6%



Note slightly different trace impedance. Complete system sensitivity studies can be performed with multiple trace trace models at various impedances.

QTE/QSE Final Inch™ and 1-Meter EQCD Coax, with Accelerant Networks AN6425 PAM-4 Serdes

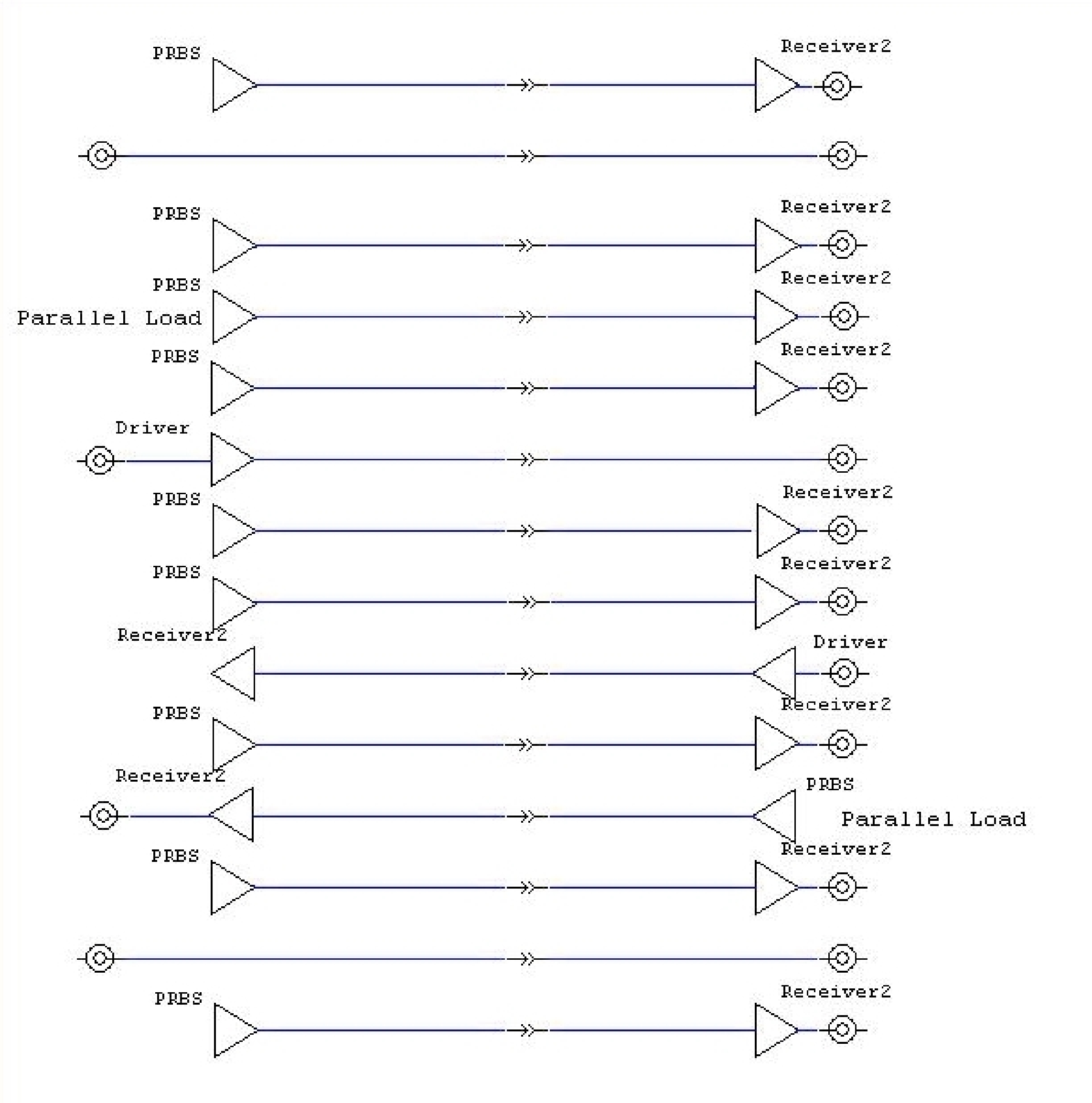


PAM-4 eye pattern for Accelerant Networks AN6425 at 6.22 Gbps with Samtec QSE/QTE Final Inch™ test board and a 1-meter long 38 AWG micro coax assembly showing excellent eye opening.

10 Gbps Technology Demonstration

- Demo > 10GBS reliable data transfer over the QTE/QSE connector.
- Use existing low cost parts.
- Ability to instrument all data lines.
- Show total performance including crosstalk.
  - 12 - 10 Gbps drivers and receivers.
  - 2 - differential pairs with SMAs for crosstalk measurement.

Simplified 10 Gbps Concept



Description

- Each differential pair will be driven by a 9.95 Gbps serial PRBS 7 data stream.
- System allows for external data streams.
    - Ability to attach BERT for additional testing capability.
- Standard QSE/QTE connector, HFEM flex and EQCD cable systems.
    - No expensive or exotic parts and materials.

QTE/QSE 10 Gbps Serdes Demonstration Board

SMA Connectors for Instrumentation

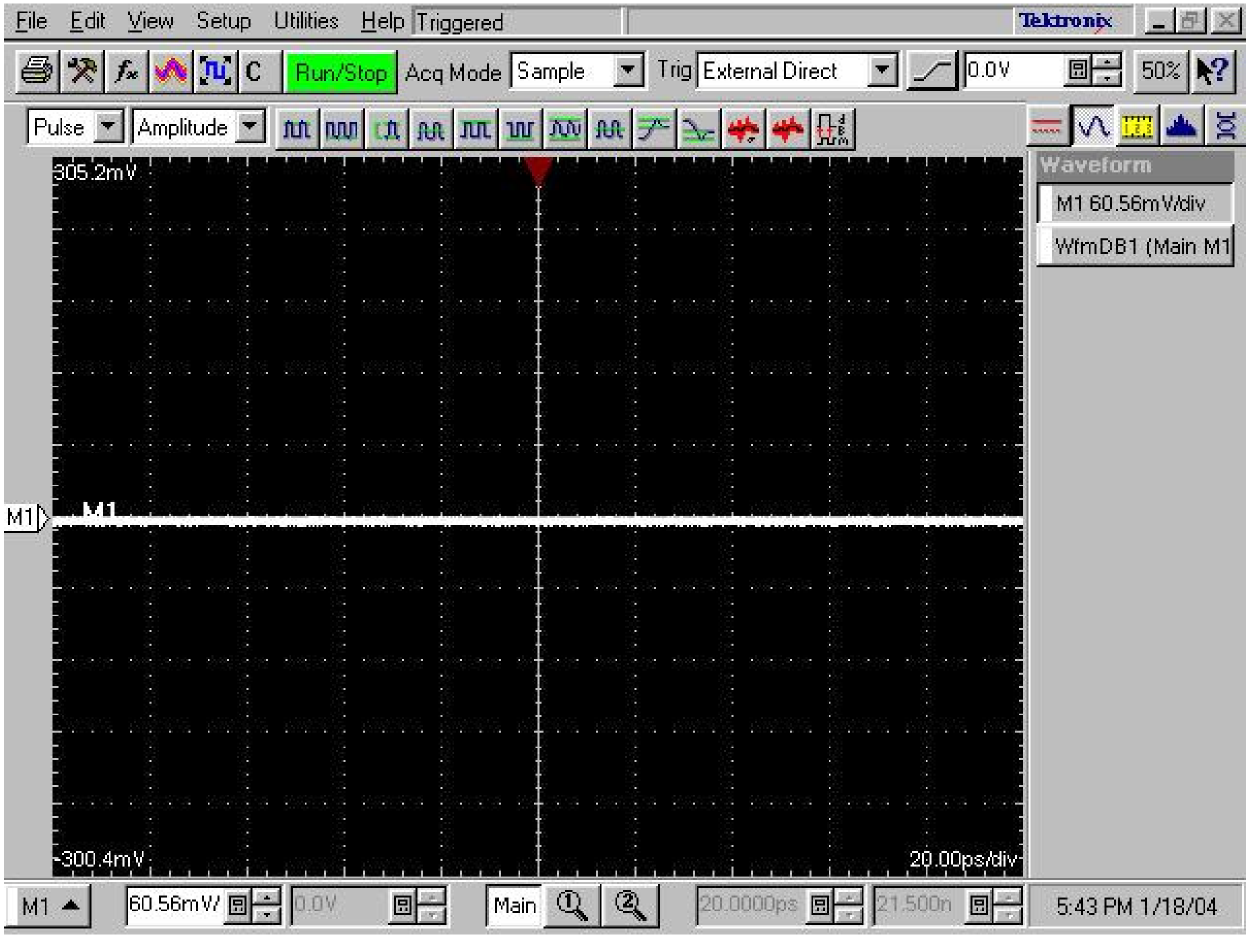
Primary Receive board

Primary Transmit board

Bi-directional transmit and receive boards shown with Twin-ax cable attached.

Instrumentation Noise Floor

Less than
5 mV
instrument
noise floor.



Triggered

Acq Mode Sample

Trig External Direct

0.0V

50%

M1 60.56mV/div

WfmDB1 (Main M1

60.56mV/

0.0V

20.0000ps

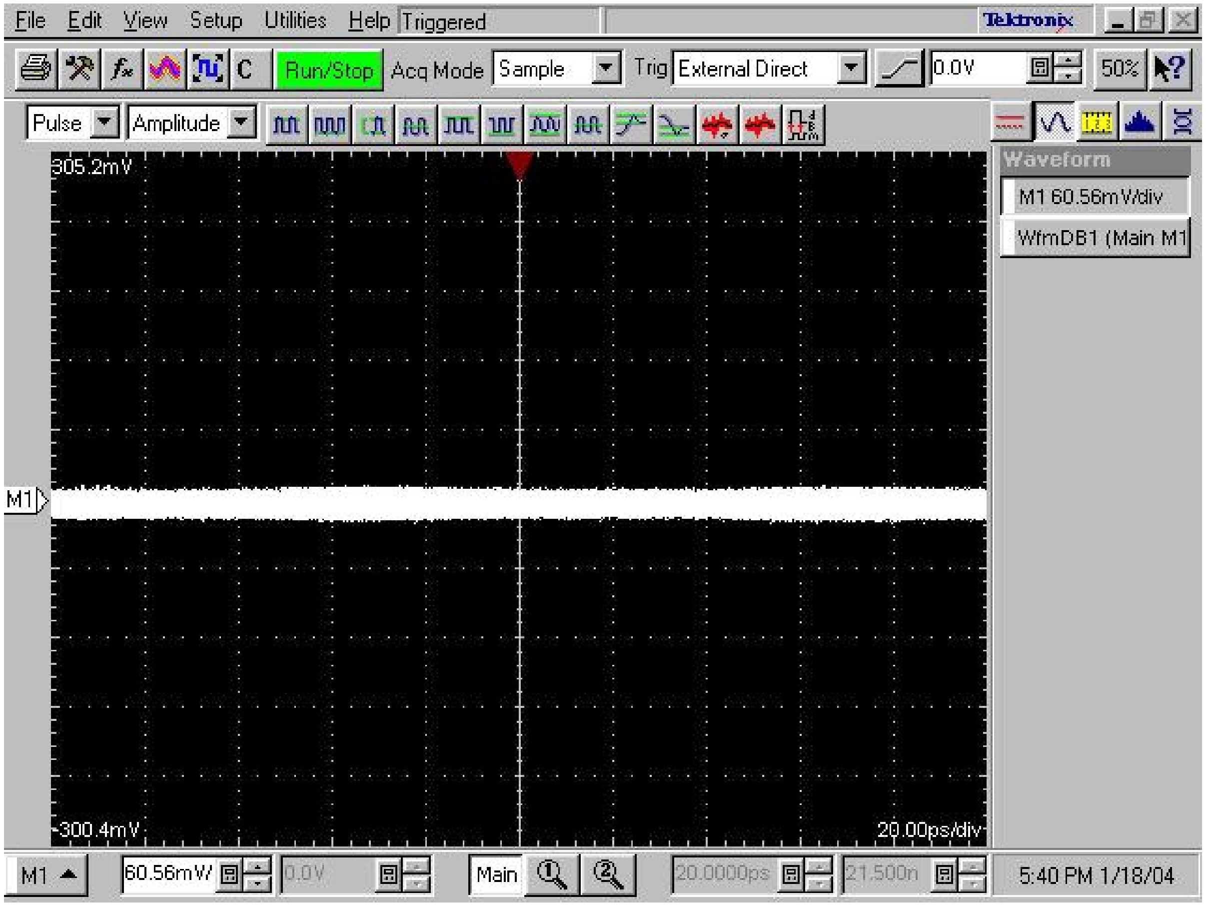
21.500n

5:43 PM 1/18/04

Measurement noise floor.

Crosstalk Measurement

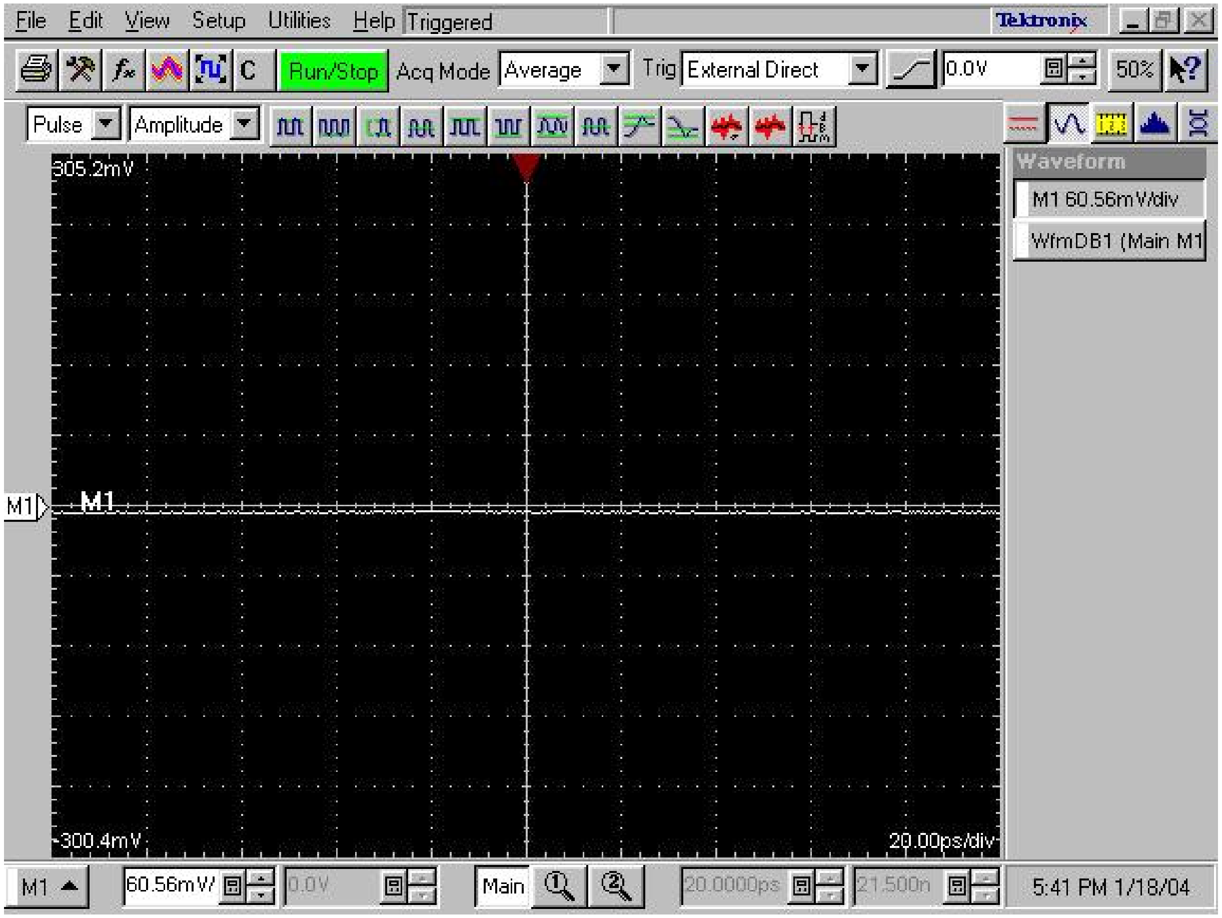
Less than
20 mV
total xtk.



Triggered
Acq Mode Sample
Trig External Direct 0.0V
M1 60.56mV/div
WfmDB1 (Main M1
M1 60.56mV 0.0V
20.0000ps 21.500n
5:40 PM 1/18/04

Negligible differential crosstalk with 12 simultaneous 10 Gbps pseudo-random data transmissions. Operational crosstalk is only slightly above measurement noise.

Crosstalk Averaging



Acq Mode Average

Trig External Direct

M1 60.56mV/div

WfmDB1 (Main M1

M1 60.56mV/ 0.0V

20.0000ps 21.500n

5:41 PM 1/18/04

Crosstalk averaging shows no uncorrelated data dependent crosstalk and verifying random aggressor patterns.

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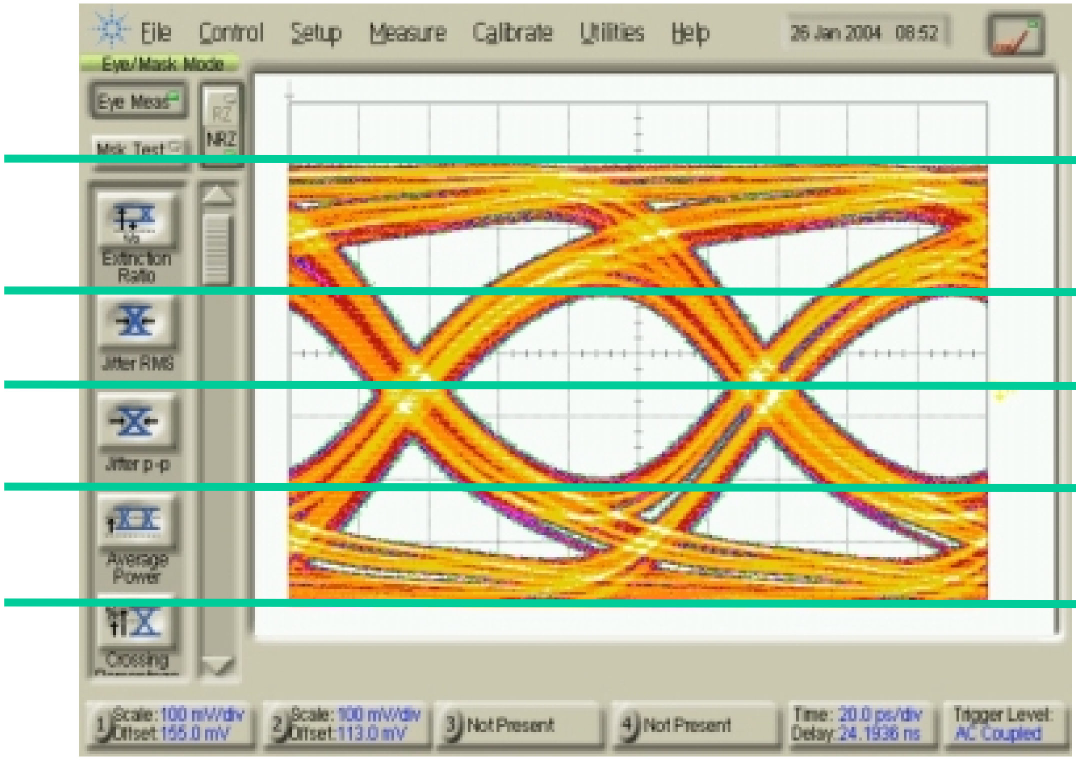
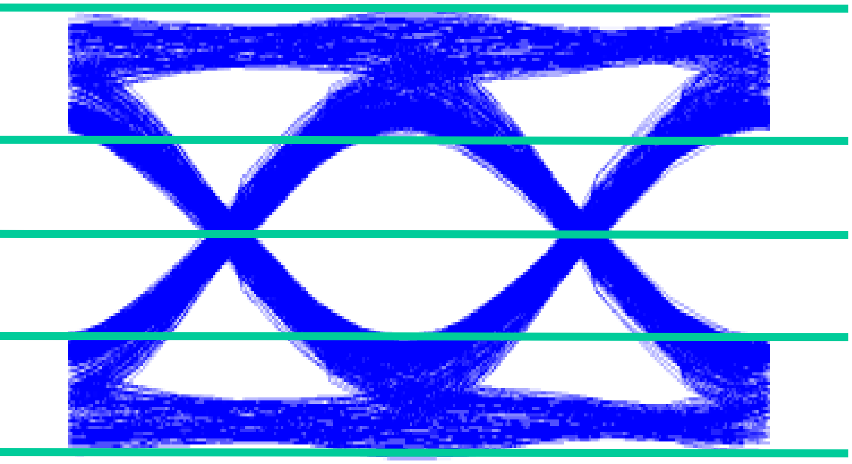
Measurement vs. Simulation



1) Scale: 100 mV/div Offset: 155.0 mV
2) Scale: 100 mV/div Offset: 113.0 mV
3) Not Present
4) Not Present
Time: 20.0 ps/div Delay: 24.1936 ns
Trigger Level: AC Coupled

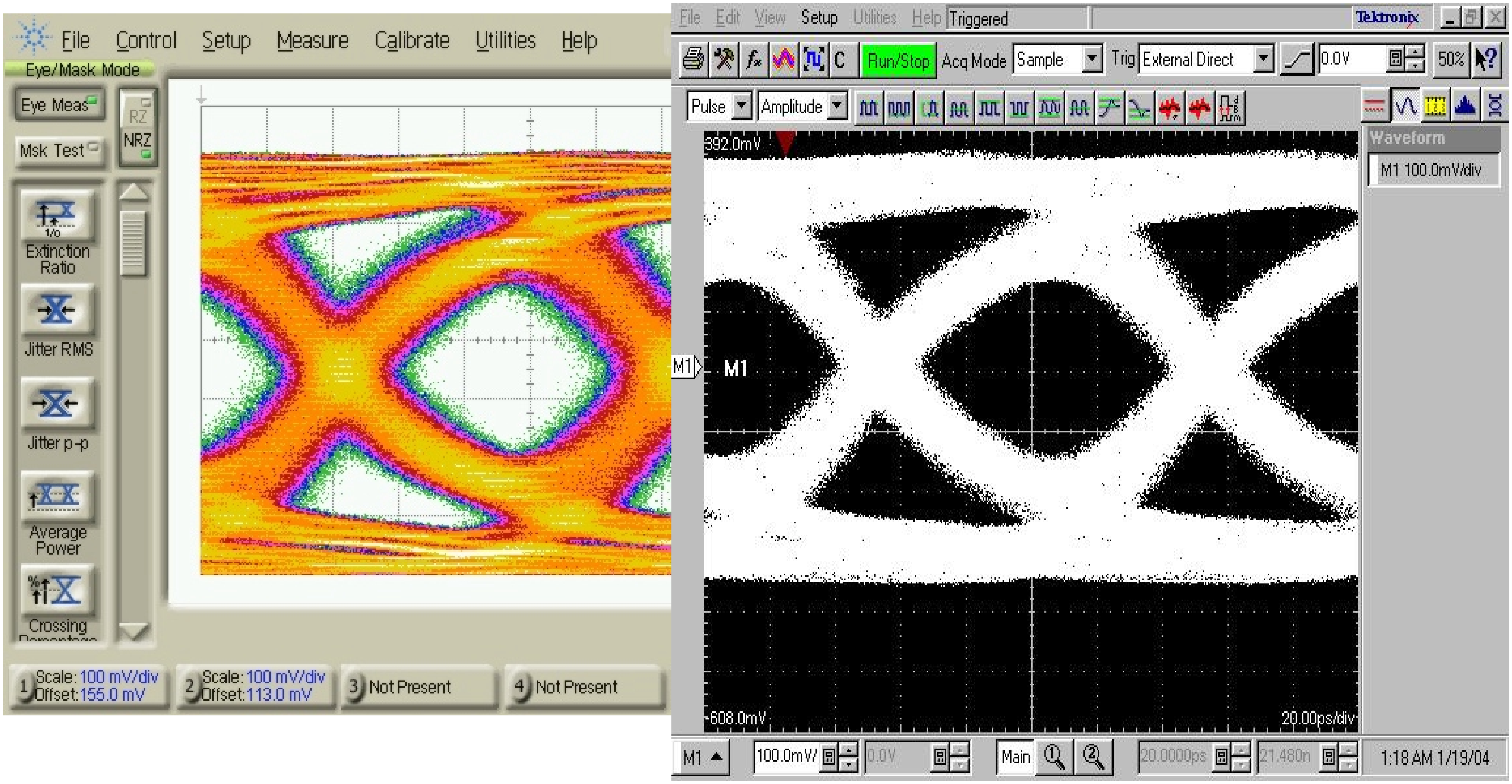


PRBS 7 Simulation of Modeled Interconnect w/o Driver

PRBS 7 Measurement

PRBS pattern as transmitted through connectors and PCB only.
(9.95 Gbps actual data rate)
Measurement differences due to additional loss and jitter in MAX3952 driver (9ps deterministic jitter).

65 GHz vs. 20 GHz Sampling



1 Scale: 100 mV/div Offset: 155.0 mV

2 Scale: 100 mV/div Offset: 113.0 mV

Triggered

Acq Mode Sample

Trig External Direct

0.0V

50%

392.0mV

-608.0mV

20.00ps/div

M1 100.0mV/div

100.0mV/

0.0V

20.0000ps

21.480n

1:18 AM 1/19/04

PRBS pattern as transmitted through connectors and PCB only, with 65 GHz and 20 GHz sampling heads.
(9.95 Gbps actual data rate)

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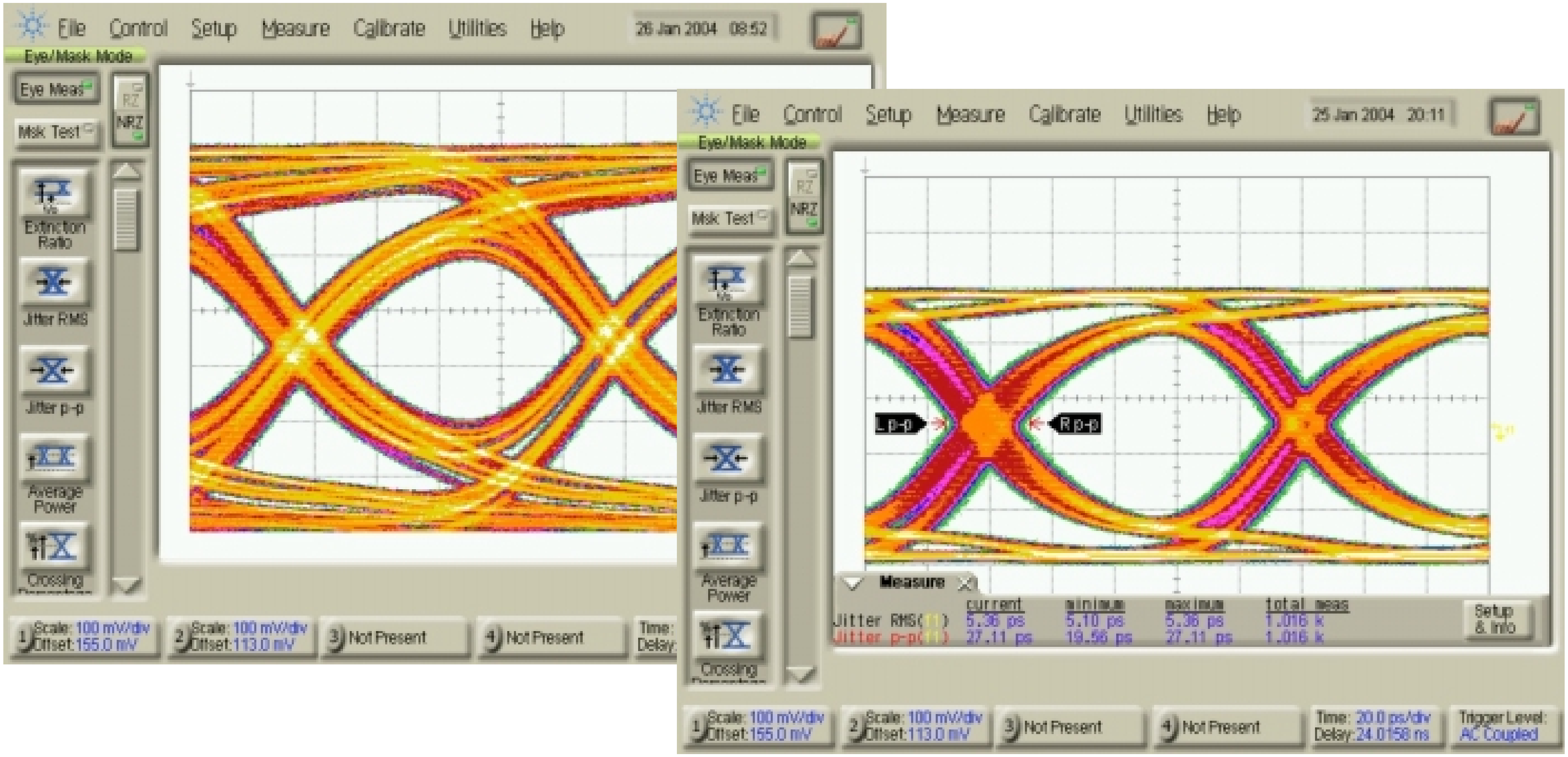
Board to Board With and Without Equalization



	current	minimum	maximum	total meas
Jitter RMS(f1)	5.36 ps	5.10 ps	5.36 ps	1.016 k
Jitter p-p(f1)	27.11 ps	19.56 ps	27.11 ps	1.016 k

1 Scale: 100 mV/div Offset: 155.0 mV
2 Scale: 100 mV/div Offset: 113.0 mV
3 Not Present
4 Not Present
Time: 20.0 ps/div Delay: 24.0158 ns
Trigger Level: AC Coupled

Binary eye pattern for MAX3952 PRBS, PCB trace, QTE/QSE connectors, and MAX3805 adaptive equalizer shows excellent eye opening.

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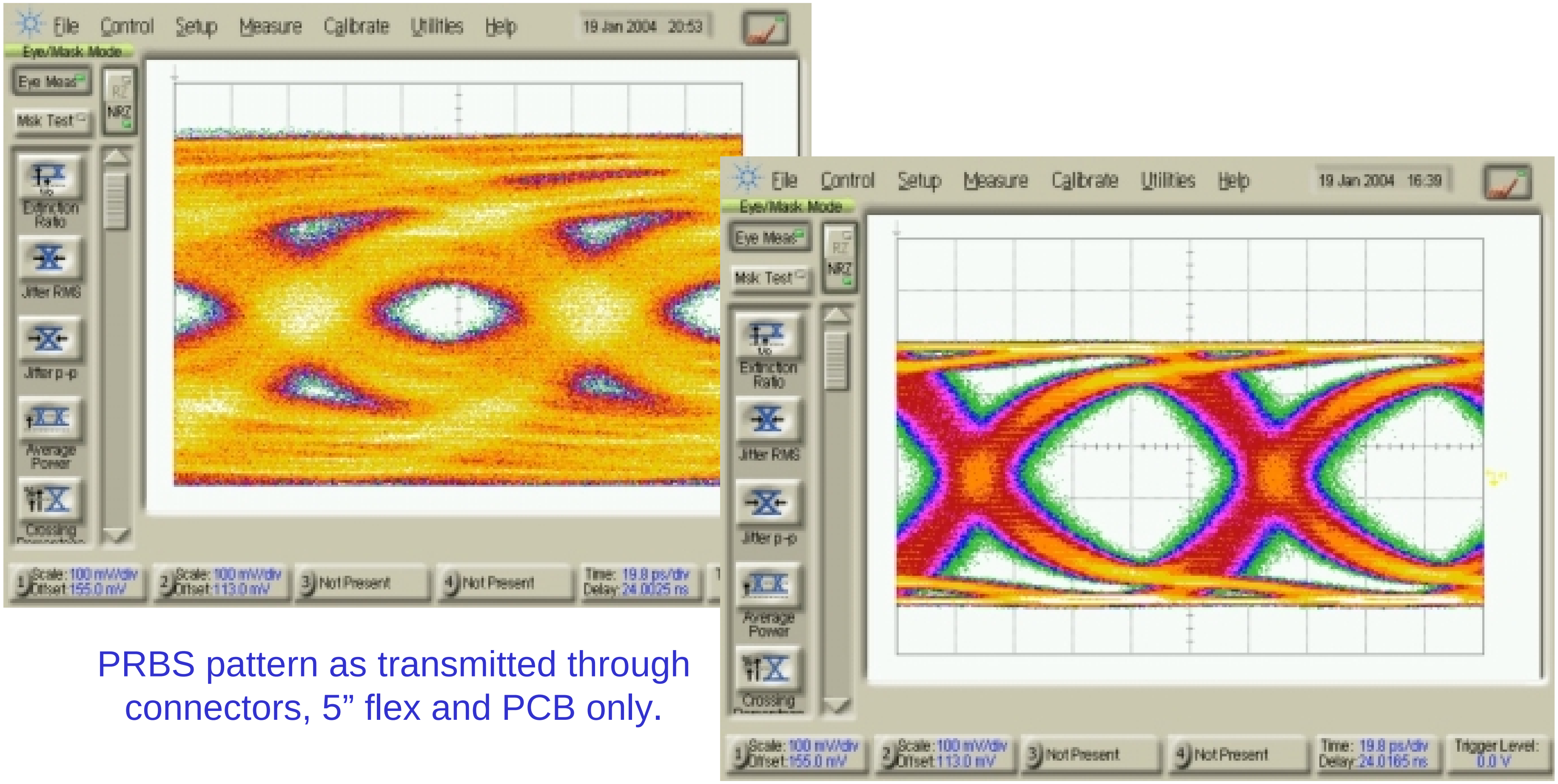
Boards With 5” Flex With and Without Equalization



1 Scale: 100 mV/div Offset: 155.0 mV
2 Scale: 100 mV/div Offset: 113.0 mV
3 Not Present
4 Not Present
Time: 19.8 ps/div Delay: 24.0025 ns

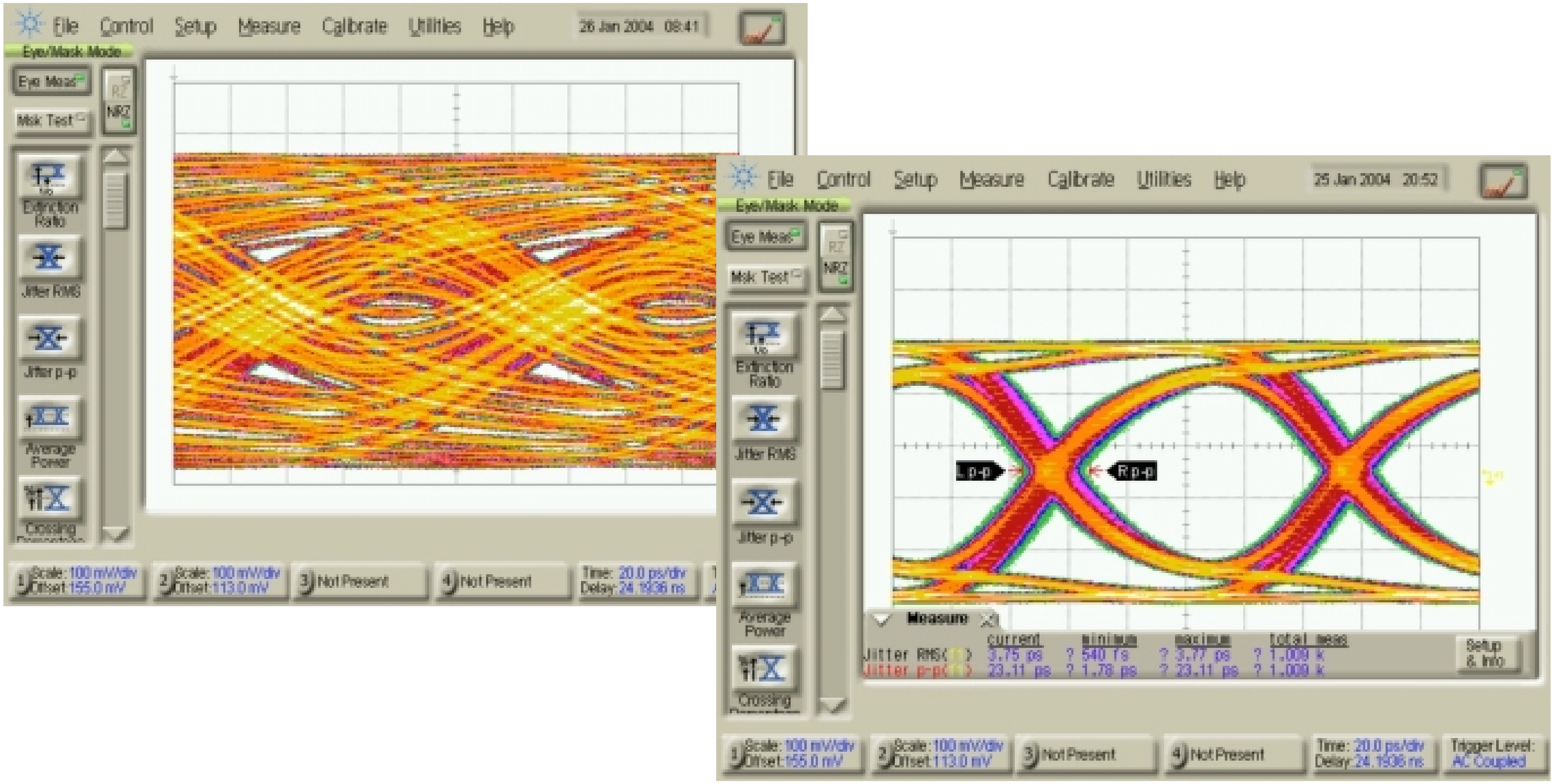
1 Scale: 100 mV/div Offset: 155.0 mV
2 Scale: 100 mV/div Offset: 113.0 mV
3 Not Present
4 Not Present
Time: 19.8 ps/div Delay: 24.0165 ns
Trigger Level: 0.0 V

PRBS pattern as transmitted through connectors, 5” flex and PCB only.

Equalized

Binary eye pattern for MAX3952 PRBS, PCB trace, QTE/QSE connectors, 5” HFEM flex assembly and MAX3805 adaptive equalizer.

Boards With 10” Flex With and Without Equalization

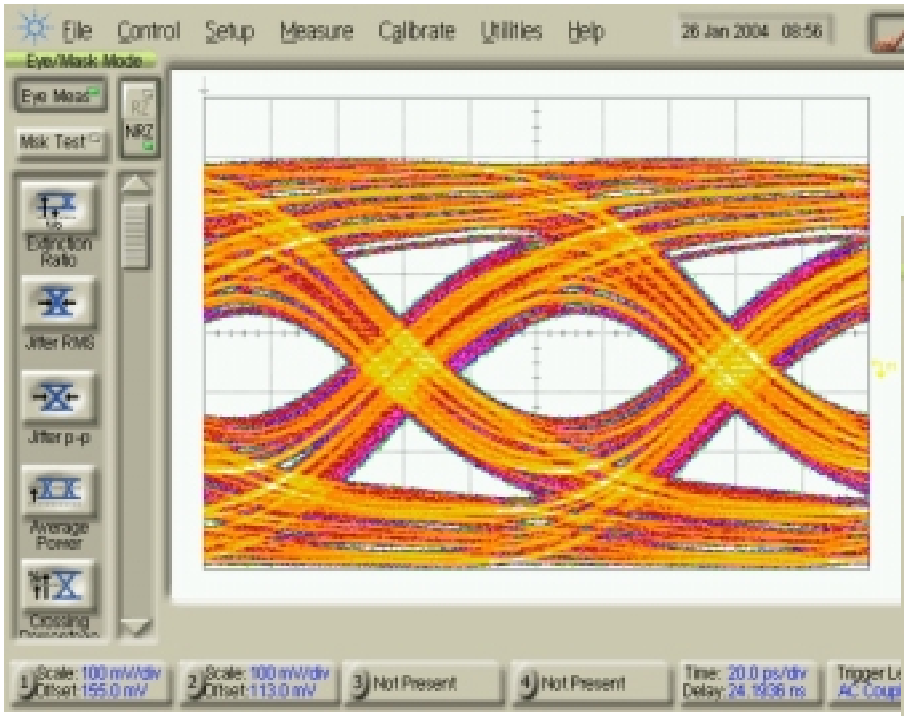


	current	minimum	maximum	total meas
Jitter RMS( )	3.75 ps	? 540 fs	? 3.77 ps	? 1.009 k
Jitter p-p( )	23.11 ps	? 1.78 ps	? 23.11 ps	? 1.009 k

1 Scale: 100 mV/div Offset: 155.0 mV
2 Scale: 100 mV/div Offset: 113.0 mV
3 Not Present
4 Not Present
Time: 20.0 ps/div Delay: 24.1936 ns
Trigger Level: AC Coupled

Binary eye pattern for MAX3952 PRBS, PCB trace, QTE/QSE connectors, 10” HFEM flex assembly and MAX3805 adaptive equalizer.

Boards With 6” Coax With and Without Equalization



26 Jan 2004 08:56

1 Scale: 100 mV/div Offset 155.0 mV

2 Scale: 100 mV/div Offset 113.0 mV

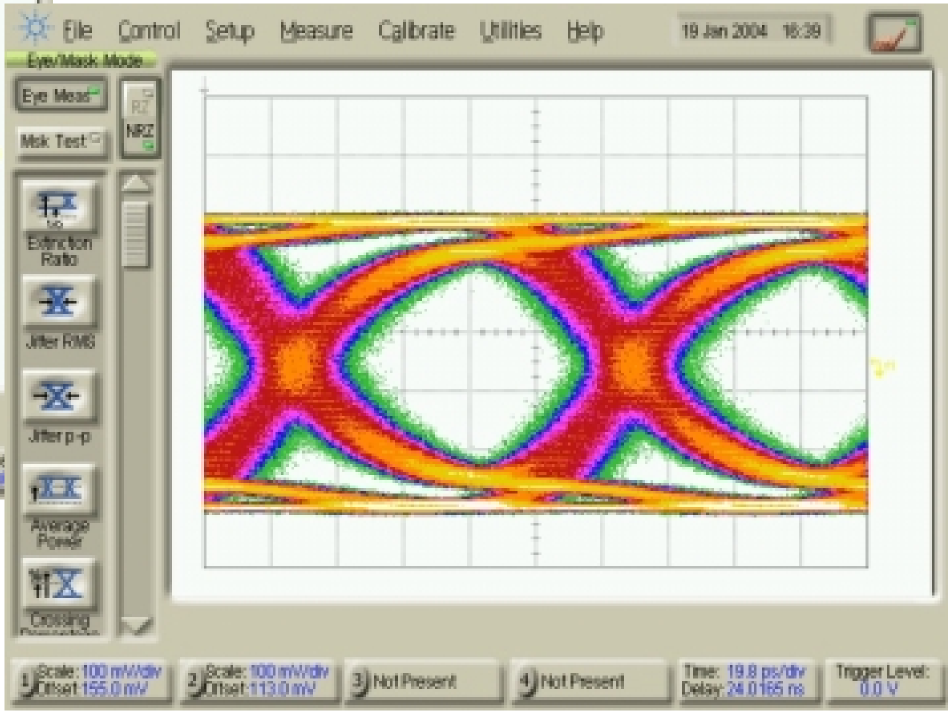
3 Not Present

4 Not Present

Time: 20.0 ps/div Delay: 24.1936 ns

Trigger Le AC Coup

PRBS pattern as transmitted through connectors, 6” cable and PCB only.



19 Jan 2004 18:39

1 Scale: 100 mV/div Offset 155.0 mV

2 Scale: 100 mV/div Offset 113.0 mV

3 Not Present

4 Not Present

Time: 19.8 ps/div Delay: 24.0165 ns

Trigger Level: 0.0 V

Equalized

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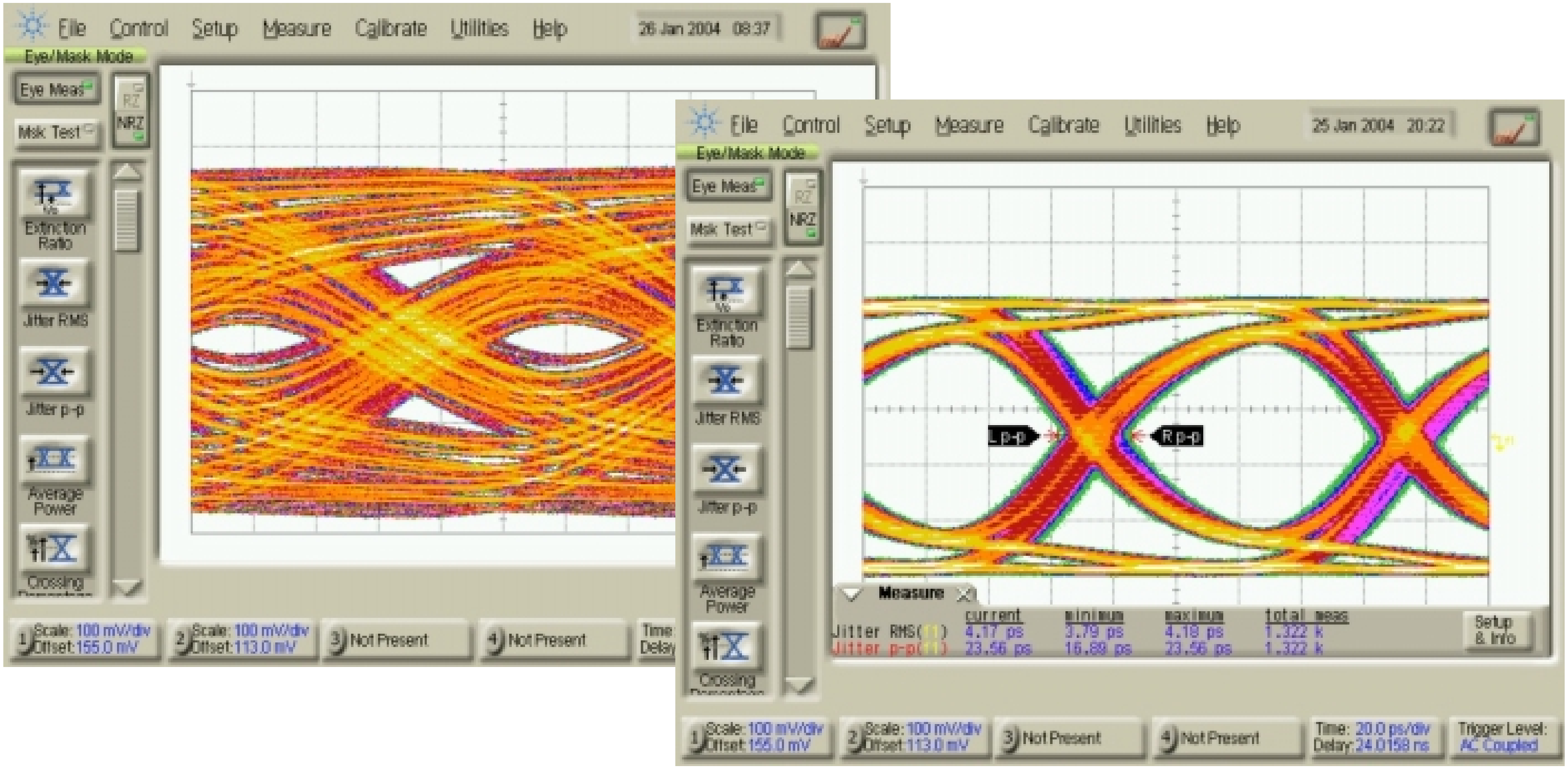
Boards With 0.5 Meter Coax With and Without Equalization

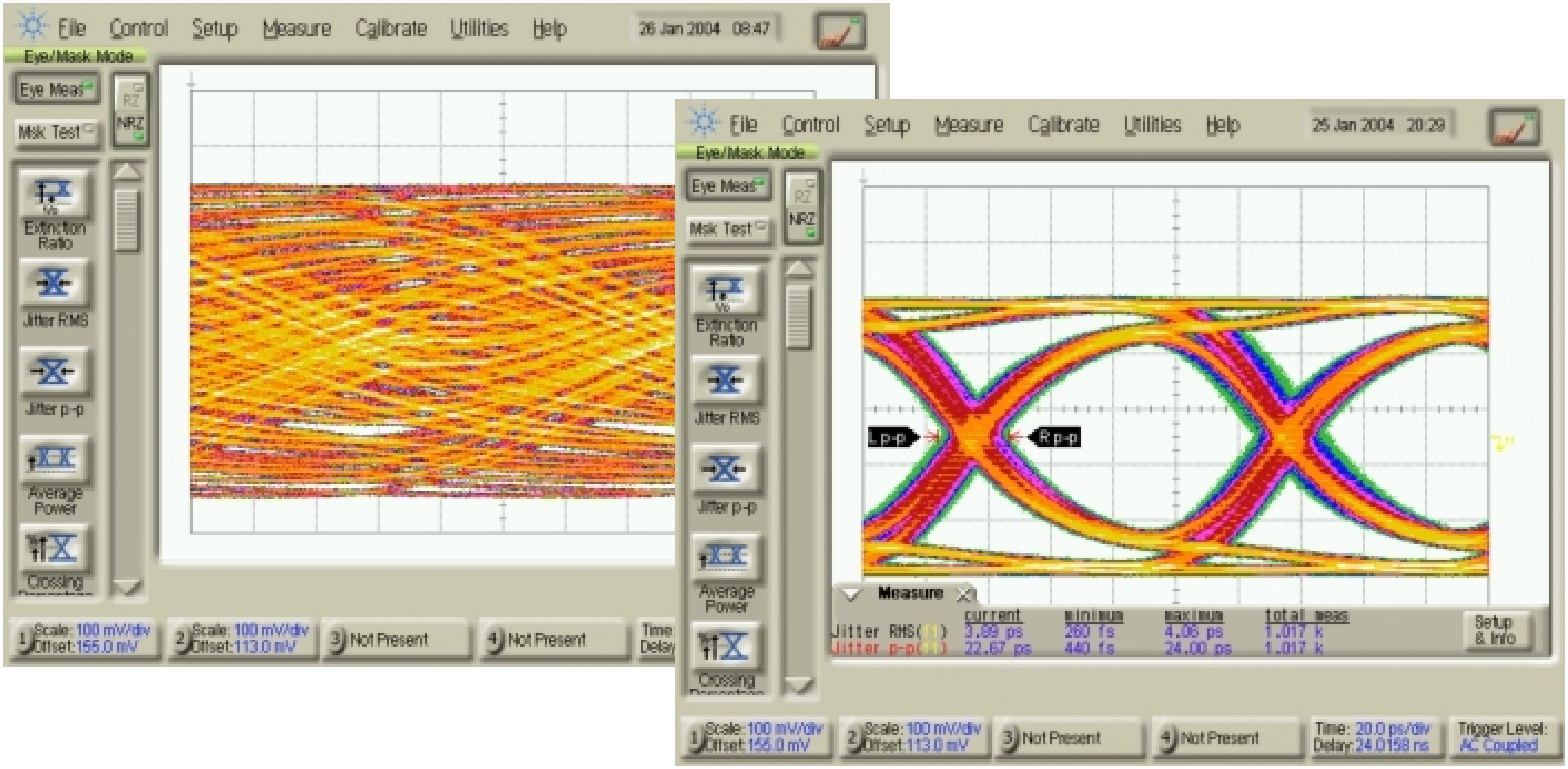


```
            current    minimum    maximum    total meas
Jitter RMS(1)  4.17 ps    3.79 ps    4.18 ps    1.322 k
Jitter p-p(1)  23.56 ps   16.89 ps   23.56 ps   1.322 k
```

1 Scale: 100 mV/div Offset: 155.0 mV
2 Scale: 100 mV/div Offset: 113.0 mV
3 Not Present
4 Not Present
Time: 20.0 ps/div Delay: 24.0158 ns
Trigger Level: AC Coupled

Binary eye pattern for MAX3952 PRBS, PCB trace, QTE/QSE connectors, 0.5-meter long 38 AWG EQCD micro-coax and MAX3805 adaptive equalizer shows excellent eye opening.

1 Meter Coax With and Without Equalization



26 Jan 2004 08:47

1 Scale: 100 mV/div Offset: 155.0 mV
2 Scale: 100 mV/div Offset: 113.0 mV
3 Not Present
4 Not Present

25 Jan 2004 20:29

```
              current    minimum    maximum    total meas
Jitter RMS(1) 3.89 ps    280 fs     4.06 ps    1.017 k
Jitter p-p(1) 22.67 ps   440 fs     24.00 ps   1.017 k
```

1 Scale: 100 mV/div Offset: 155.0 mV
2 Scale: 100 mV/div Offset: 113.0 mV
3 Not Present
4 Not Present
Time: 20.0 ps/div Delay: 24.0158 ns
Trigger Level: AC Coupled

Binary eye pattern for MAX3952 PRBS, PCB trace, QTE/QSE connectors, 1-meter long 38 AWG EQCD micro-coax and MAX3805 adaptive equalizer.

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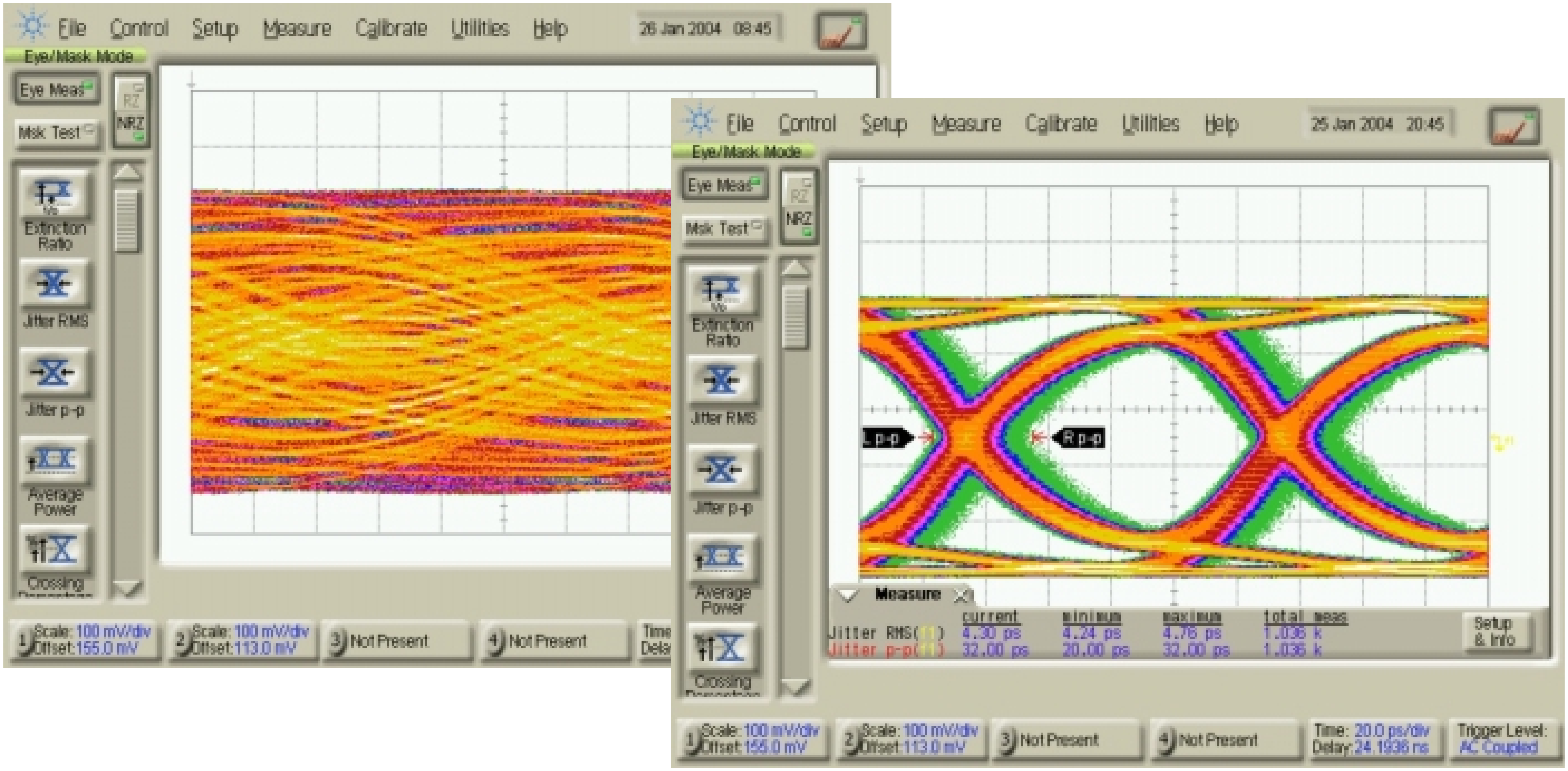
2 Meter Twin-ax With and Without Equalization



```
Measure
                current    minimum    maximum    total meas
Jitter RMS(1)   4.30 ps    4.24 ps    4.76 ps    1.036 k
Jitter p-p(1)   32.00 ps   20.00 ps   32.00 ps   1.036 k
```

1 Scale: 100 mV/div Offset: 155.0 mV
2 Scale: 100 mV/div Offset: 113.0 mV
3 Not Present
4 Not Present
Time: 20.0 ps/div Delay: 24.1936 ns
Trigger Level: AC Coupled

PRBS pattern as transmitted through connectors,
2 m Twin-ax and PCB with equalization.

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For More Information

- Final Inch^{TM} – A method for the design, modeling, simulation and evaluation of high performance board-to-board interconnects.
  - Where:
    - Everything matters
    - Everything is modeled
    - The results speak for themselves

- www.samtec.com
  - Finalinch@samtec.com
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