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Measurement-Assisted Electromagnetic Extraction of Interconnect Parameters on Low-Cost FR-4 boards for 6-20 Gb/sec Applications

Y. Shlepnev, Simberian Inc.

A. Neves, Teraspeed Consulting Group LLC

T. Dagostino, Teraspeed Consulting Group LLC

S. McMorrow, Teraspeed Consulting Group LLC

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Outline

- Goals of the project
- Challenges
- Test board overview
- Selection of dispersive dielectric model
- Measurement methodology
- Identification of dielectric parameters
- Comparisons of measurements are simulations
- Conclusion

Goals of the Project

- **High Confidence Design** Method for 10 Gb/sec
  - Material extraction DK and LT versus frequency
  - Build 3D electromagnet models and confirm with measured data, compare with very simple schematic models
- Build pristine measurement **de-embedding** capability
- Models versus measurements
  - 1% correspondence performance up to 20GHz
  - No “cheating” with manipulation of final data
  - Models must be easy to develop
  - Allow for weave and material variability, make study realistic and represent practical design

Challenges

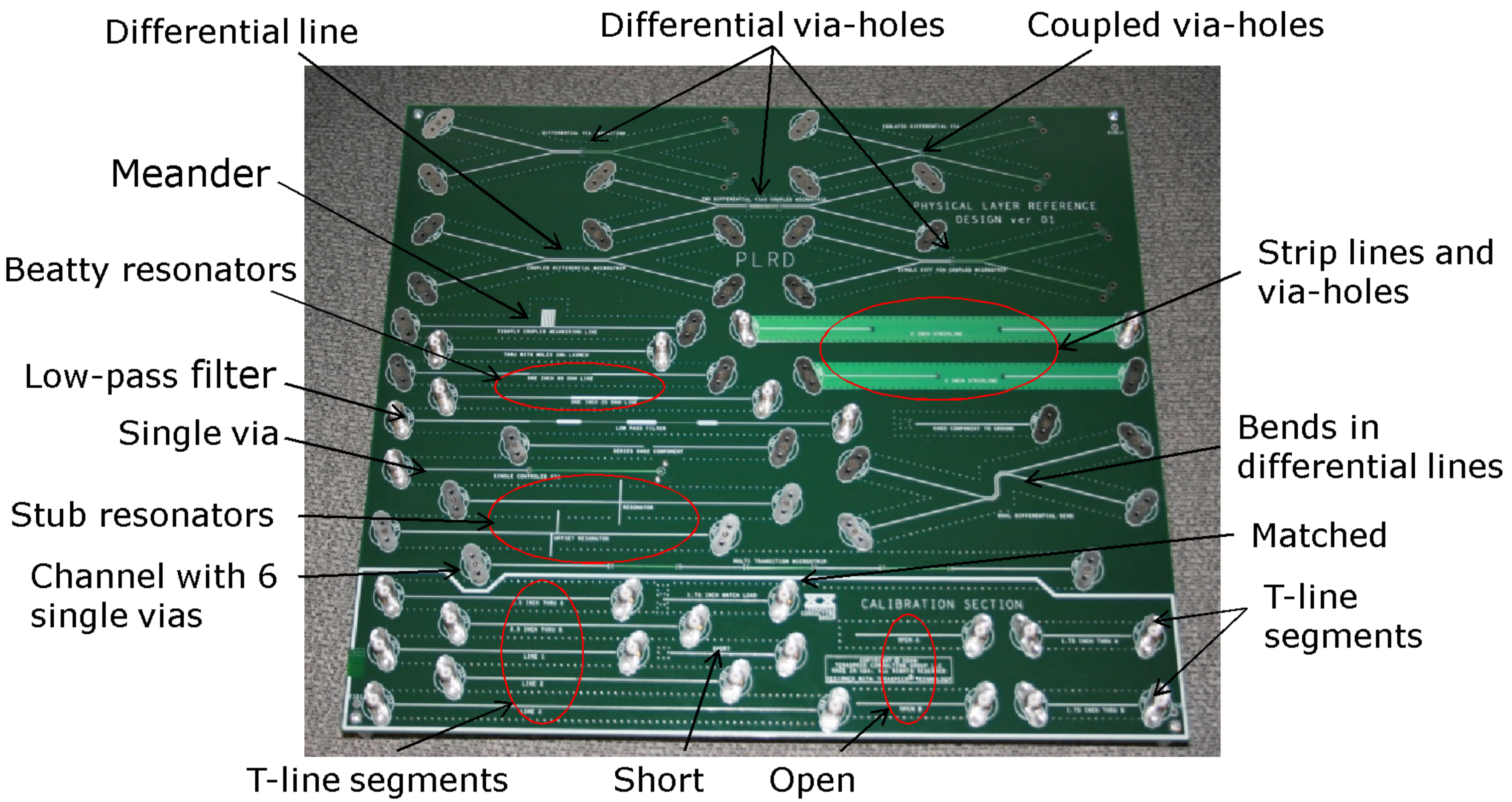
- Design of interconnects on PCBs for 6-10 Gb/s data rates requires electromagnetic **modeling from DC to at least 20 GHz**
- Manufacturers of low-cost FR-4 PCBs typically provide values for **DK and LT either at one frequency** or without specifying frequency value at all
  - The properties of the composite dielectrics is frequency-dependent and needs to be modeled accordingly
- Build software with suitable **dielectric and conductor loss models**
- Build suitable measurements **de-embedding** methodology
- Design a **PCB test vehicle** with 30 test structures to validate the extraction methodology and to verify possibilities to predict interconnect parameters with electromagnetic analysis on low-cost FR-4 boards

Dielectric Identification Techniques

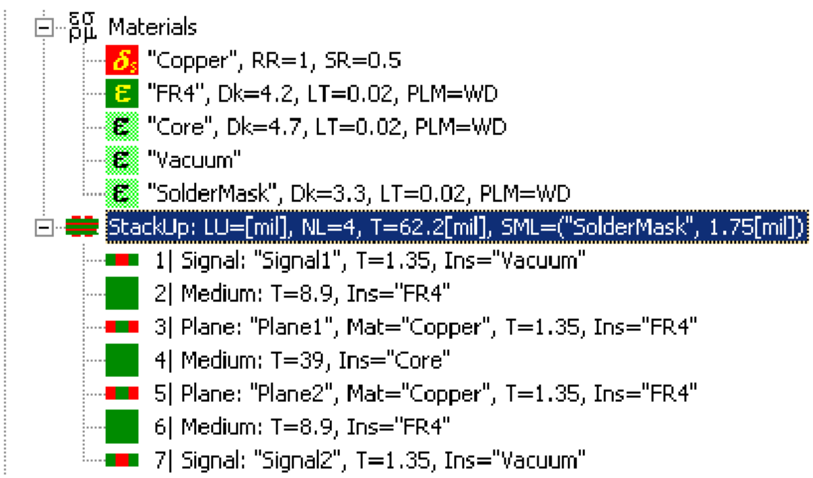
- Measurements
  - **S-parameters** measured with VNA (**de-embedded** or not)
  - TDR/TDT measurements
  - Combination of both
- Correlated with a numerical model
  - Analytical or closed-form
  - Static or quasi-static field solvers
  - **3D full-wave solvers**
- For test structures
  - **Transmission line segments**
  - Patch or parallel-plate resonators
  - **Resonators coupled or connected to a transmission line**

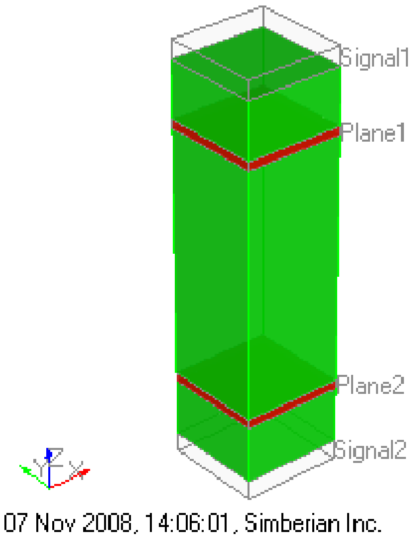
PLRD-1 Physical Layer Test Vehicle

- 30 test structures – all equipped with SMA connectors with optimized launch



Step 1: Materials and Stackup





- **Start with properties provided by board vendor**:
  - Copper bulk resistivity 1.724e-8 Ohm meters, roughness 0.5 um (roughness factor 2 is guessed)
  - Solder mask: DK=3.3, LT=0.02
  - FR-4 core dielectric: DK=4.7, LT=0.02
  - **FR-4 dielectric between signal and plane layers: DK=4.2, LT=0.02 – will be adjusted on the base of measurements and simulations**
  - Measurement frequency for all dielectrics is guessed to be 1 GHz

Step 2: Selecting Dielectric Dispersion Model

- Simplest Model: Constant DK and LT versus frequency
  - Simple, easy to measure, included in all microwave software
  - Model is **non-causal** and does not corresponds to the observed behavior – although very popular model, non-causal, BAD!
- Multi-pole Lorentzian (used in some researches)
  - No evidence of complex poles for composite dielectrics – not acceptable
- Multi-pole Debye
  - Perfectly suitable with 4-5 poles over the investigated frequency band
  - Complicated fitting: At least 4-5 coefficients have to be identified by comparison – not good
- **Wide-band Debye (Djordjevic-Sarkar)**
  - Close to observed behavior of composite dielectrics (supported by multiple publications)
  - Requires only two coefficients to fit - we like it!

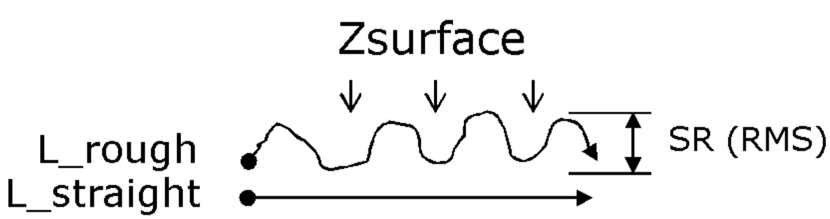
Step 4: Review Electromagnetic Analysis Requirements and Select Software

- **3D full-wave** analysis of t-lines and discontinuities
- Causal dispersive dielectric model –multi-pole or **wideband Debye**
- **Broadband conductor loss and dispersion models** valid and causal over 4-5 frequency decades (skin, edge, and proximity effects, conductor plating)
- Conductor **surface roughness**
- **High-frequency dispersion** effect
- Extract **de-embedded S-parameters** for discontinuities
- Extract frequency-dependent RLGC per unit length parameters for transmission lines

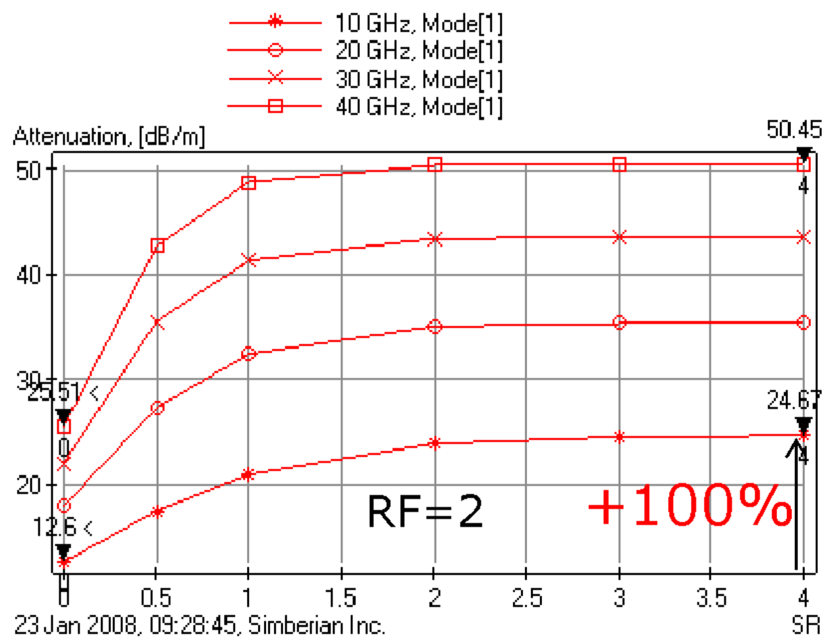
Step 4 - Deal with Surface Roughness

- No roughness model: observed LT may be overestimated – not acceptable
- Conductivity adjustment (Grios): overestimates conductor losses – not acceptable
- Hammerstad-Bekkadal or Morgan's models: do not account variation of roughness on opposite surfaces of strip – not acceptable
- Local conductor surface impedance adjustment during electromagnetic extraction: versatile and accurate - we use it!

Two parameters SR and RF have to be measured on microphotograph for instance



Roughness Factor: RF=L_rough/L_straight



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Step 5: Making Measurements – Developing the Approach

1. Delta Match Calibration (applies to Agilent N5230A 4 port)
2. Create TRL/LRM cal kit using defined cal set
3. Confirm de-embedding using THRU
4. Measure S-parameters of LINES 1,2,3, THRU, OPEN, LOAD, and all test structures
5. Restore passivity, reciprocity and symmetry and filter the measured S-parameters to increase accuracy of the multiport model conformance

TRL/LRM Design Approach

1. Decide on a maximum frequency – we typically like to make max frequency higher than the VNA
2. LRM (Load-Reflect-Match) makes low frequency de-embedding easier, you don't need long lines, just matched load line.
3. Measure Low Band matched 50ohm load S11, it needs to have good return loss past frequency of longest line (typically100 to 200MHz) in your cal kit (surface mount resistors also work).
4. Determine frequency span of either 6 or 8
5. Use the Molex spreadsheet for TRL calculation of lengths (be careful, this chart uses effective Dk, don't use 4.2 with FR4 for Microstrip!)

Molex TRL/LRM Spreadsheet

TRL Calibration Calculator for Microstrip

Inputs:	Effective Dk	Reference Length(mm)	Reference Length(in)	Frequency Ratio	Low Phase	High Phase
	3.2	44.45	1.75	5	30°	150°

Outputs	Start Frequency (Ghz)	Stop Frequency (Ghz)	Time Delay (ps)	Line Length (mm)	Line Length (in)
Short/Open			0	44.45	1.75
Load	0	183.31	0	44.45	1.75
Line 3	183.31	916.55	454.61	165.0873	6.4995
Line 2	917.92	4589.6	90.79	104.1146	4.099
Line 1	4585.76	22928.8	18.17	91.94546	3.6199
Thru			0	88.9	3.5

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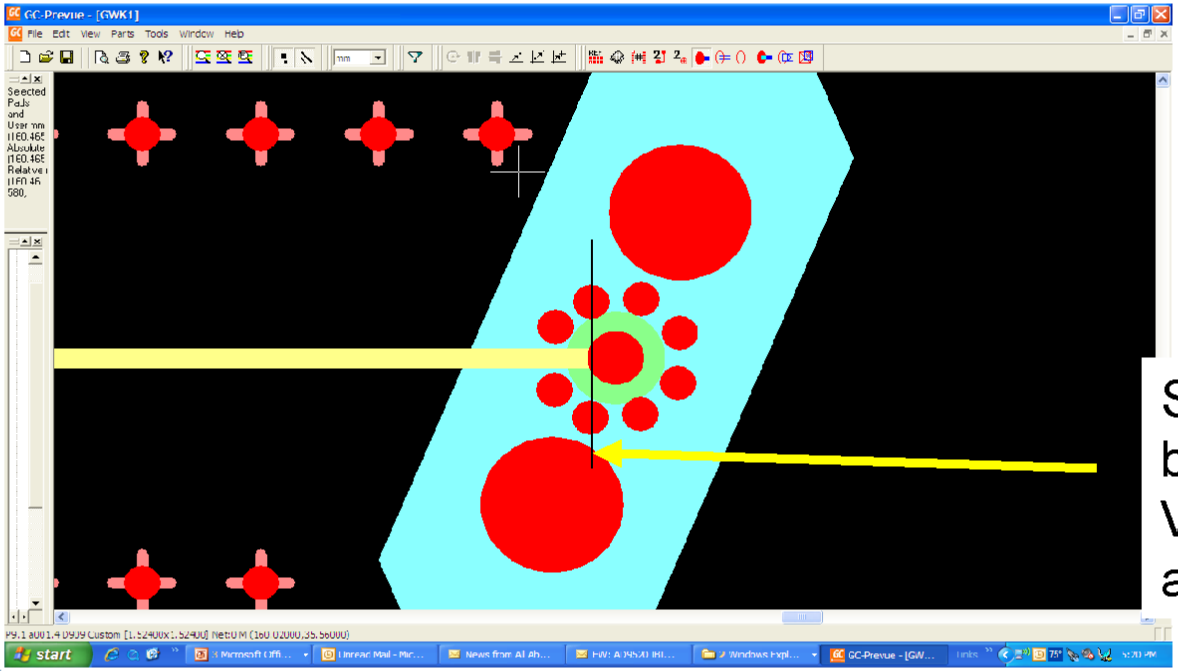
Caveat on Lengths for TRL/LRM Cal Kit

1. Carefully determine all lengths in pre-layout verification using a Gerber or Allegro viewer
2. Make sure all lengths are measured consistently



Start at boundary of VIA pad for all cases

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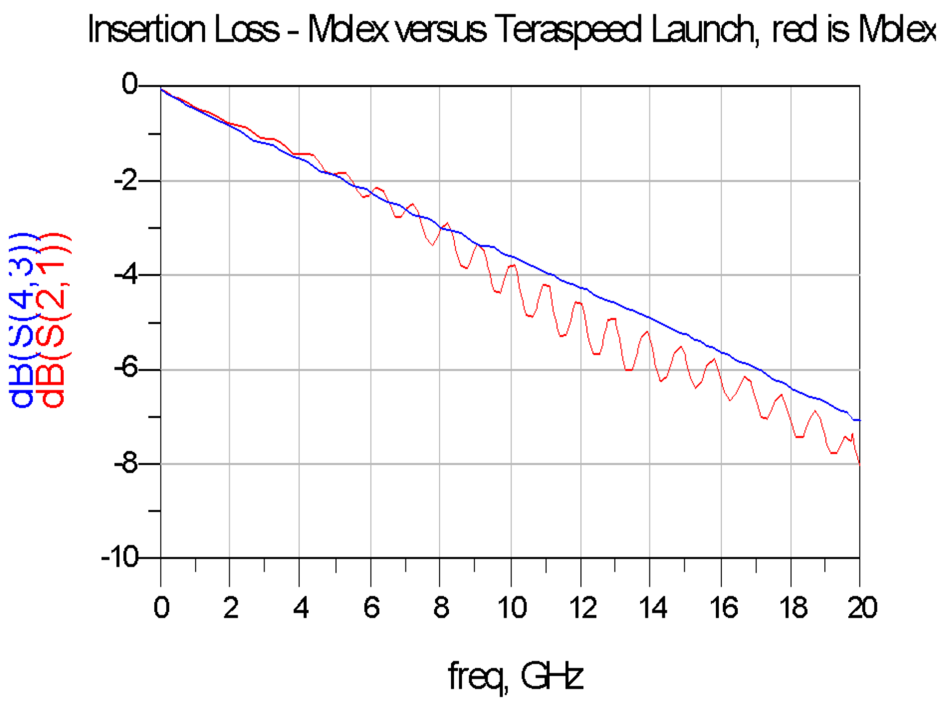
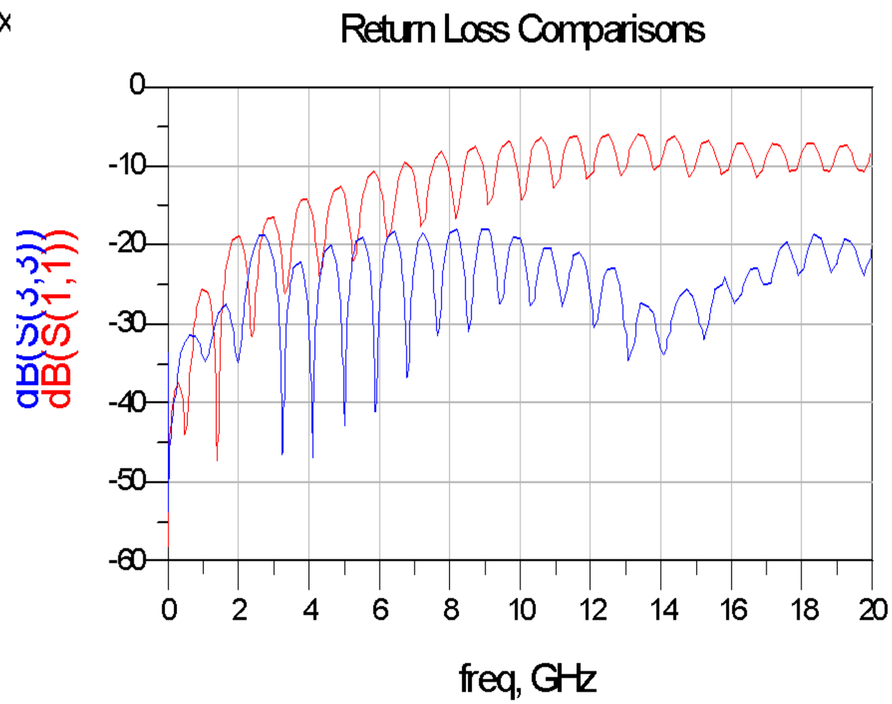
Tuned SMA launch used in BLUE





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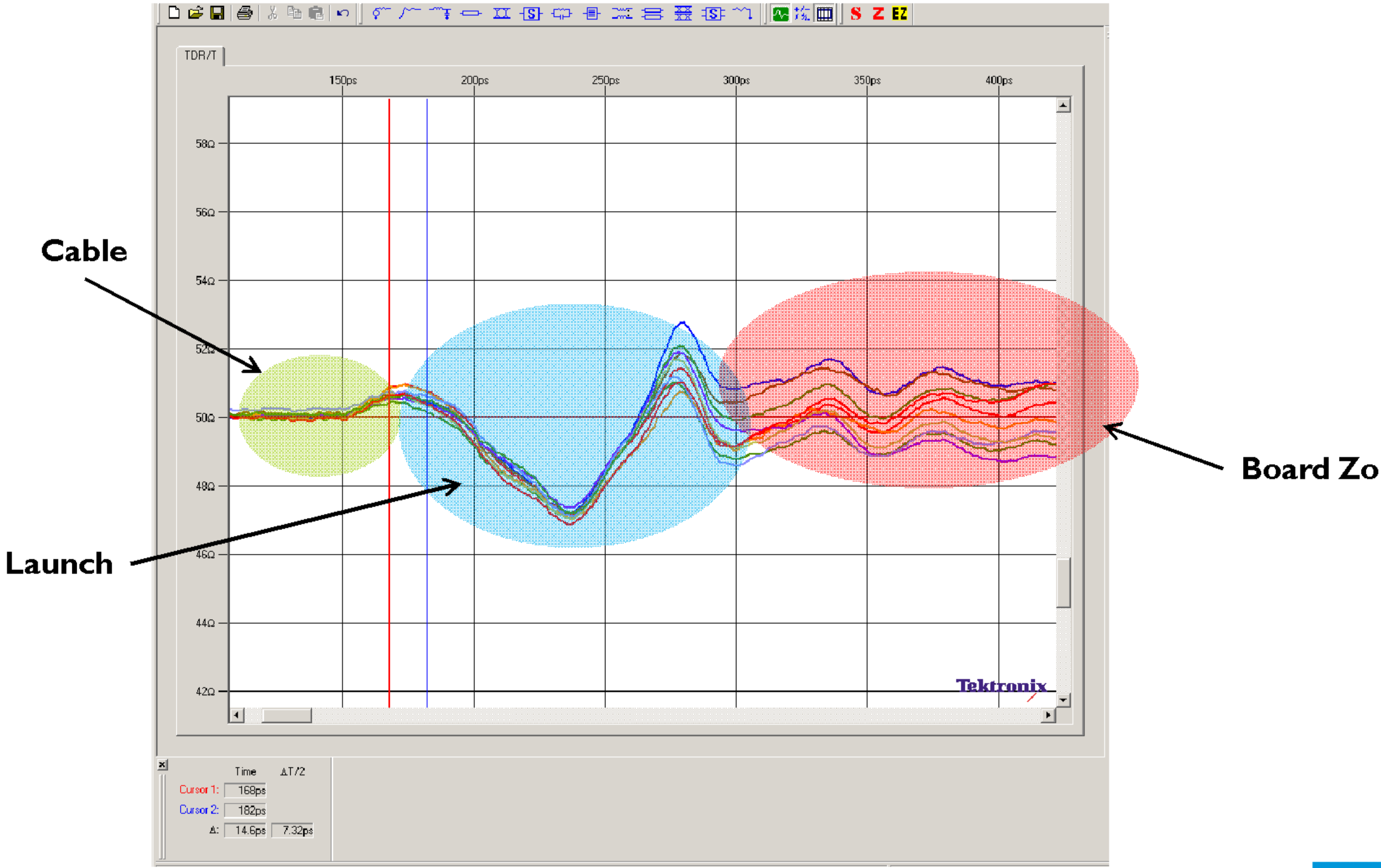
Used TDR to Insure SMA Connector Repeatability



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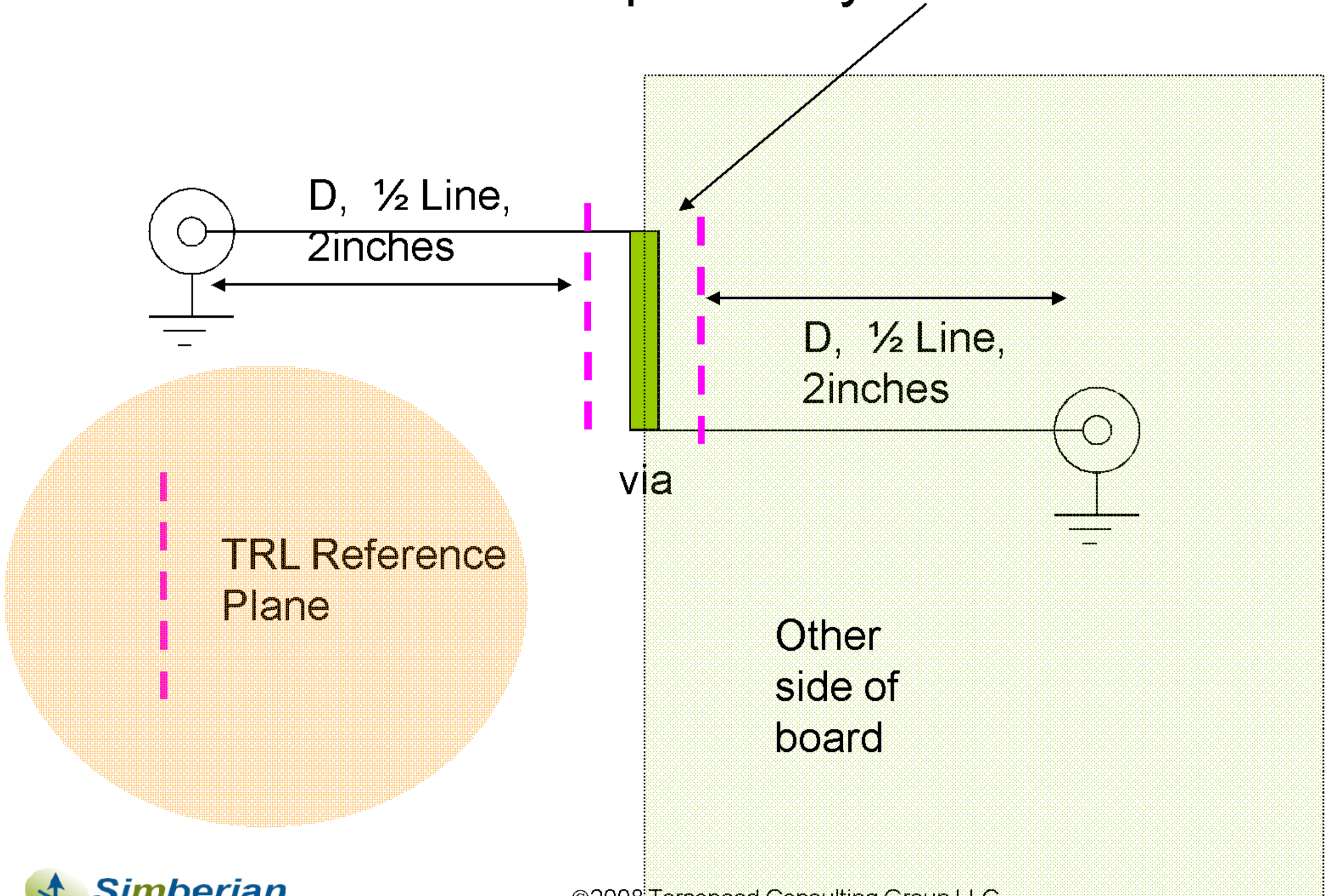
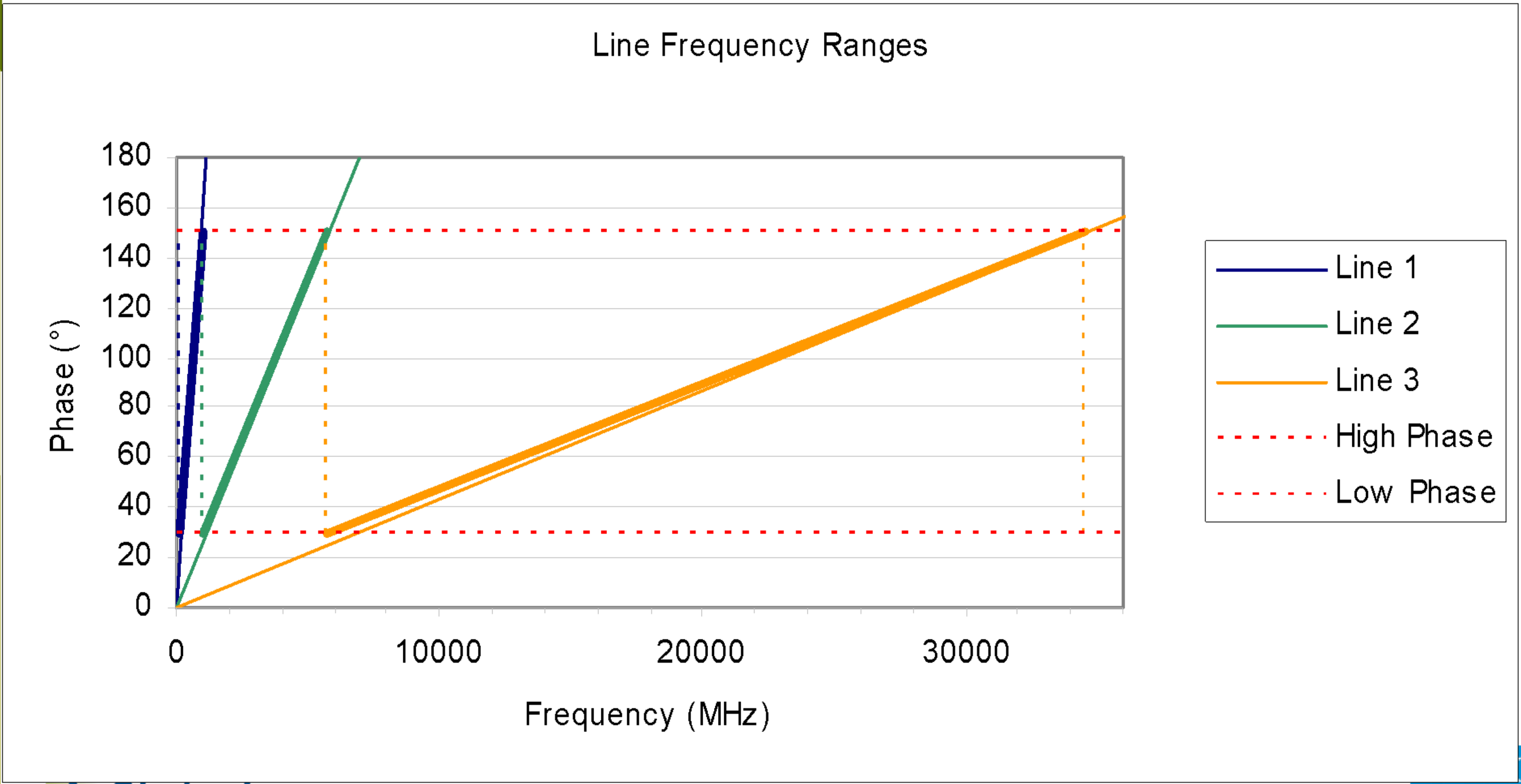
Caveat – Relieve TRL reference plane

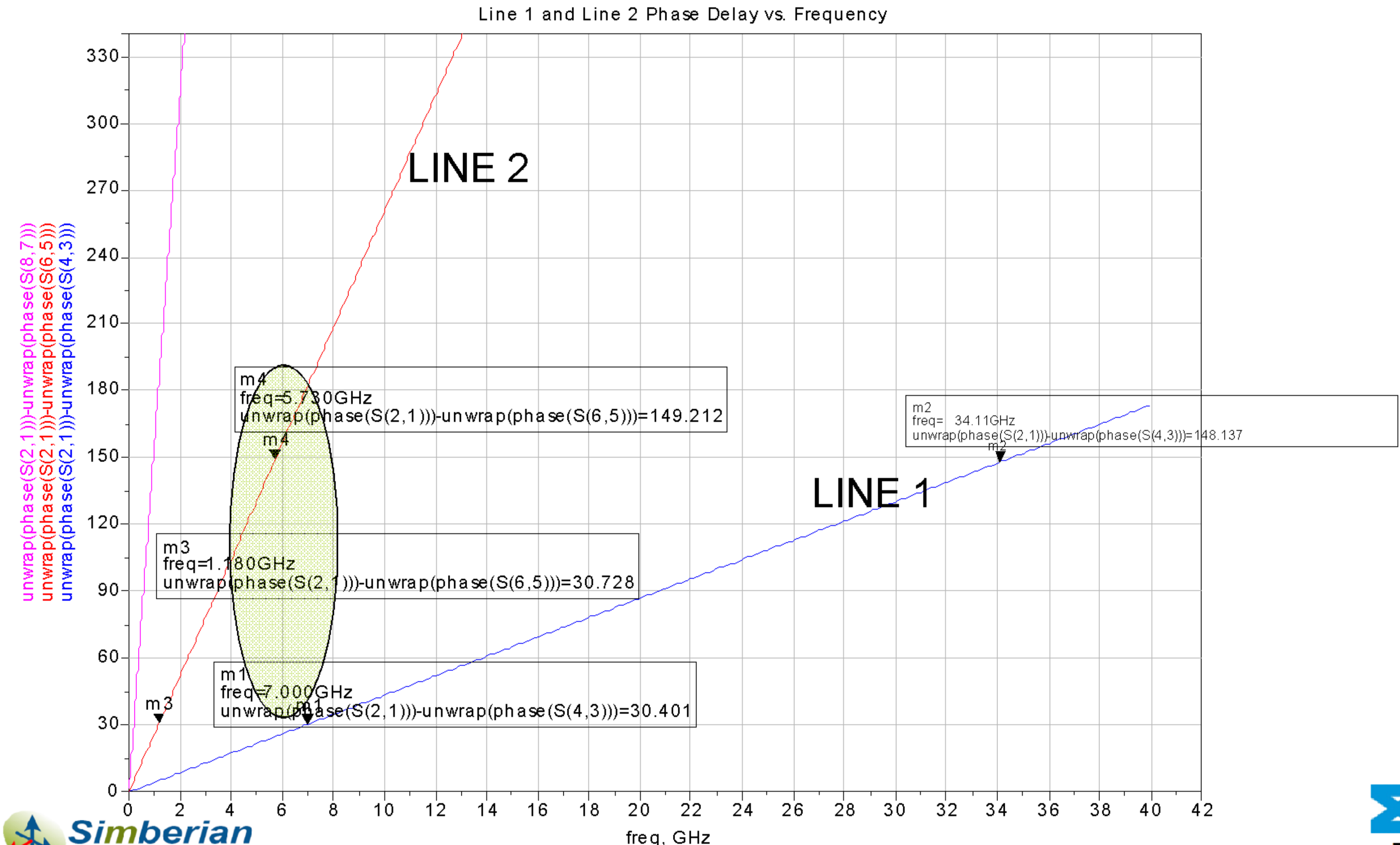
2. Relieve reference planes by 100-250mils



Line Length Frequencies Stripline, 30 and 150 Degrees – From Molex Spreadsheet



Line 1,2, and 3 Unwrapped Phase – from ADS2008 Initial Model



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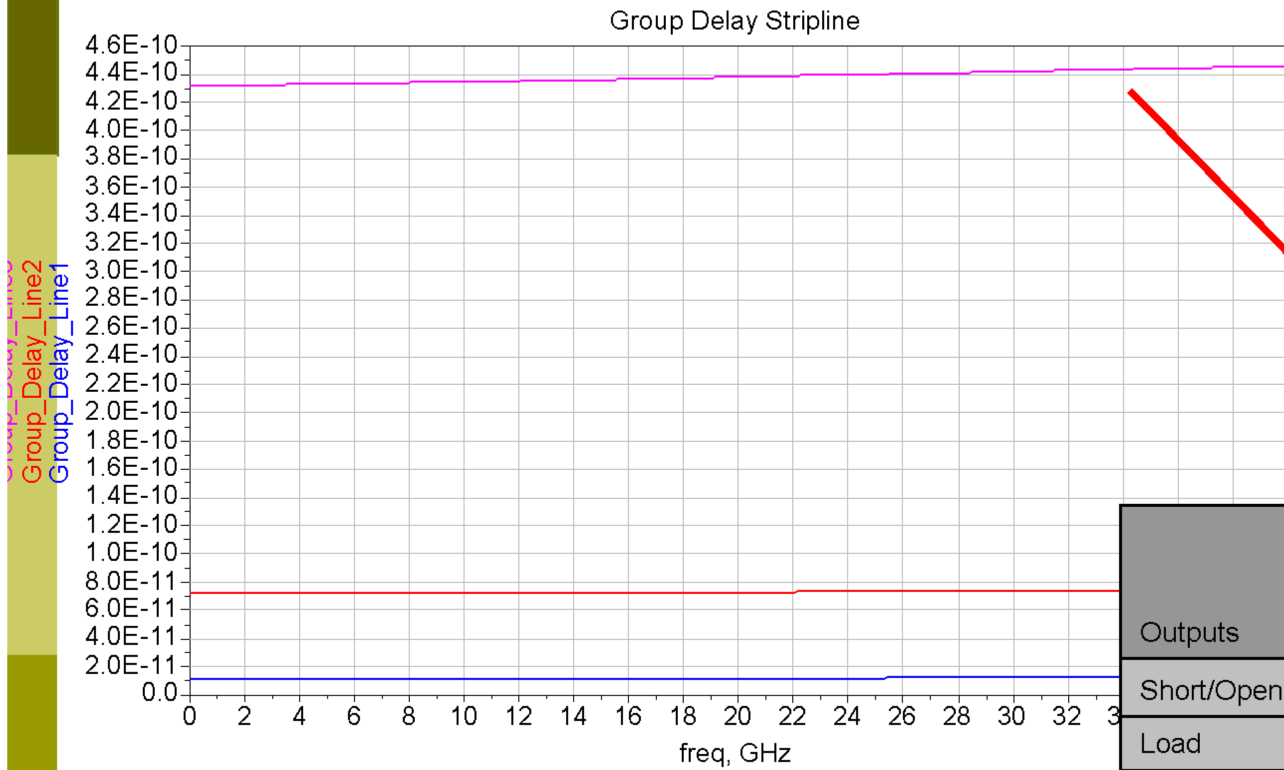
Verification of LINE delays in ADS2008



Outputs	Start Frequency (Mhz)	Stop Frequency (Mhz)	Time Delay (ps)
Short/Open			0
Load	0	160	0
Line 1	160	960	434.03
Line 2	960	5760	72.34
Line 3	5760	34560	12.06
Thru			0

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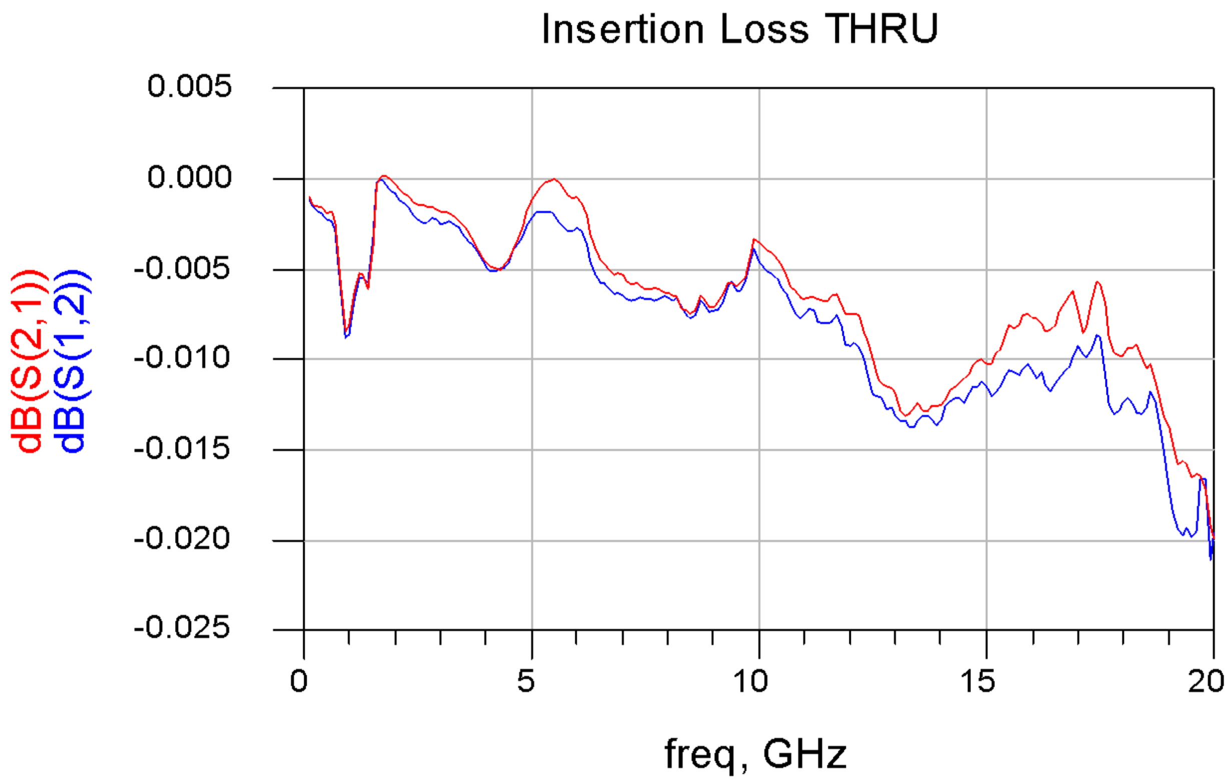
TRL/LRM Measurement of THRU



THRU should have 0dB of magnitude loss, 0dB of phase, 0psec of Group Delay

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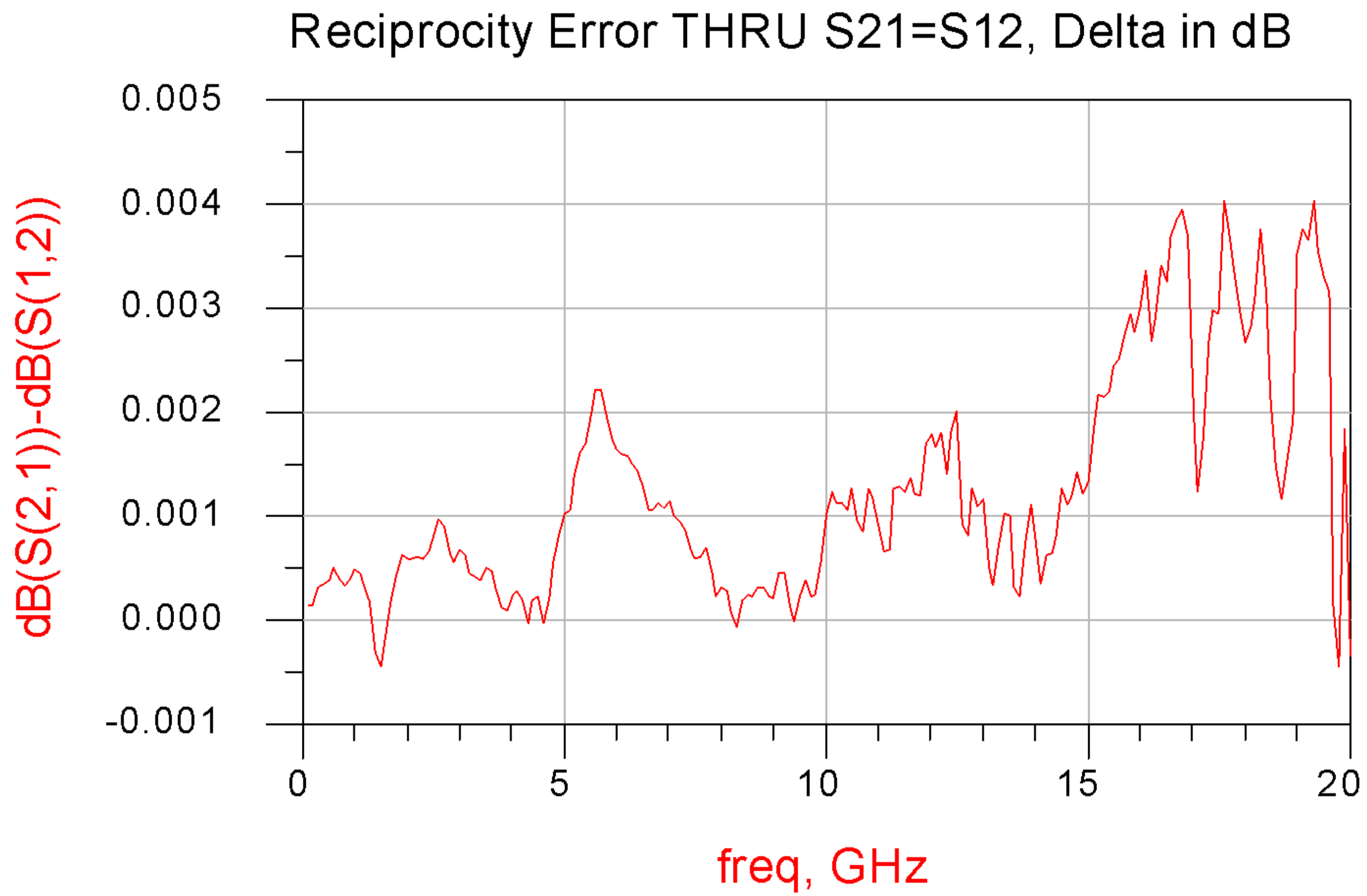
Very Low Reciprocity MAGNITUDE Error, less than 0.005dB



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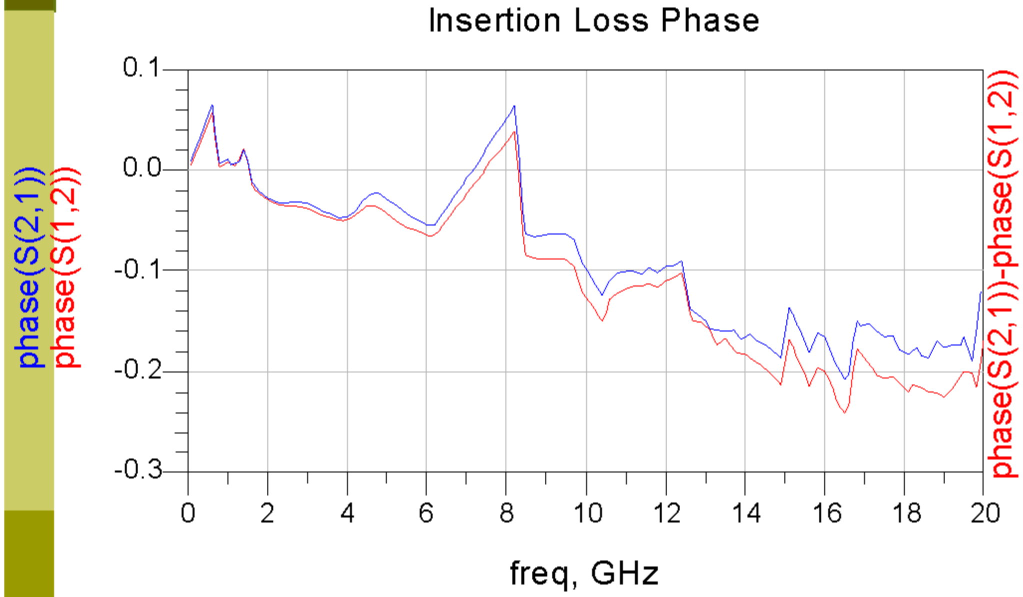
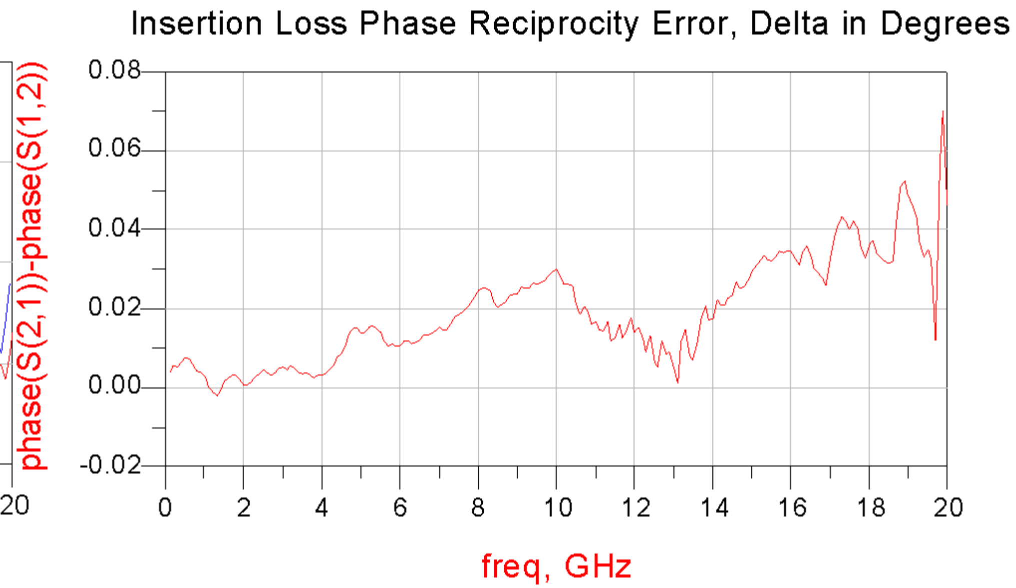
Reciprocity PHASE Error and Reciprocity for THRU Insertion, less than 0.4degrees





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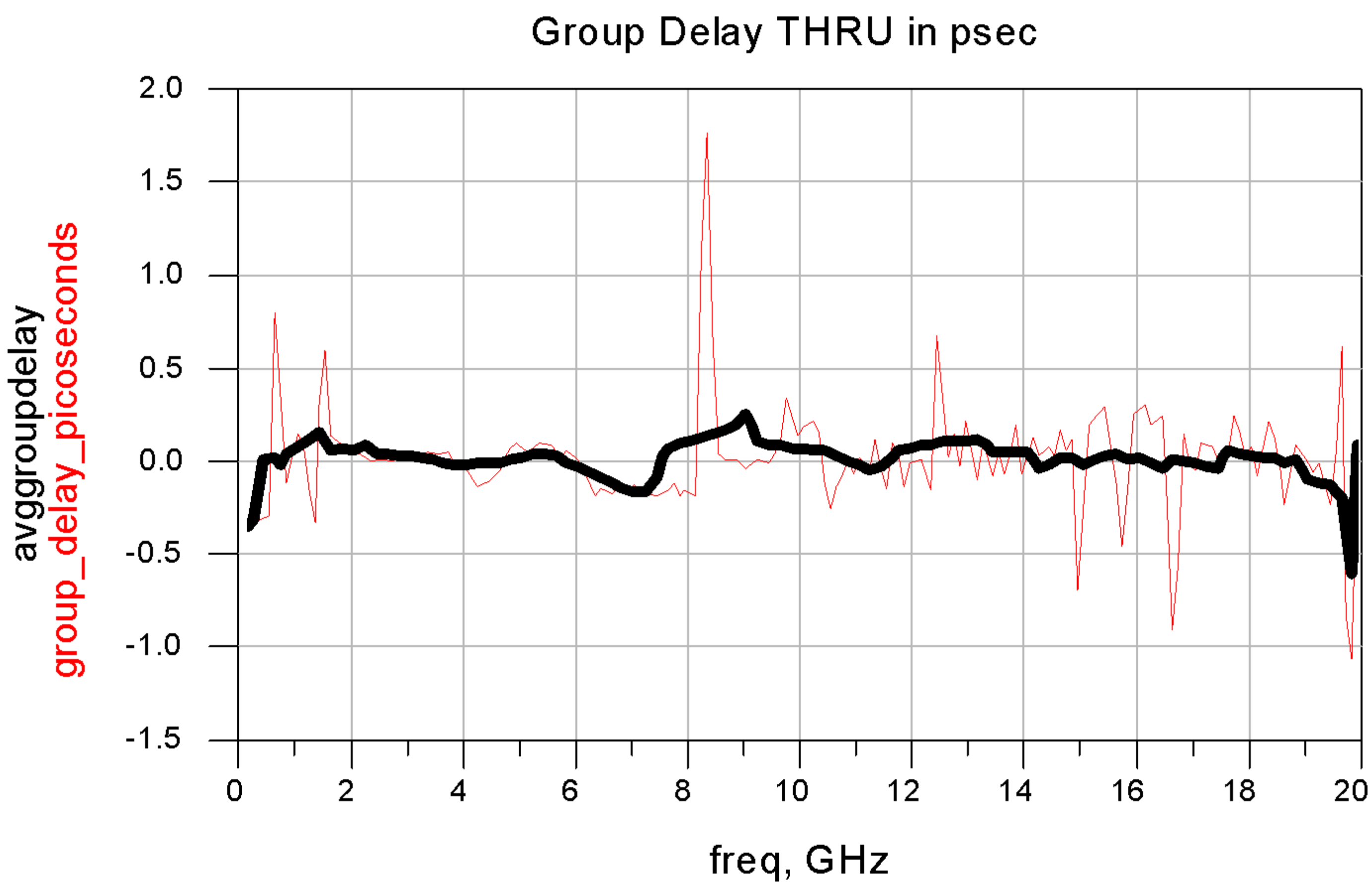
Group Delay and Box Car Average of THRU



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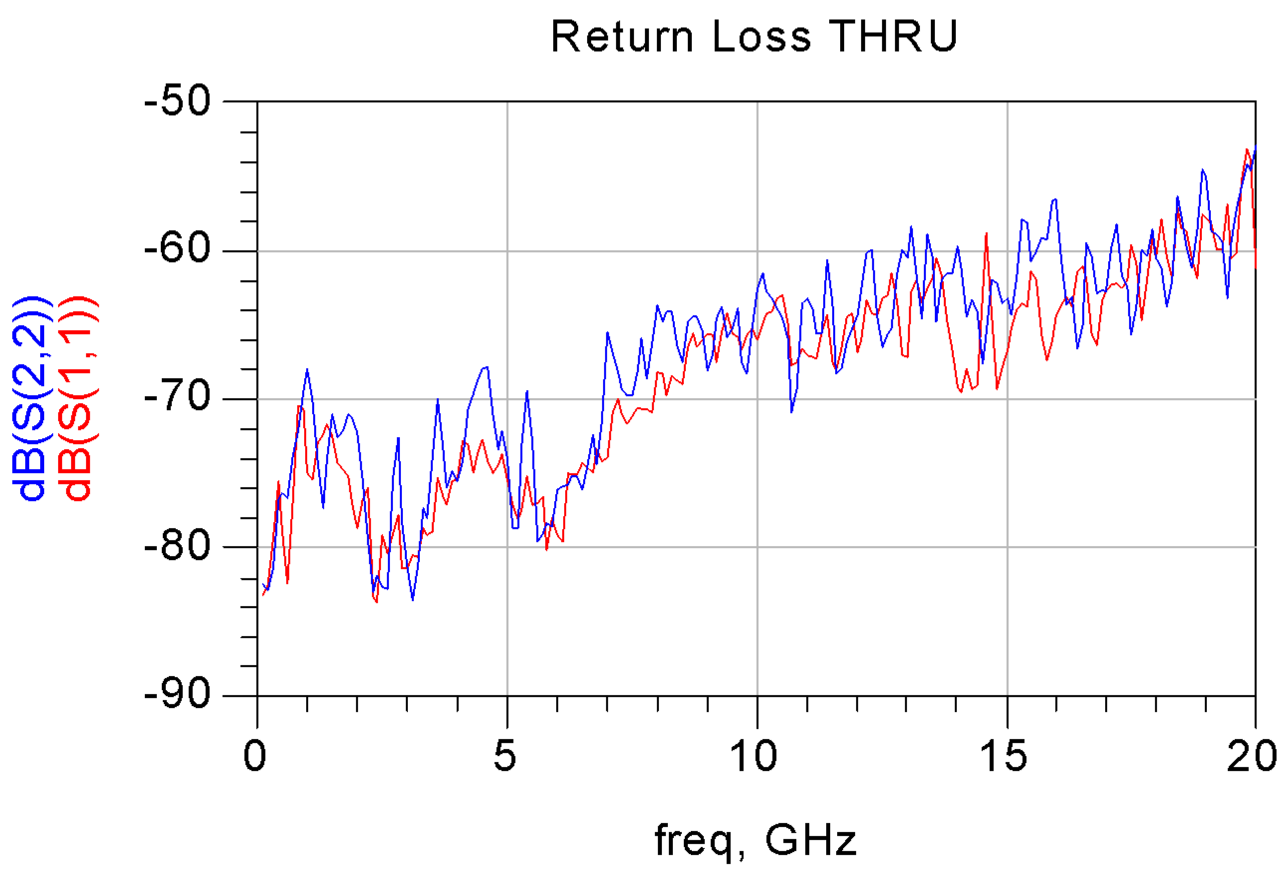
Return Loss THRU



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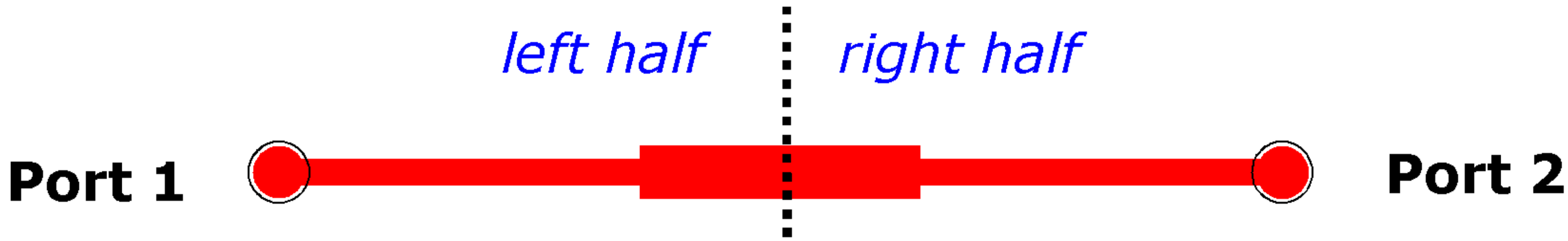
Step 5: Improving TRL De-Embedded Data

Given a simple structure such as Beatty standard:



- Structure has 1st order geometric **symmetry** if (left half)=(right half), or reflection coefficients are equal: **S11=S22**
- Structure is reciprocal if no anisotropic materials used or **S21=S12**
- Structure is passive if no energy generated of *eigenvals*(**S**)<=**1.0**

$$[\,\mathbf{S}\,] = \begin{vmatrix} S11 & S12 \\ S21 & S22 \end{vmatrix}$$

Pain-Free Dielectric Properties Extraction

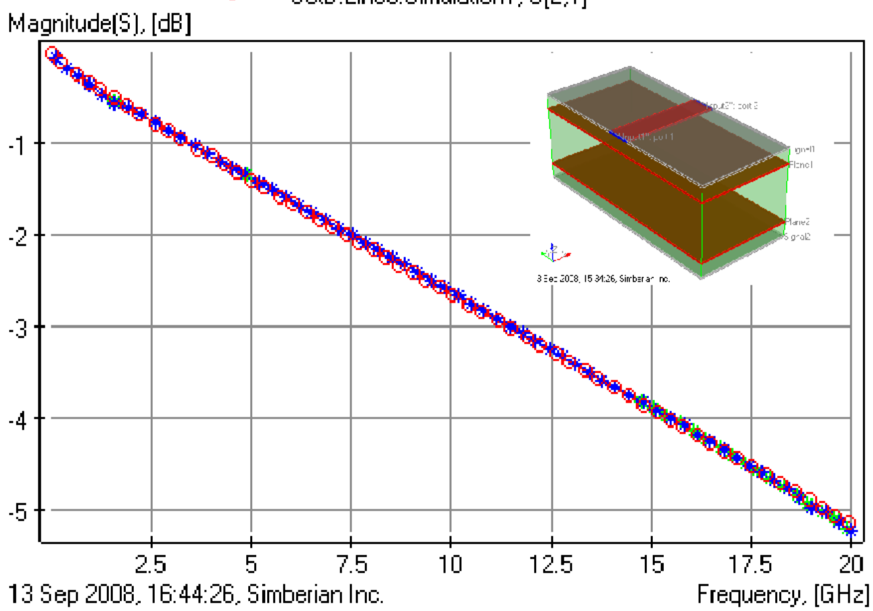
- **Measure** and de-embed S-parameters of two classes of structures:
  - **Line** segments - low reflective structure, very low S11
  - **Resonator** Class - high reflective structure, periodic S21, S11
- Create full-wave model of the structure with **wideband Debye dielectric model**
- **Fit model at one frequency (1 GHz for instance):**
  - Sweep **DK @** 1 GHz and find value with the best correspondence of resonances, transmission coefficient phase and group delay
  - Sweep **LT @** 1 GHz and find value with the best correspondence in transmission coefficient magnitude

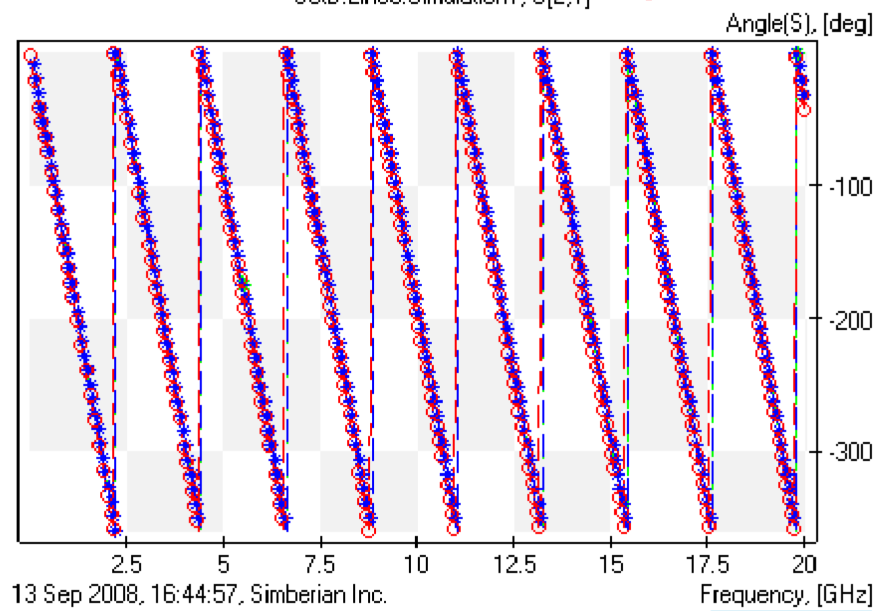
Dielectric Identification: Start with Simple T-line Segment

- 17-mil wide and 3-inch long micro-strip line, TRL de-embedding of the fixture
- Wideband Debye model: DK adjusted to 4.15 @ 1 GHz to have 1% error in phase and LT is adjusted to 0.018 @ 1 GHz to have 1% deviation in magnitude of S[2,1]

Transmission coefficients magnitude and phase

Measured – stars, simulated - circles





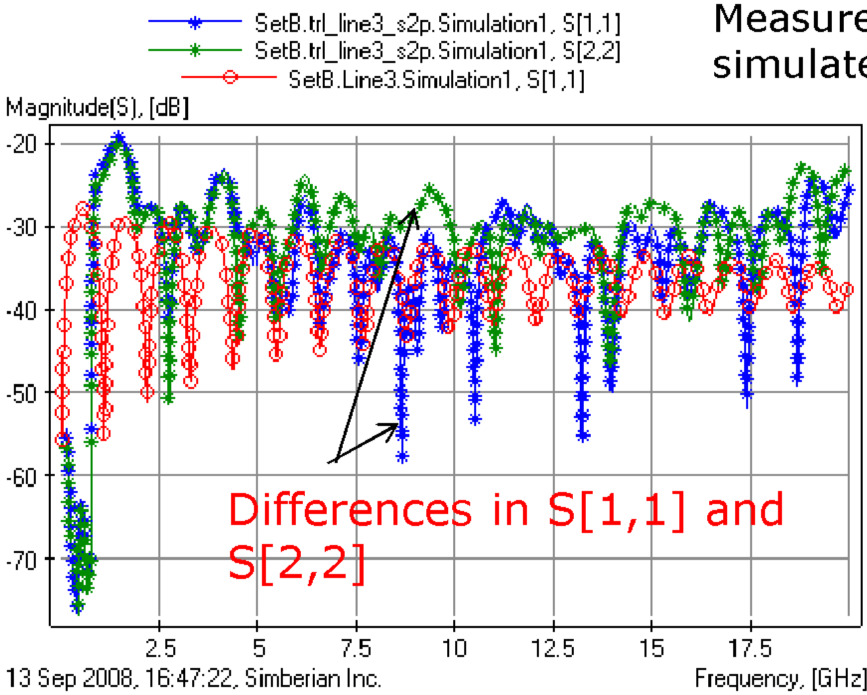
TRL Post Processing Improvment

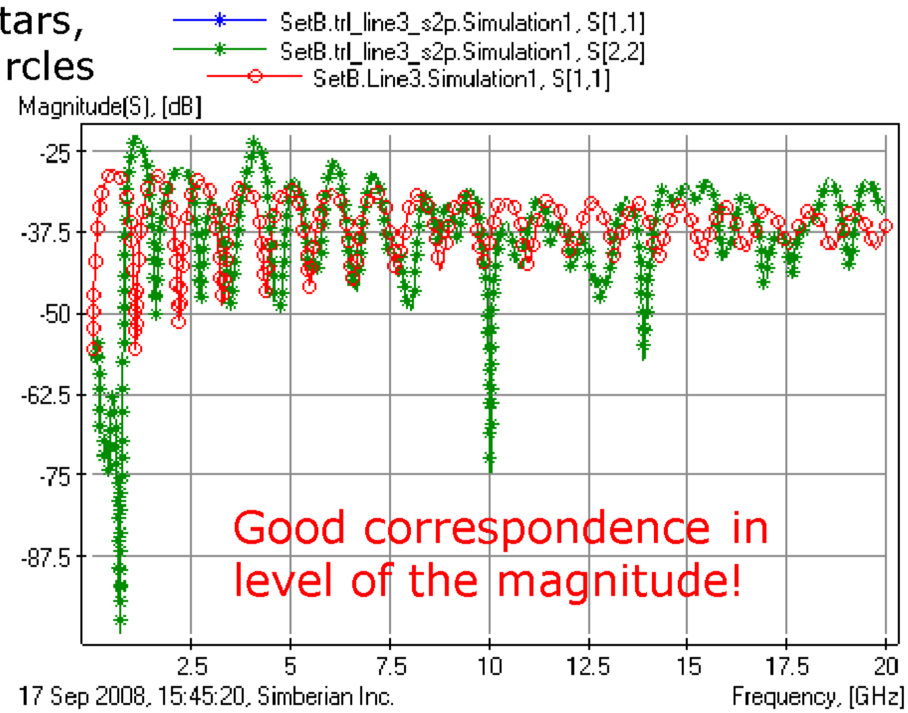
- Reflection coefficients magnitude of 3-inch micro-strip line

Original measured data – noise and non-symmetry of extracted S-parameters

After passivity, symmetry and reciprocity is enforced and data are filtered with 16th order filter

Measured – stars, simulated - circles

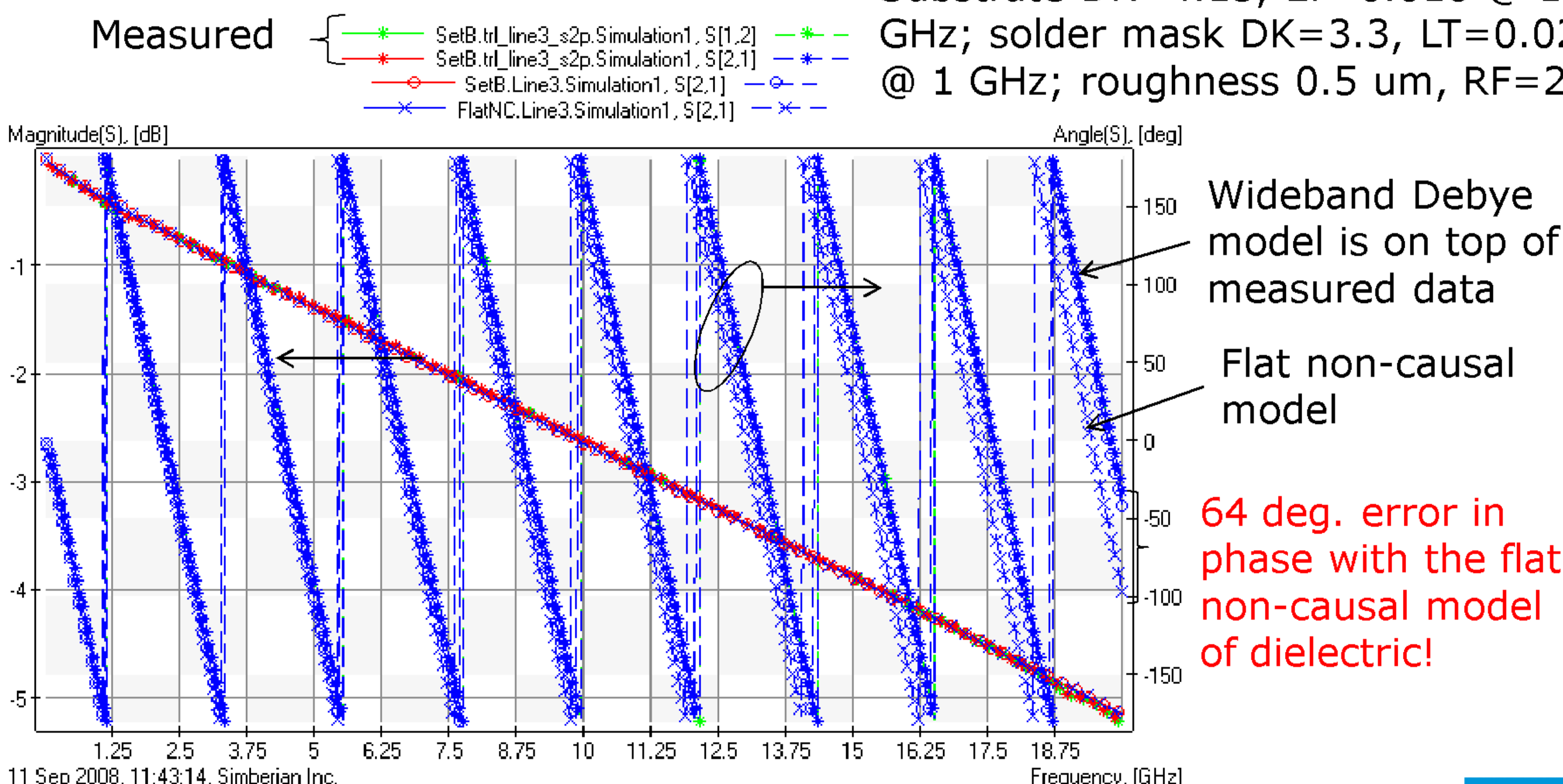




Dispersion Model Confirmation: Insertion Loss and Phase Delay

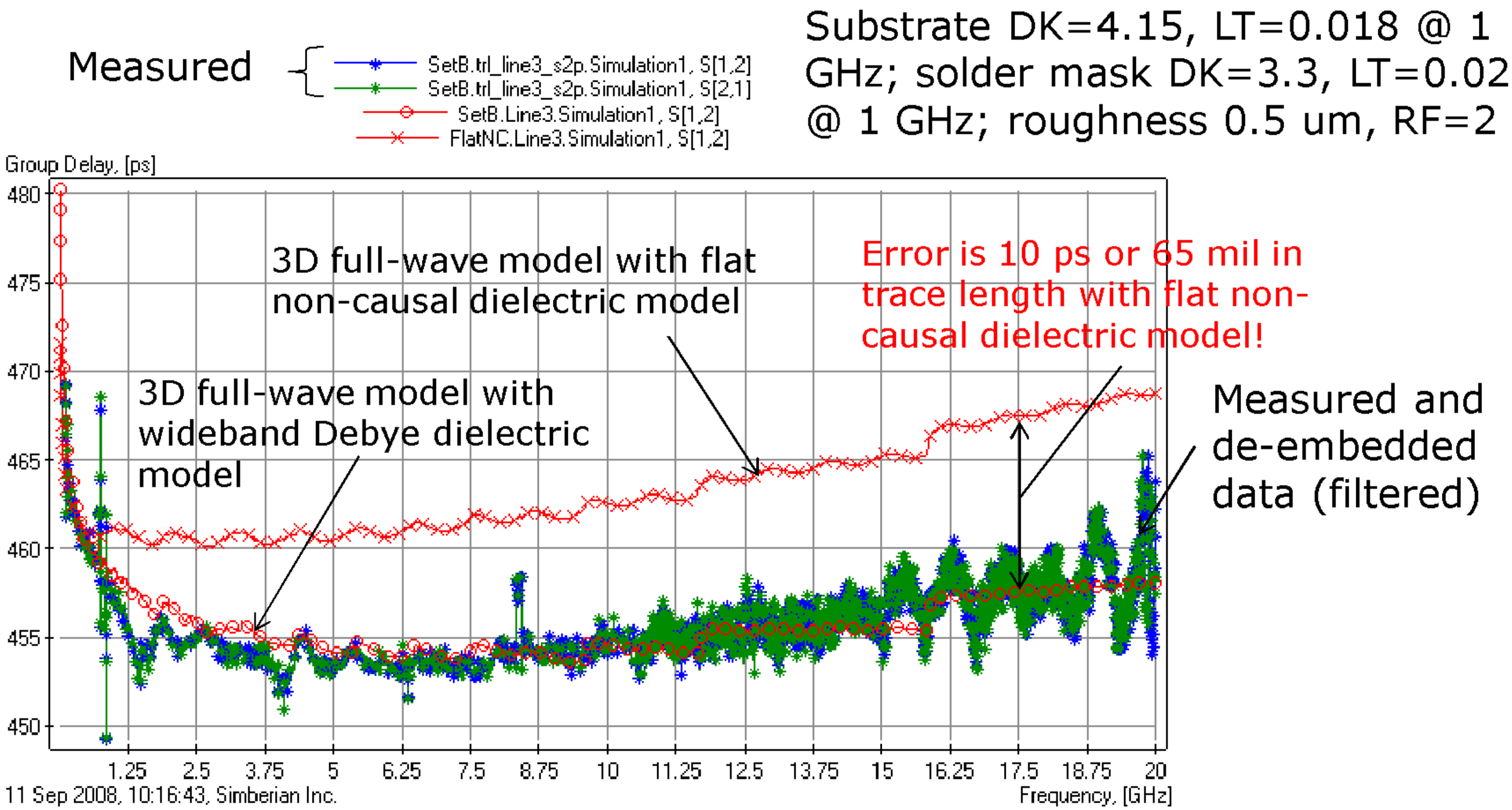
- Magnitude and angle of the transmission coefficient S[2,1] of 3-inch micro-strip line

Substrate DK=4.15, LT=0.018 @ 1 GHz; solder mask DK=3.3, LT=0.02 @ 1 GHz; roughness 0.5 um, RF=2

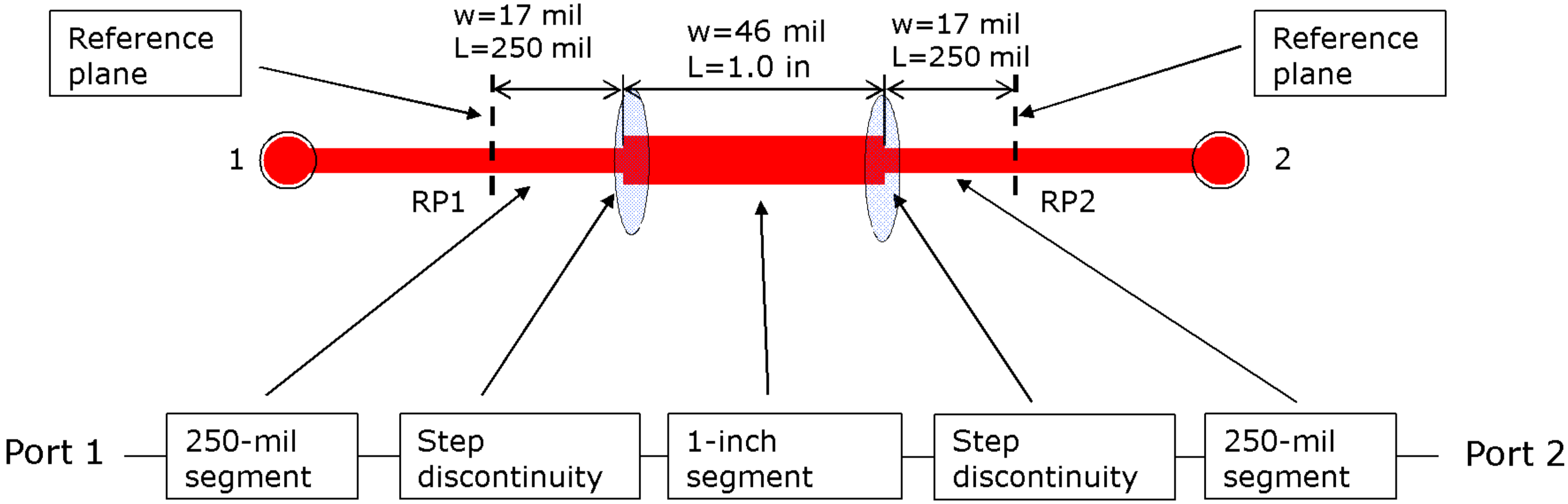


Dispersion Model Confirmation: Group Delay

- Group delay in 3-inch micro-strip line



Dielectric Identification with S-parameters of Resonator (Beatty 25 Ohm)



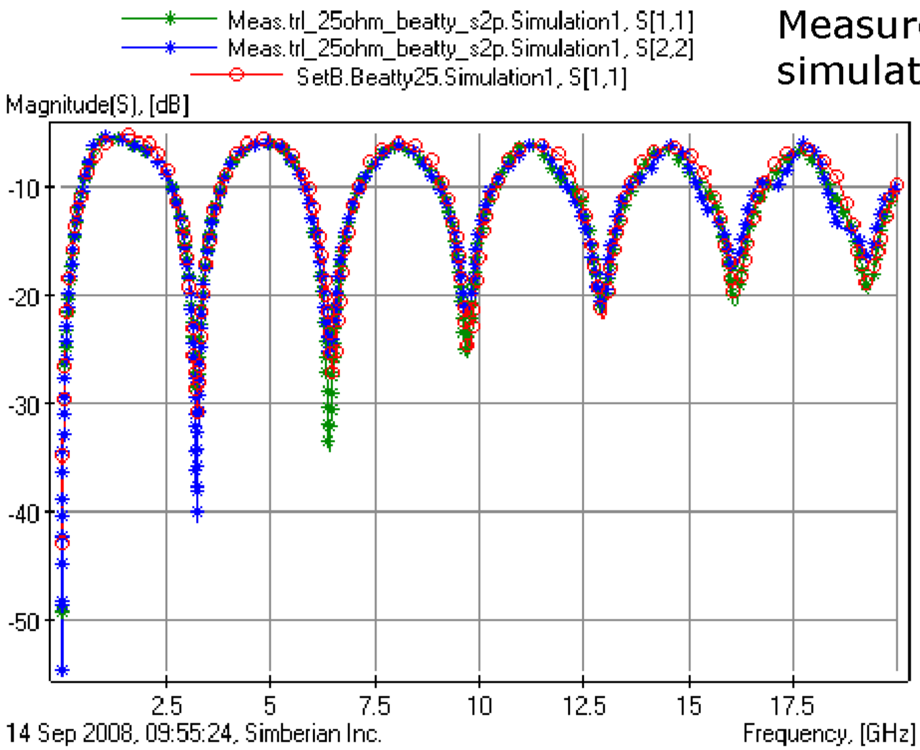
- 1-inch segment of micro-strip line with lower impedance connected with two segments of 50-Ohm micro-strip line

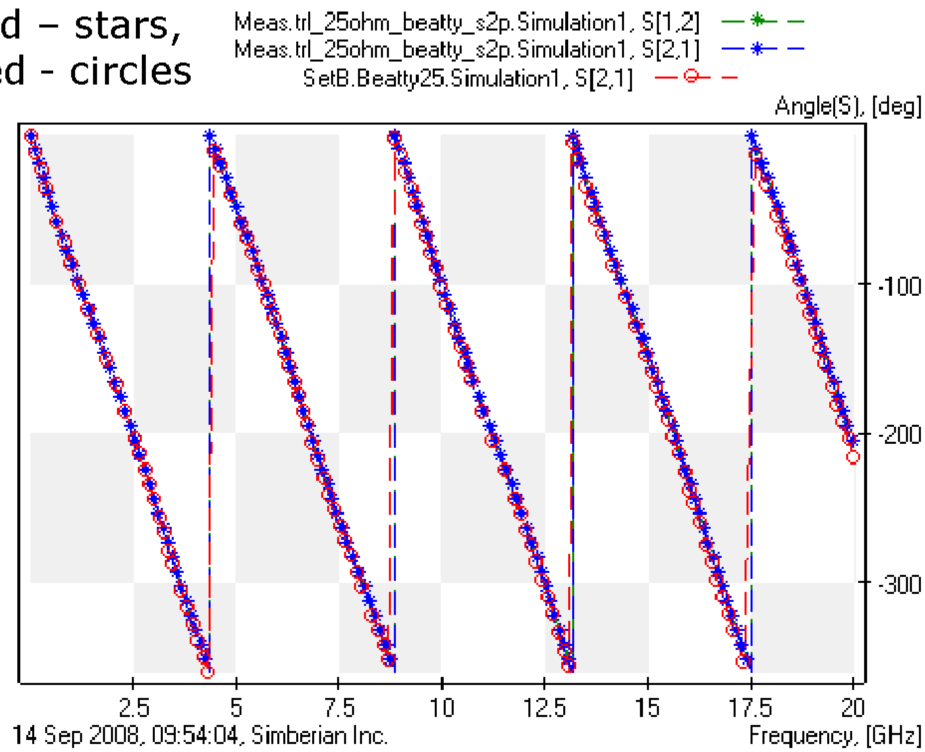
Dielectric Identification with Beatty 25-Ohm Resonator (TRL)

- Wideband Debye model: DK adjusted to 3.9 @ 1 GHz to have 1% error in phase of transmission coefficient and in position of the resonances in reflection

Reflection coefficients magnitude | Transmission coefficients phase

Measured – stars, simulated - circles



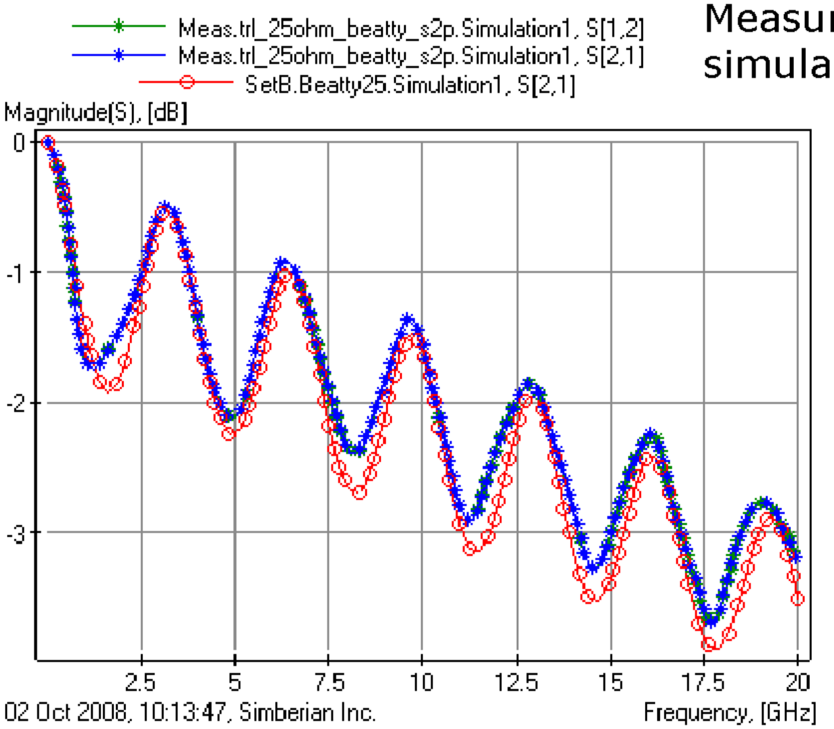


Dielectric Identification with Beatty 25-Ohm Resonator (TRL)

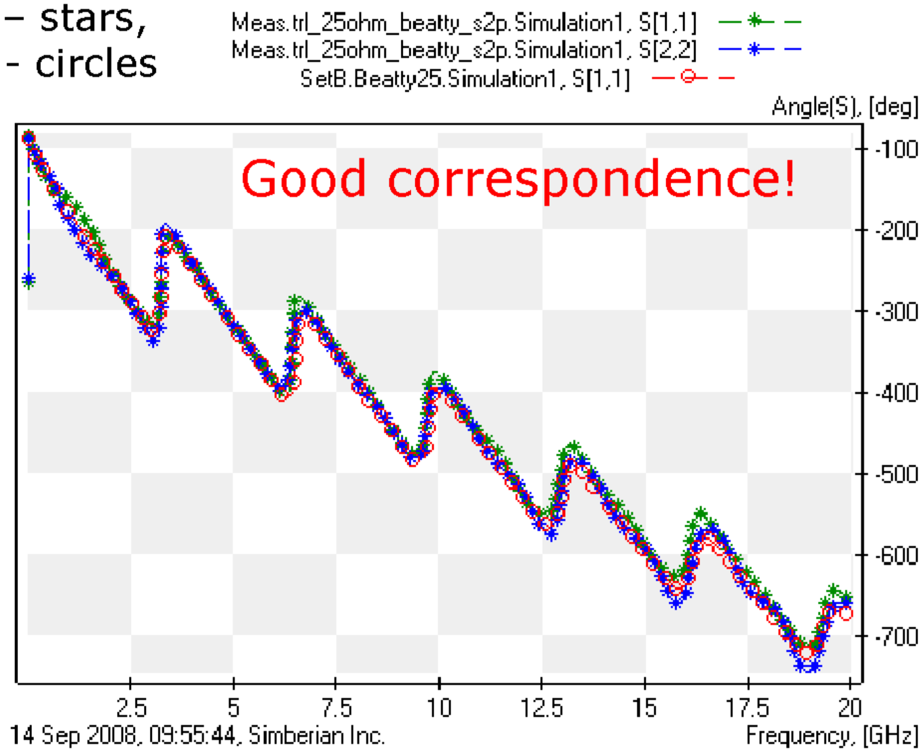
- Wideband Debye model: LT adjusted to 0.018 @ 1 GHz to minimize the difference in measured and calculated transmission coefficient

Transmission coefficients magnitude

Measured – stars, simulated - circles



Reflection coefficients phase

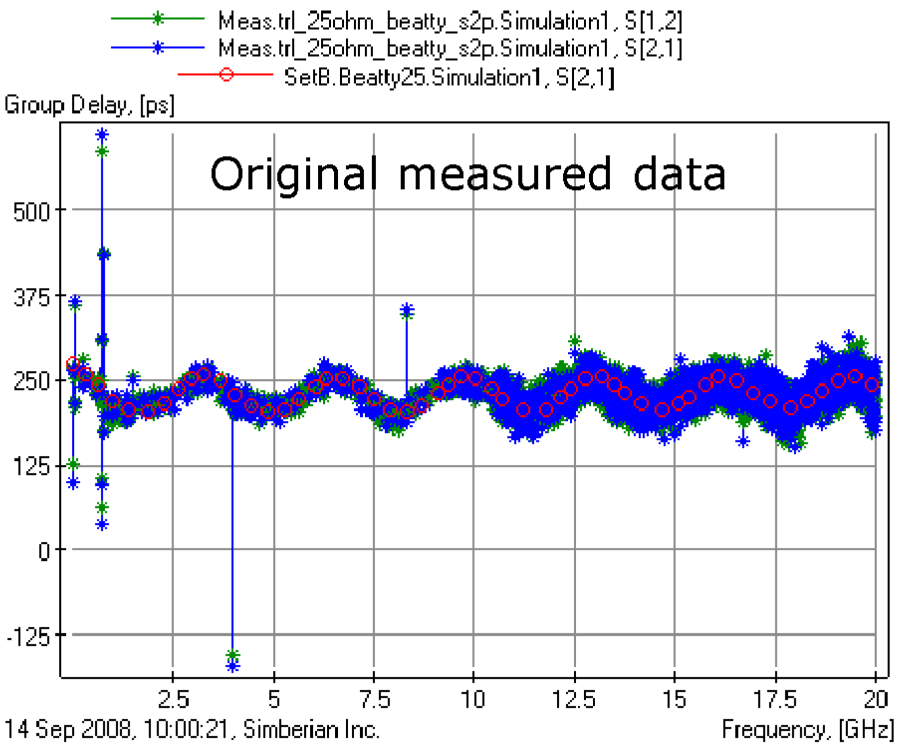


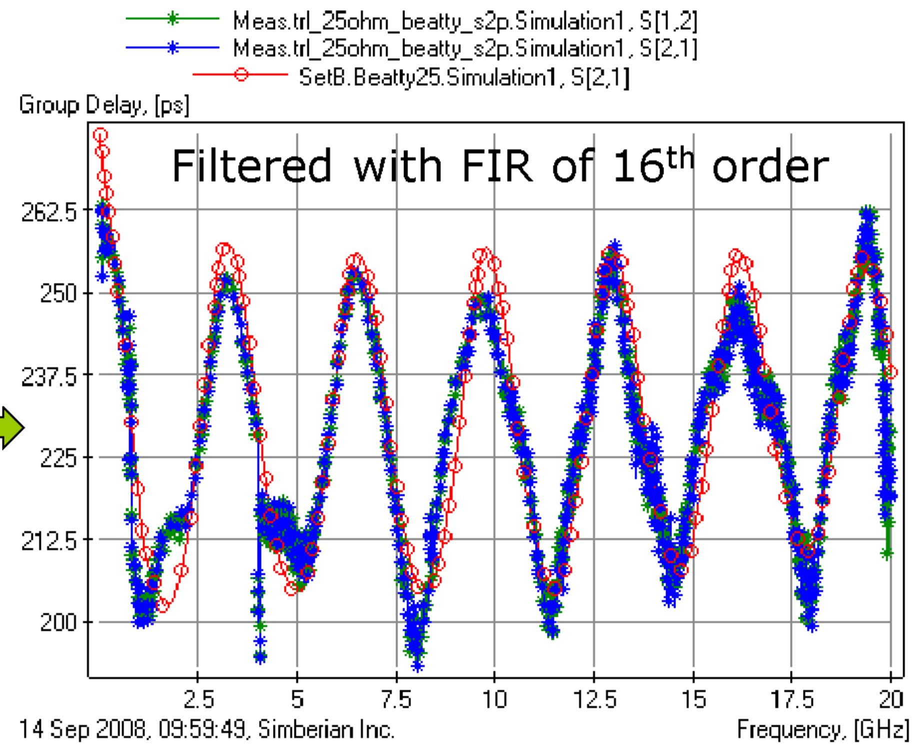
S-parameters Quality Improvement

- Group delay of Beatty 25-Ohm resonator

Measured – stars, simulated - circles

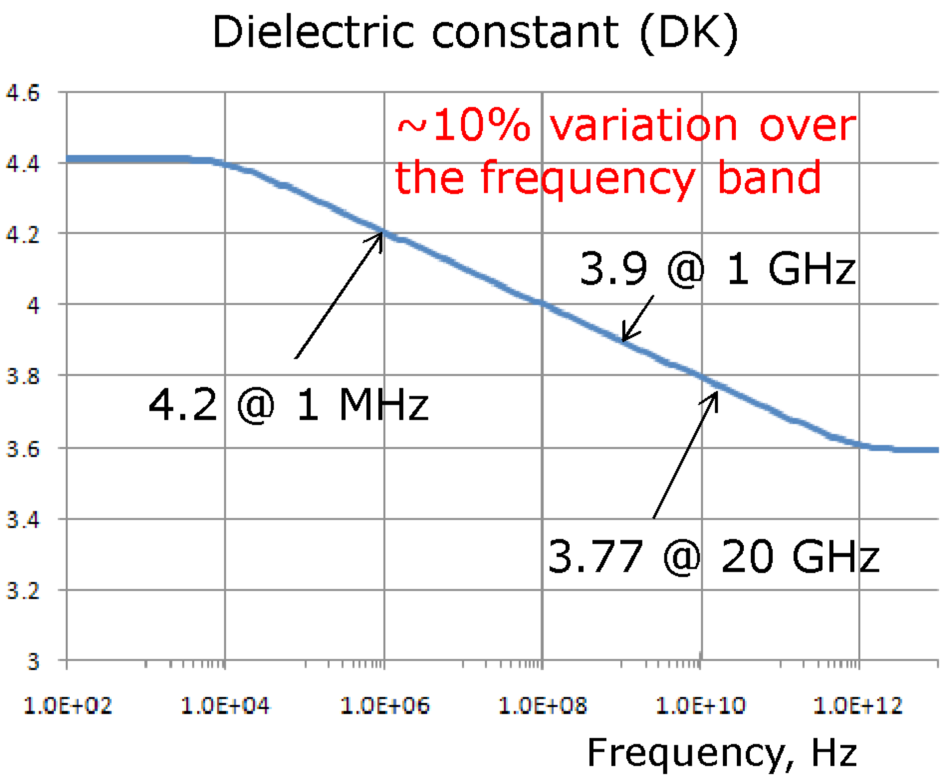
Good correspondence!

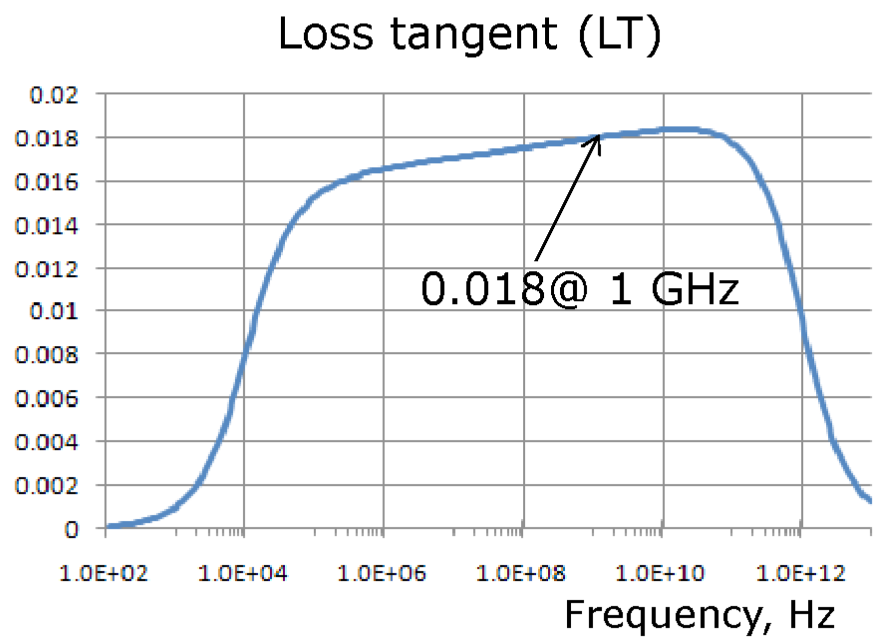




Dielectric Loss and Dispersion Model Extracted with the Beatty 25-Ohm Resonator

- DK=3.9 and LT=0.018 @ 1 GHz – this is all we need to restore frequency-dependent loss and dispersion!

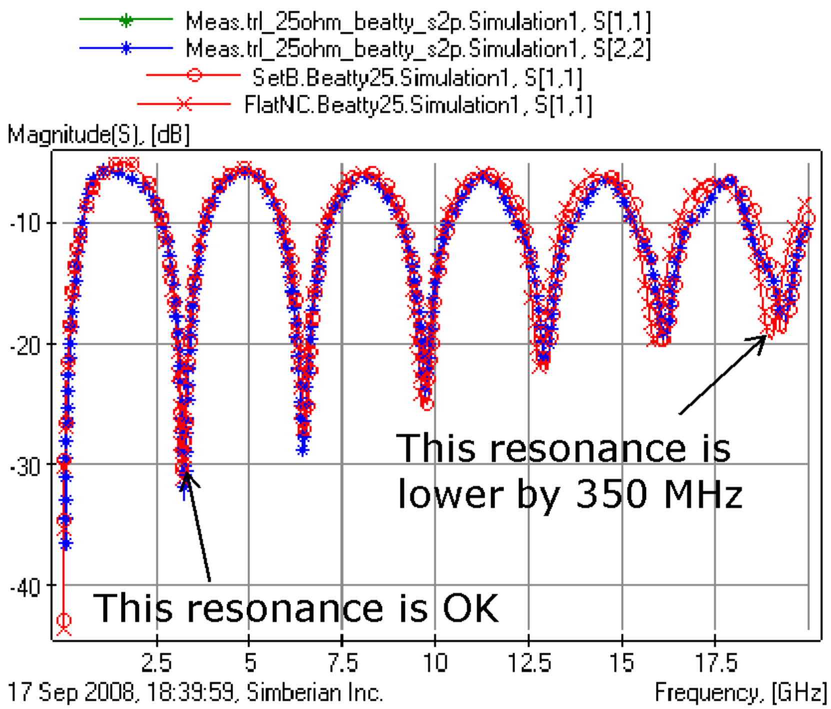


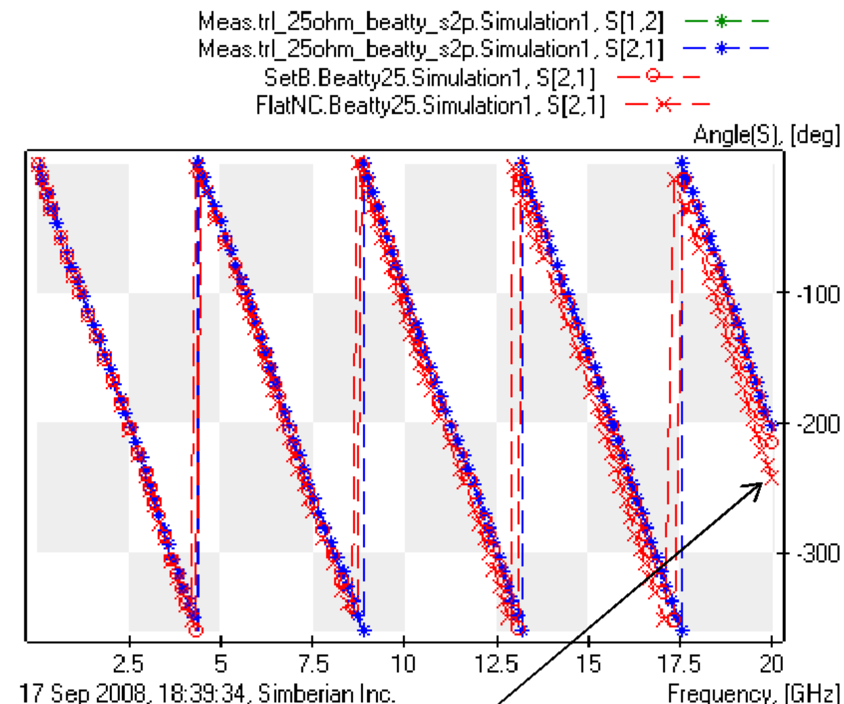


Dispersion Model Confirmation

Stars – measured, circles – simulated with wideband Debye model for substrate and solder mask with DK=3.9, LT=0.02 and DK=3.3 and LT=0.02 @ 1 GHz, crosses – simulated with flat non-causal models with the same DK and LT not changing with frequency.

It is 1-inch resonator! The difference will be up to 1 GHz in 3-inch structures.
(see E.L. Holzman, IEEE Trans. on MTT, v. 54, N7, p. 3127)





The effect is stronger for strip-lines (no compensation with high-frequency dispersion)!

Phase is larger by 40 degrees

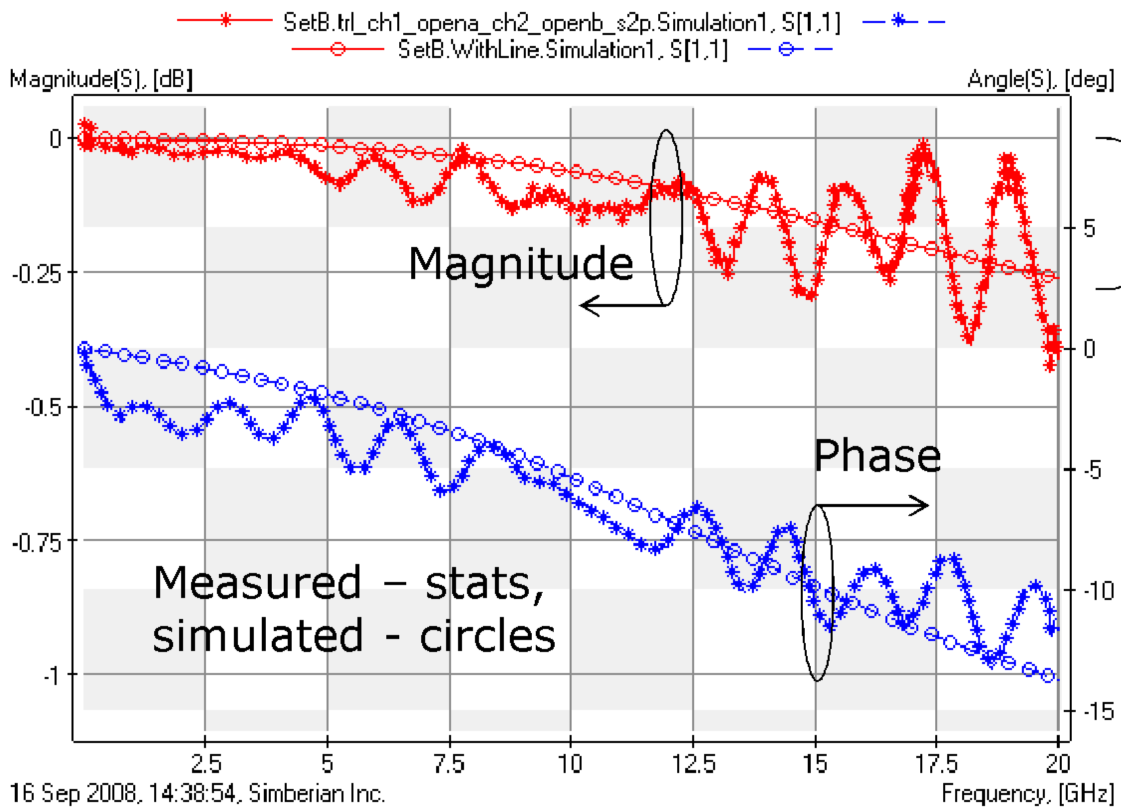
Results of Dielectric Identification with T-Line Segments and Beatty Standards

- Wideband Debye model confirmed to be best dispersion model
- Established 2 corner values of Dk and LT using Lines
  - DK ranges from 3.9 to 4.25 (about 8%)
  - LT ranges from 0.018 to 0.02 (about 10%)
- Extraction with S-parameters of 4 resonators (2 Beatty and 2 stub)
  - Extracted DK ranges from 3.9 to 4.0 (about 2.5%)
  - Extracted LT ranges from 0.018 to 0.02 (about 10%)
- Possible sources of variations in identified parameters
  - Fiber and resin mixture is different below each structure – TDR shows different impedances and variation of impedance along the lines
  - Differences in investigated samples and de-embedding fixtures
  - Differences in physical dimensions of the actual and investigated structures

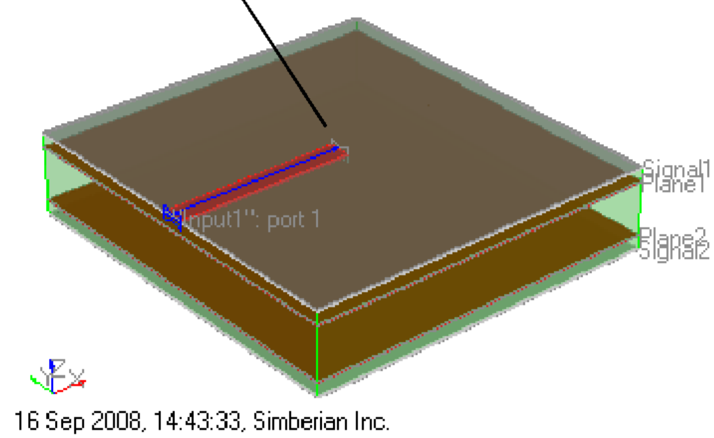
Open End: Comparison with TRL De-Embedded Measurements

- Line width 17 mil, FR4 Wideband Debye, Dk=4.0, LT=0.02 at 1 GHz
- Solder mask: Wideband Debye, Dk=3.3, LT=0.02 at 1 GHz
- RMS roughness 0.5 um, roughness factor 2

Good correspondence!

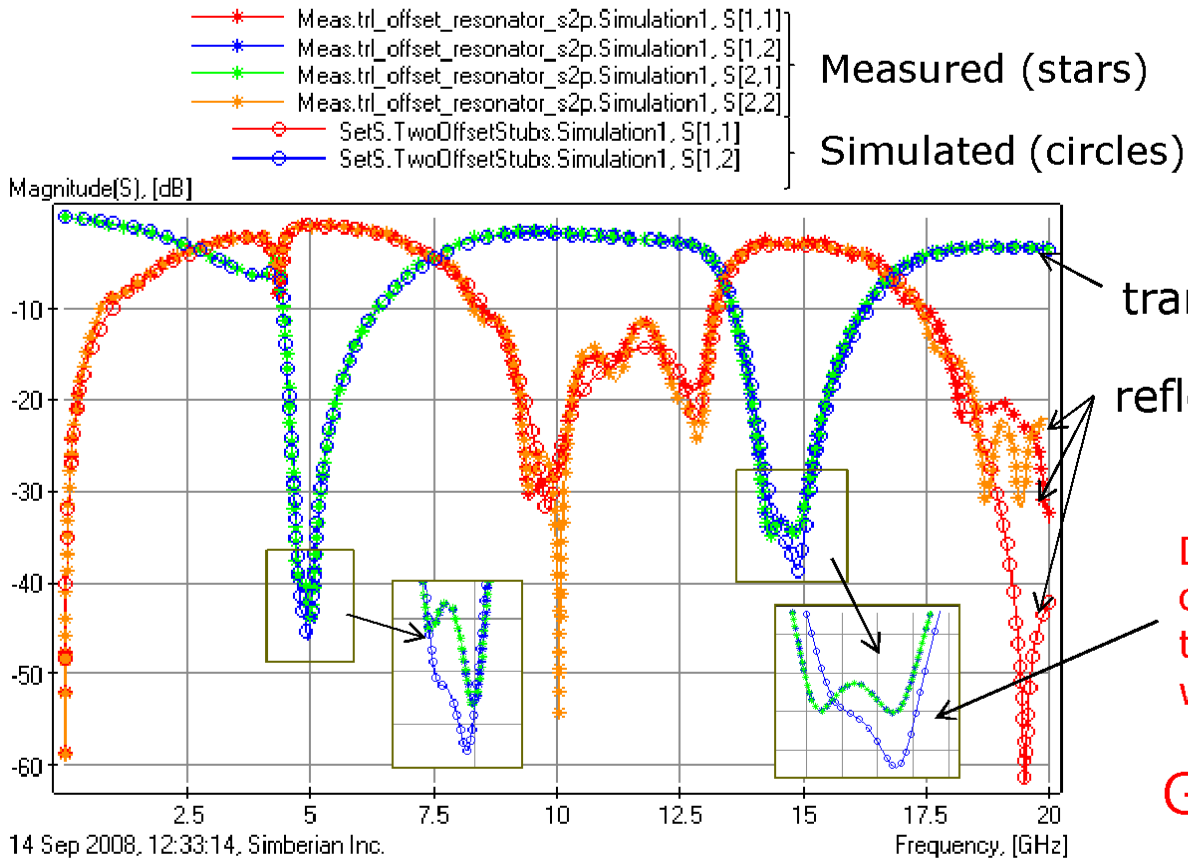


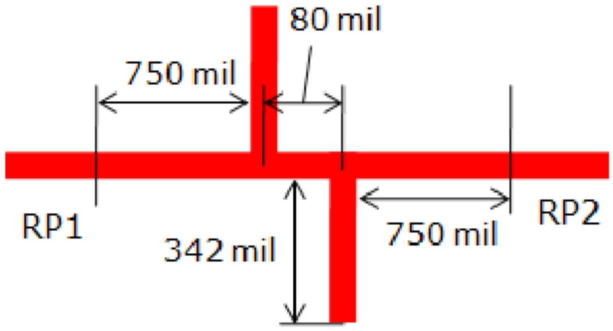
Radiation loss!



Offset Stubs: Comparison with TRL De-Embedded Measurements

- Magnitudes of S-parameters





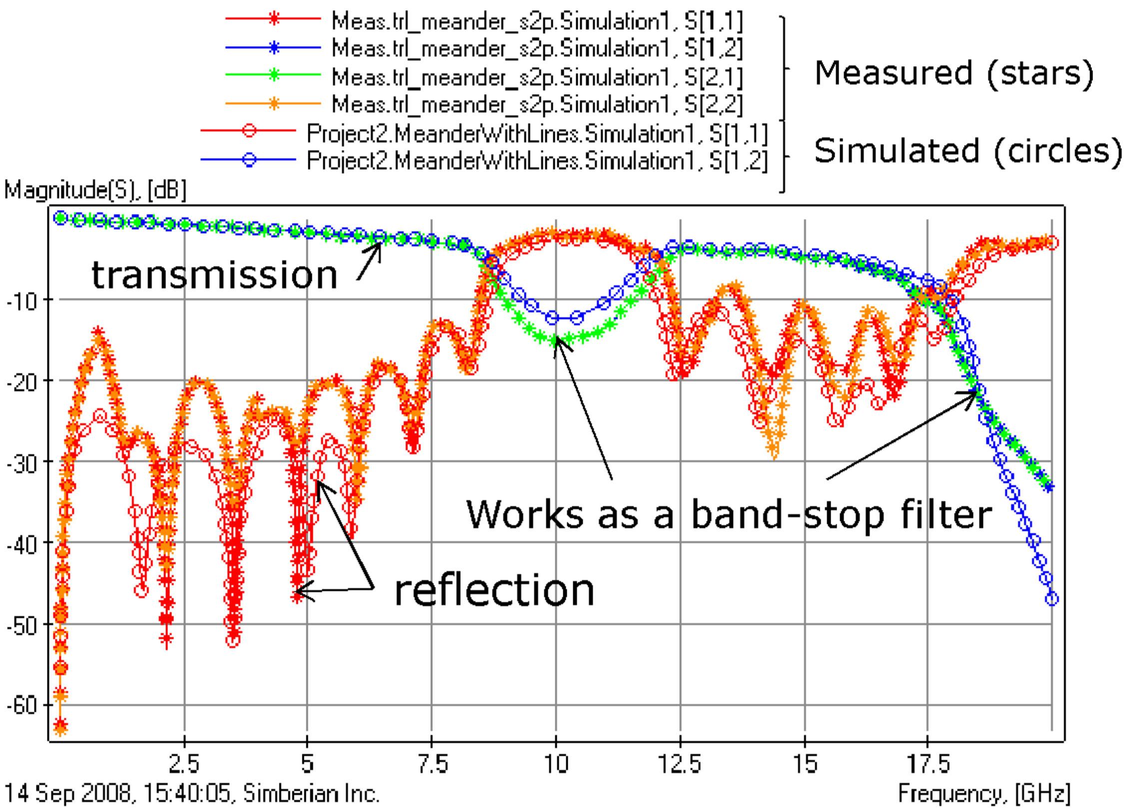
DK=4.0, LT=0.02 @ 1 GHz

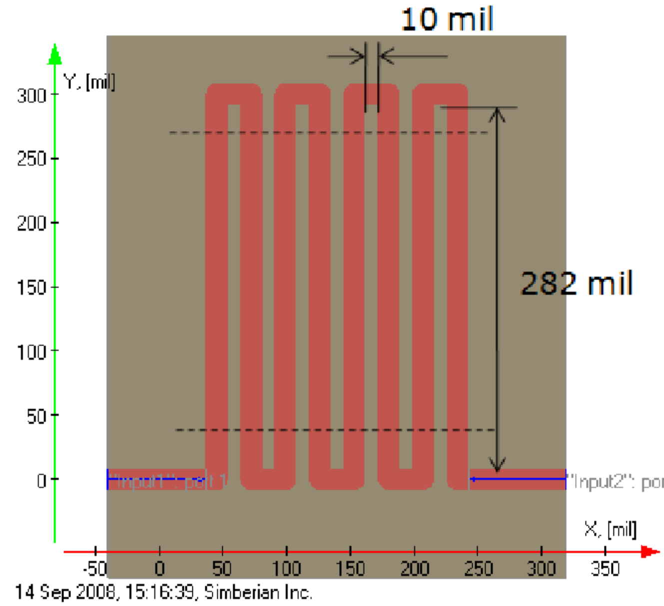
Double resonances is the effect of high-order modes between two tees (can be captured only with the full-wave analysis)

Good correspondence!

Meandering Line: Comparison with TRL De-Embedded Measurements

- Magnitudes of S-parameters



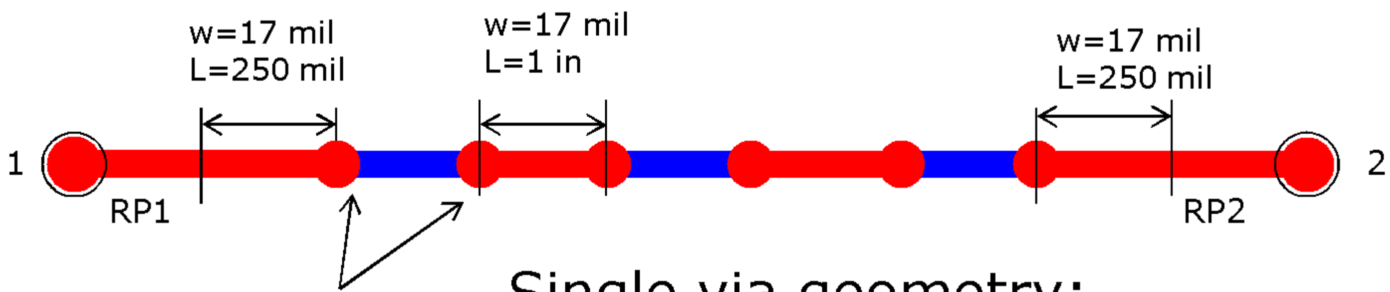


17-mil micro-strip, 390 mil of straight line on both sides, DK=4.0, LT=0.02 @ 1 GHz

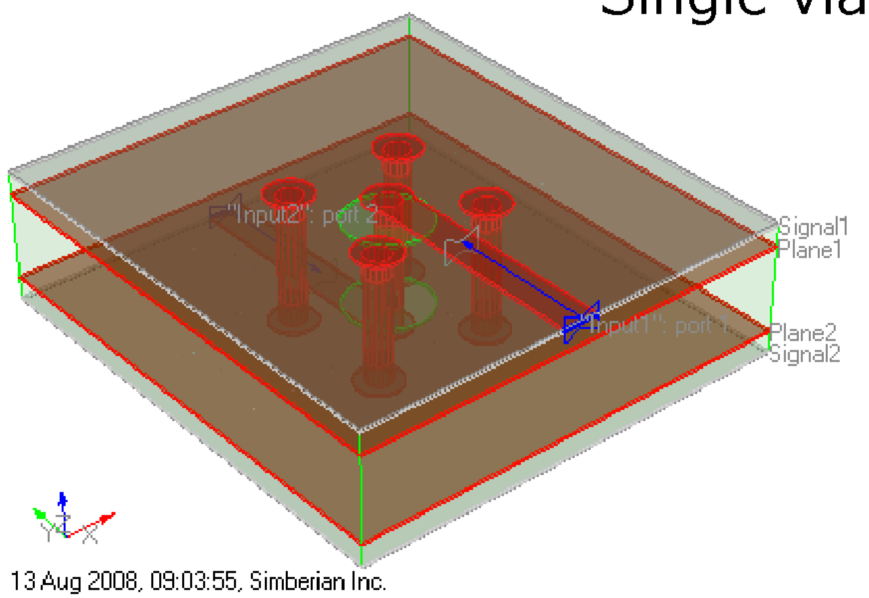
Acceptable correspondence!

Multiple Via-Hole Transitions Through Board

- 6 through via-holes with 4 stitching vias, separated by 1 inch segments of 17 mil micro-strip line, de-embedded to reference planes RP1 and RP2



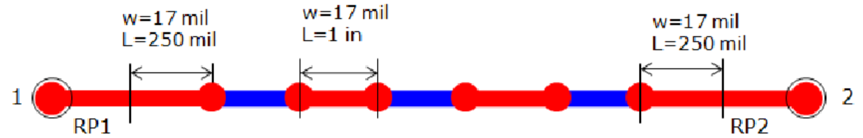
Single via geometry:

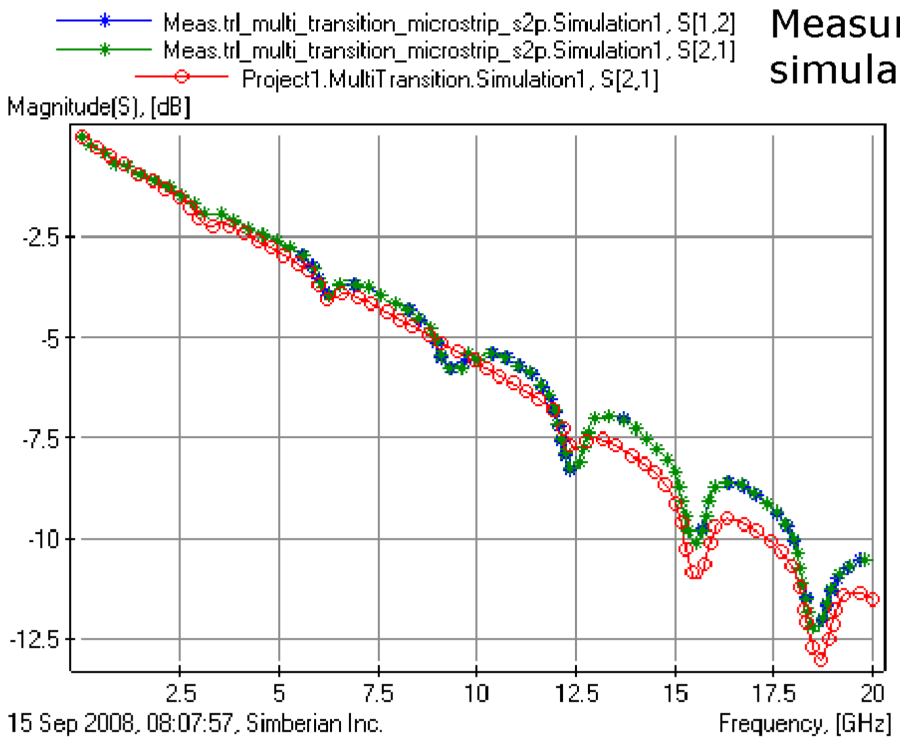


Top and bottom substrate: DK=4.0, LT=0.02 @ 1 GHz
Core: DK=4.7, LT=0.02 @ 1 GHz
Diameters of all vias are 12 mil
Pad diameter for all via is 22 mil
Antipad diameter is 40 mil
Distance between signal and stitching via is 40 mil

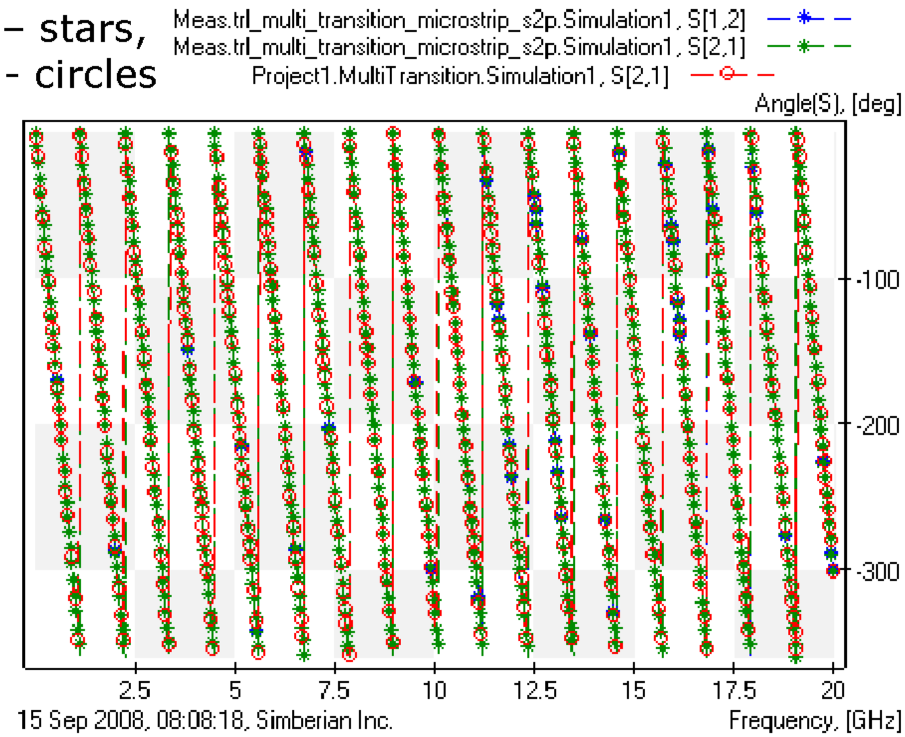
Multi-Via Transition: Comparison with TRL De-Embedded Measurements

- Transmission coefficients magnitude and phase





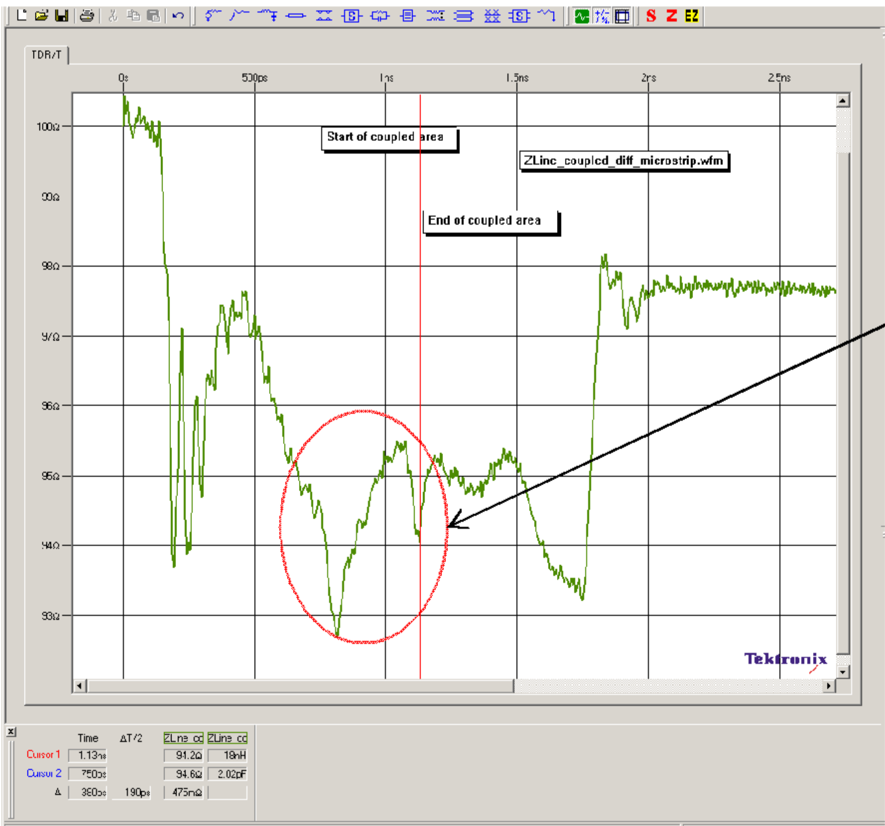
Measured – stars, simulated - circles

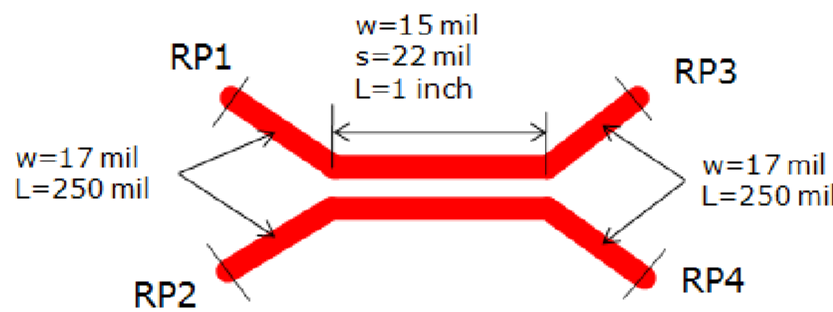


Acceptable correspondence!

Differential Micro-Strip Line Segment (TDR)

1-inch long coupled micro-strip line with 250-mil segment of 17-mil micro-strip lines



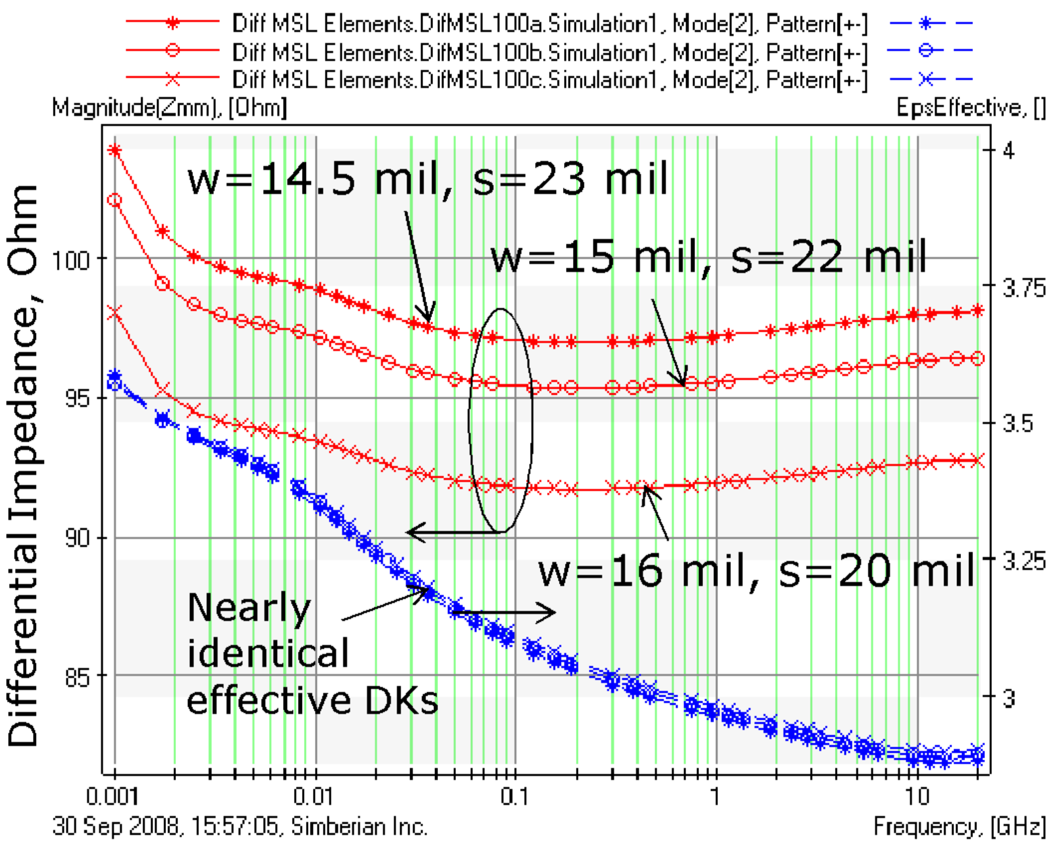


From 93 to 95 Ohm instead of expected 100!

Possible effect of plating, wider traces and conformal solder mask layer

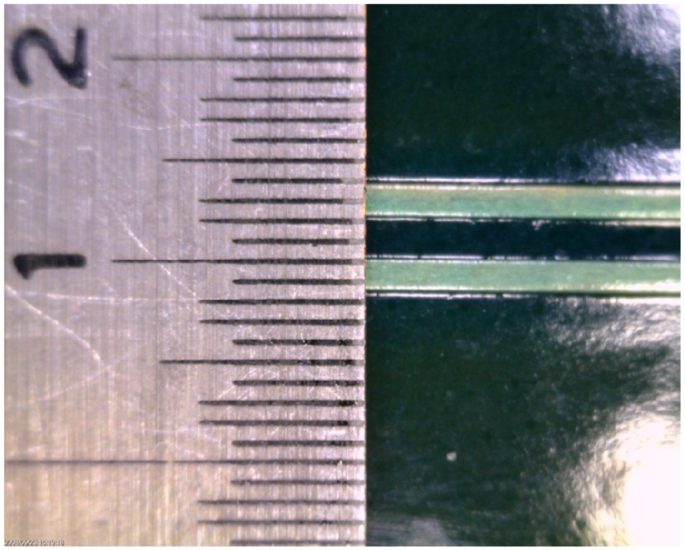
Effect of Strip Width on Differential Impedance

- Metallization is 3 mil thick (instead of expected 1.35 mil), strips are wider



DK=4.25, LT=0.02 at 1 GHz

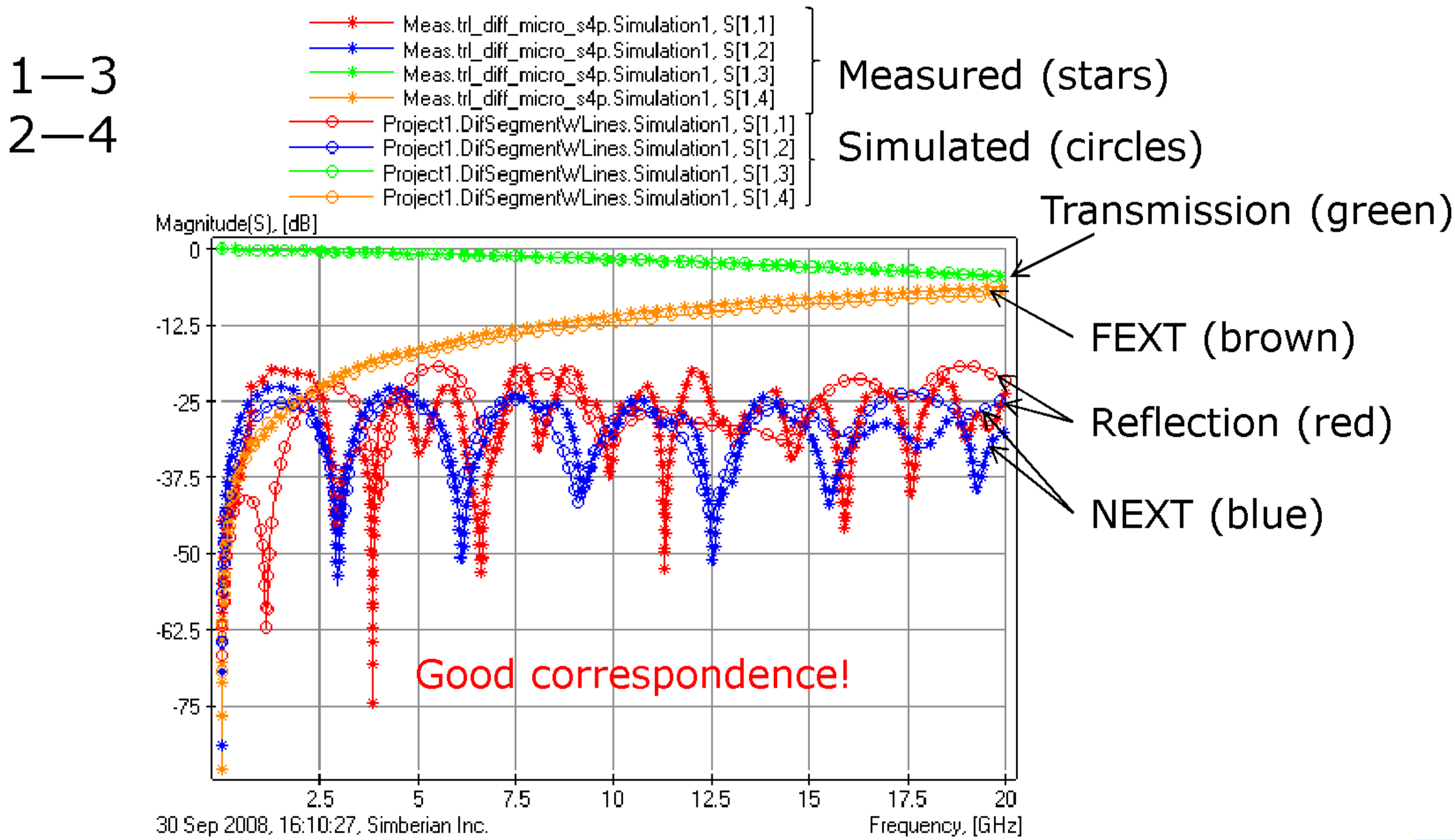
The variations 1.5 mil are within the manufacturing tolerance!



We will use w=15 mil, s=22 mil as the closest to measured on the board and to TDR profile and

Differential Segment: Comparison with TRL De-Embedded Measurements

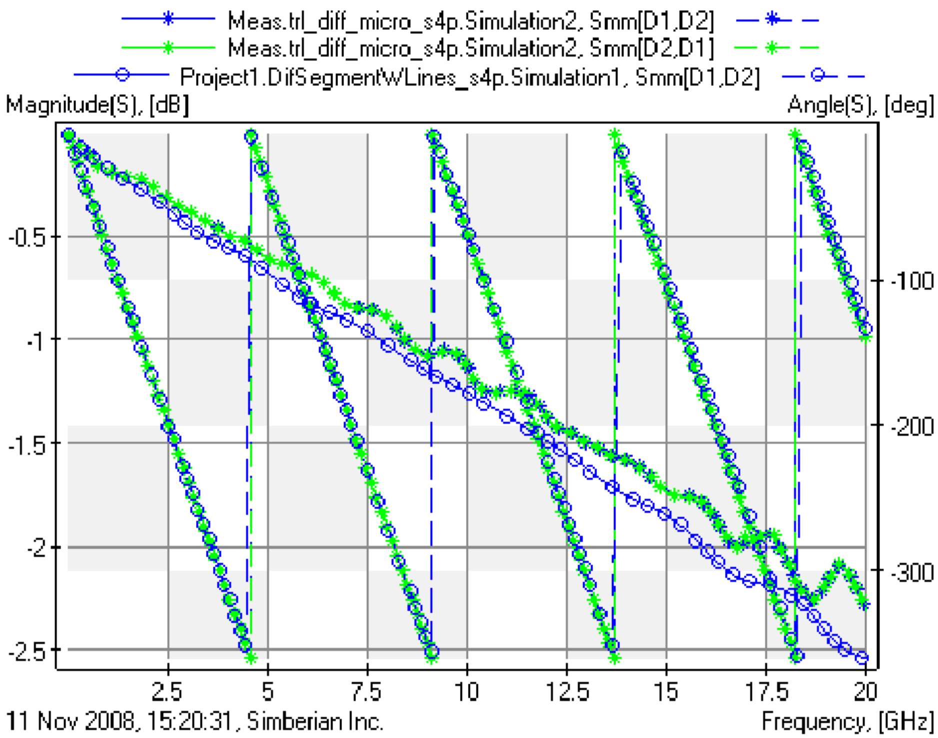
- Magnitudes of single-ended S-parameters (1 row)



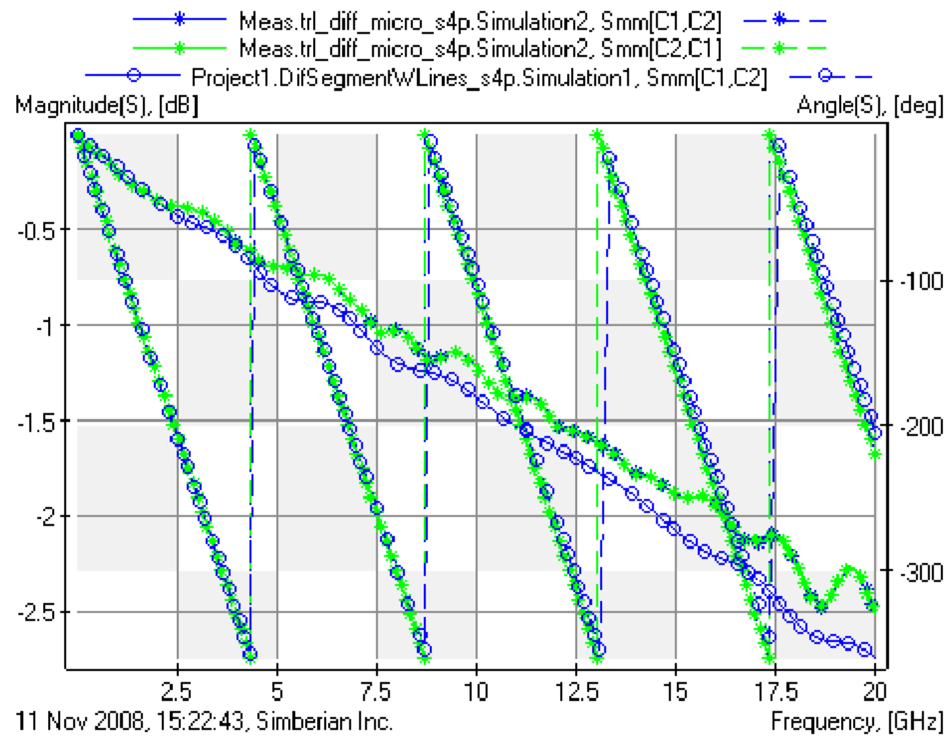
Differential Segment: Comparison with TRL De-Embedded Measurements

- Magnitudes of mixed-mode S-parameters

Differential mode transmission magnitude and phase:



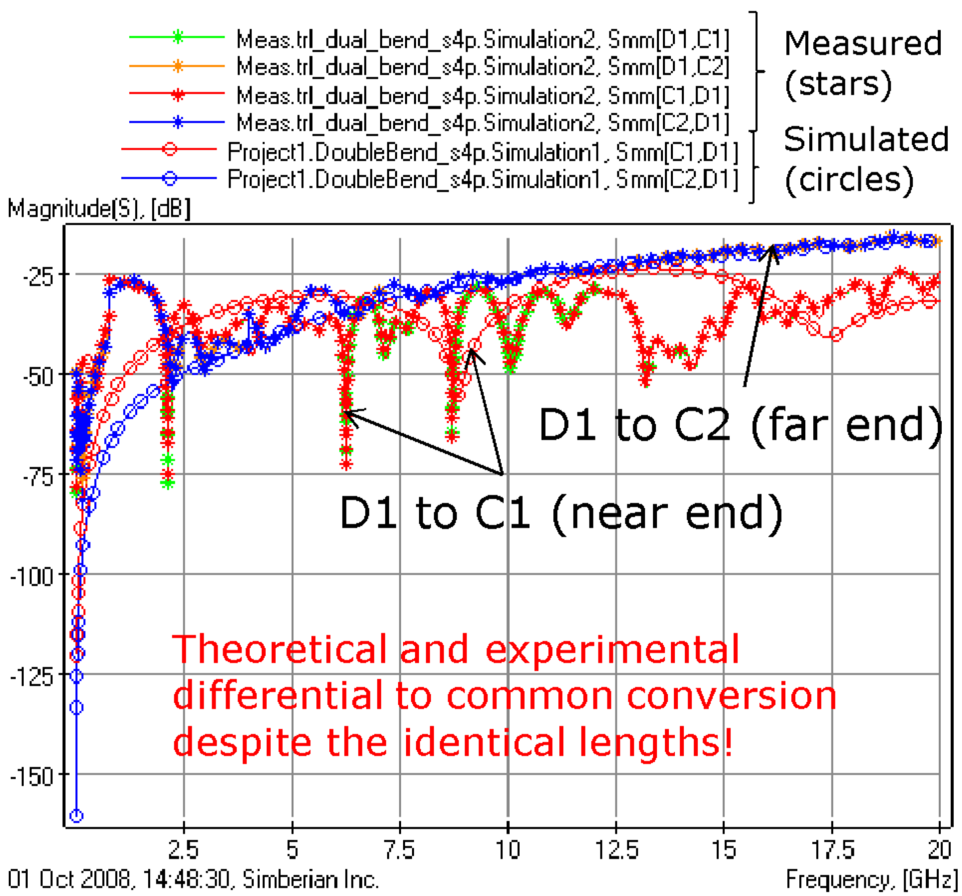
Common mode transmission magnitude and phase:

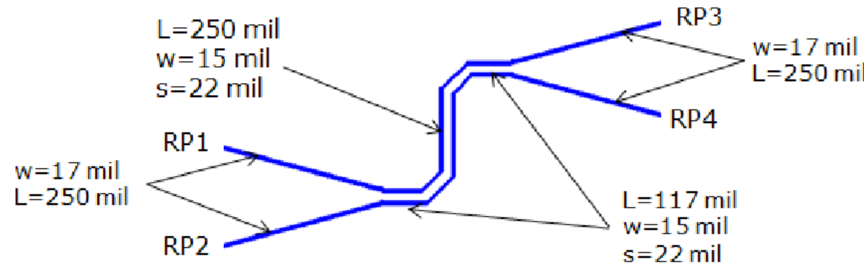


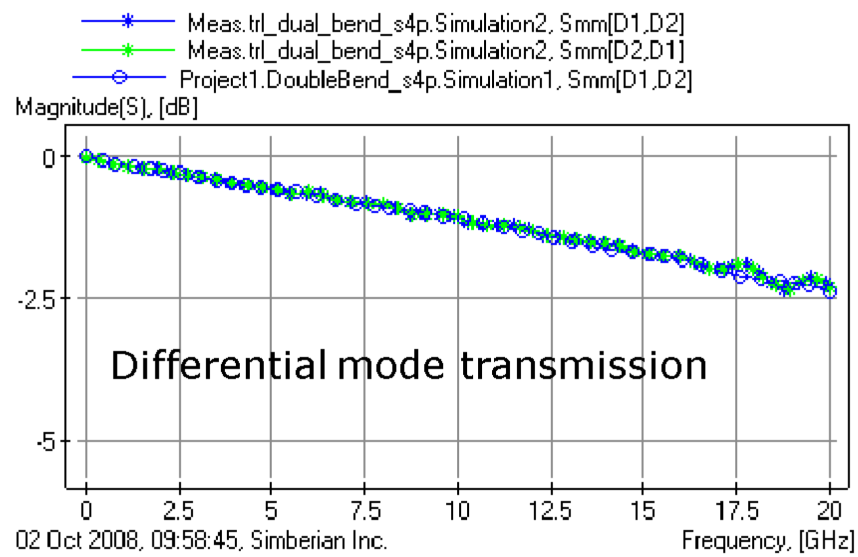
Measured – stars; Simulated - circles

Differential Bends: Comparison with TRL De-Embedded Measurements

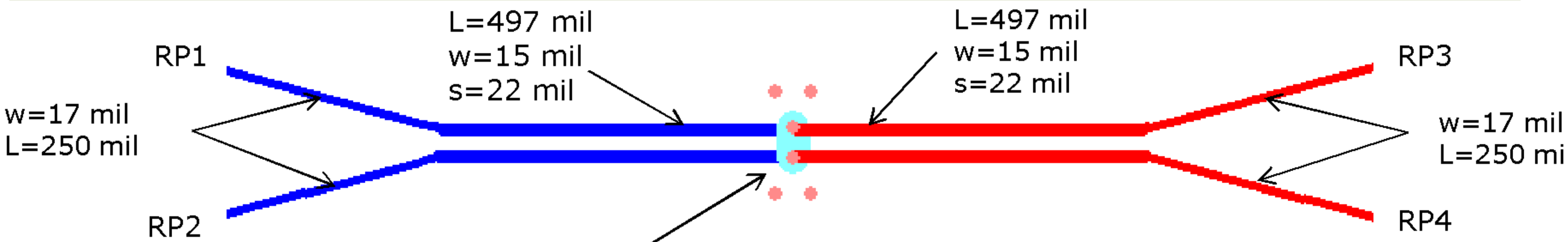
- Two bends in differential micro-strip line with 250 mil 17-mil micro-strip segments (DK=4.25, LT=0.02 @ 1 GHz, 15 mil strips, 22 mil separation)

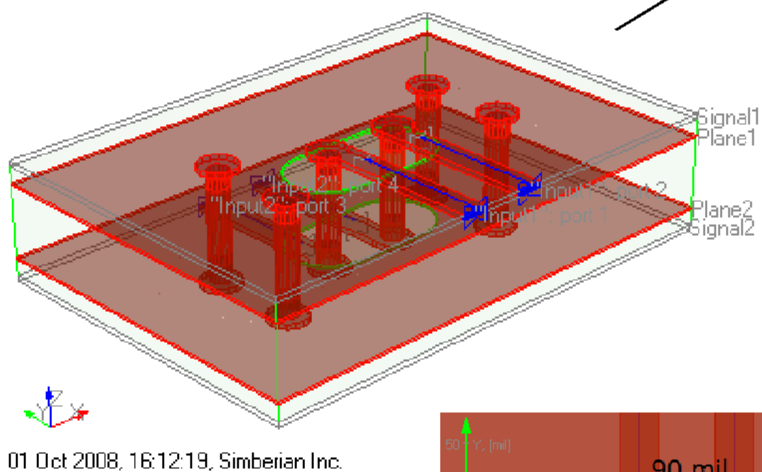




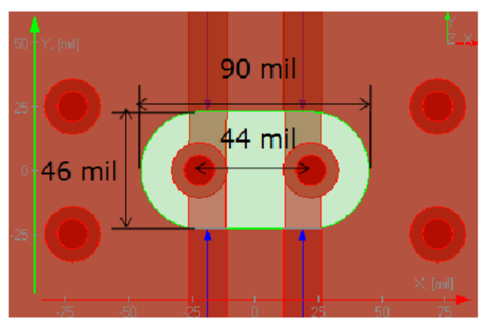


Differential Via-Holes



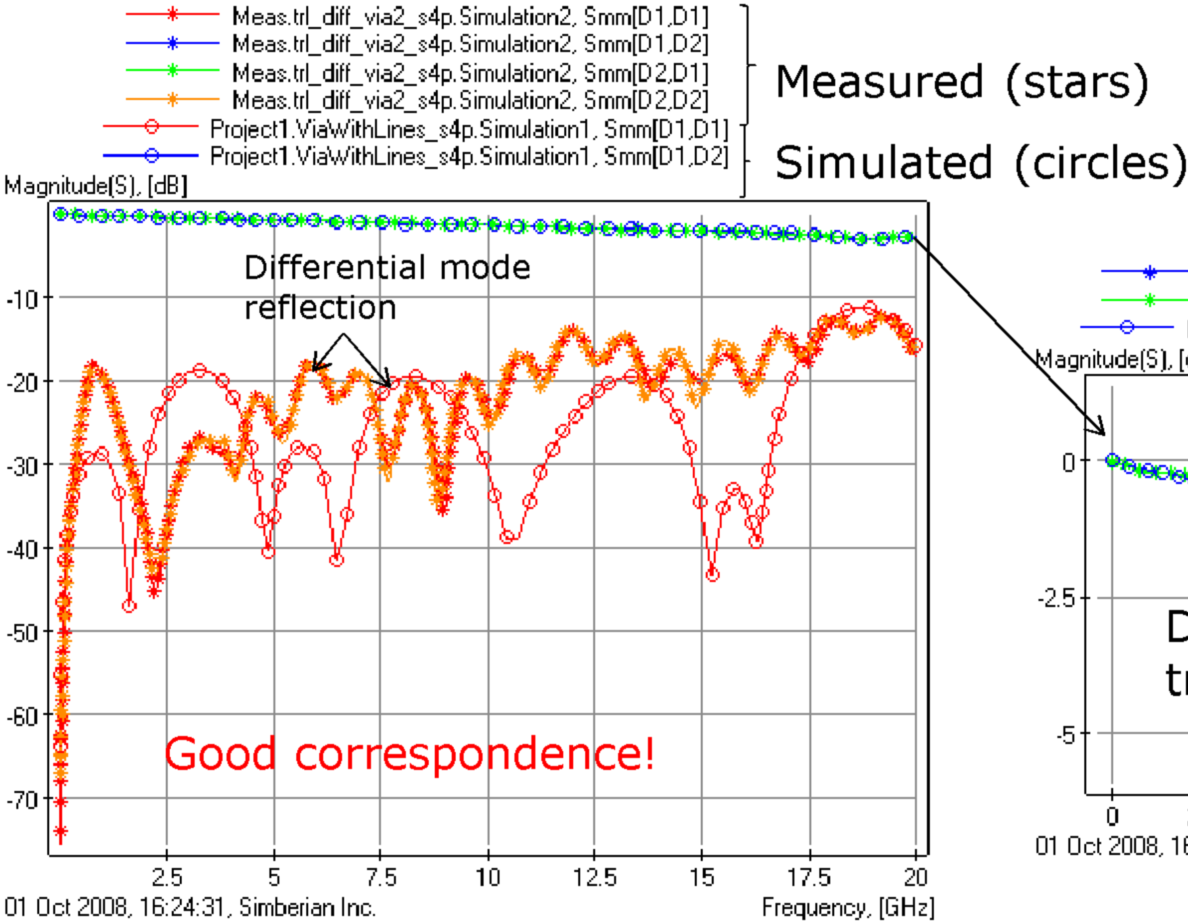


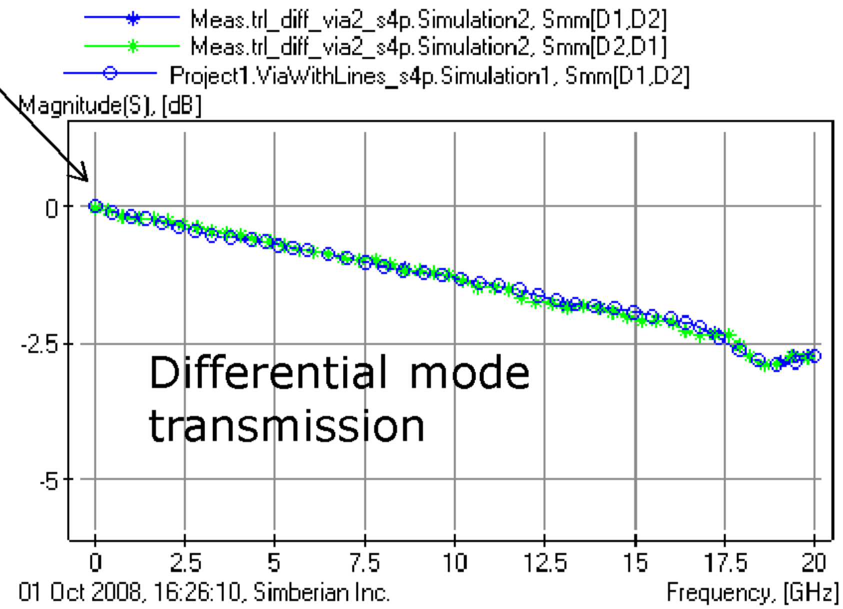
Substrate DK=4.25, core DK=4.7, LT=0.02 @ 1 GHz
15 mil strips separated by 22 mil
Diameter of vias is 12 mil
Pad diameters are 22 mil



Differential vias: Comparison with TRL De-Embedded Measurements

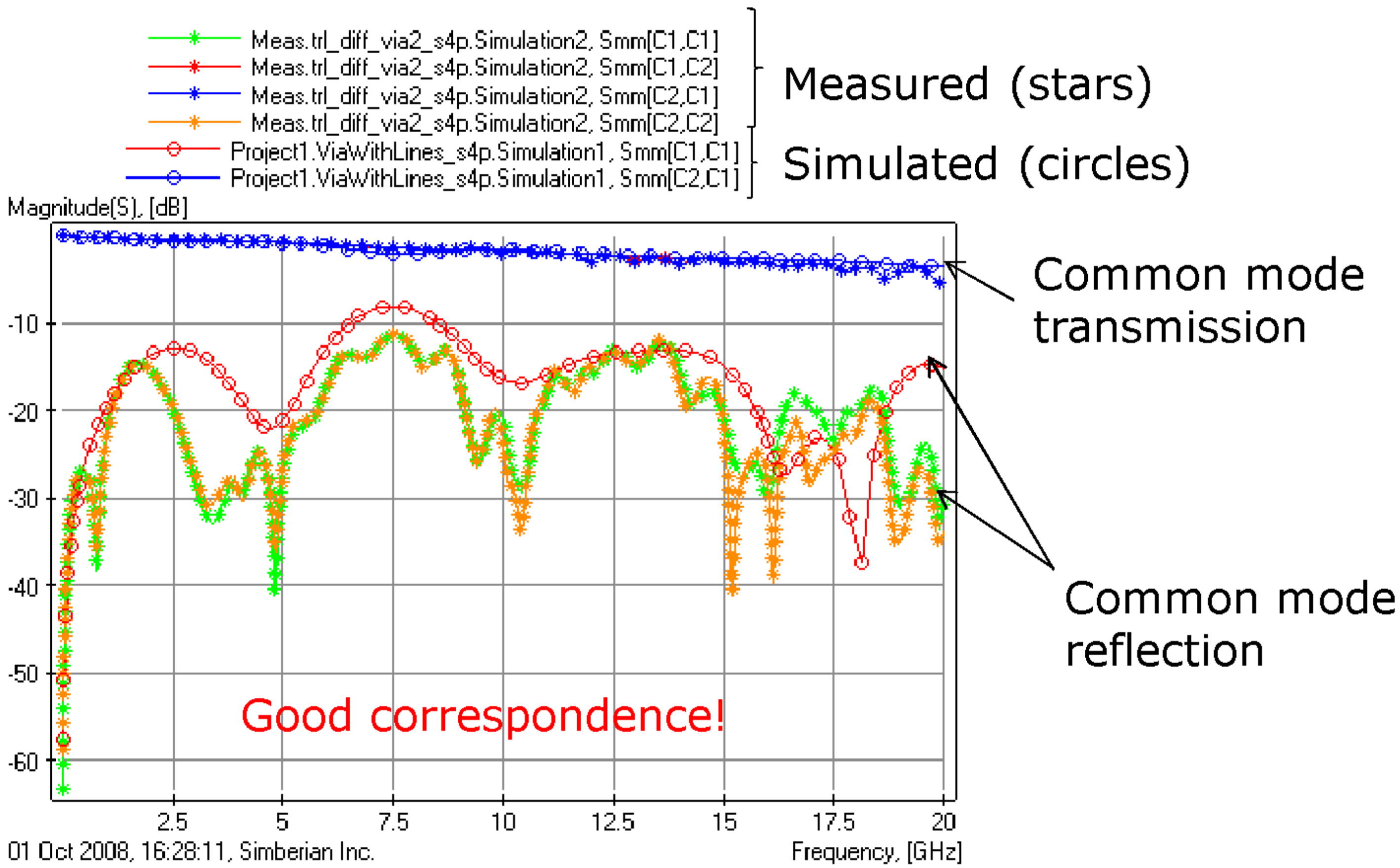
- Magnitudes of mixed-mode S-parameters (DD block)





Differential vias: Comparison with TRL De-Embedded Measurements

- Magnitudes of mixed-mode S-parameters (CC block)



Conclusion

- The main result of this investigation is a simple and practical methodology to identify properties of low-cost FR-4 dielectric on the base of two key components:
  - Precisely de-embedded S-parameters of resonators or line segments
  - Accurate full-wave electromagnetic analysis with wideband Debye dielectric model and with conductor-related and high-frequency loss and dispersion effects included
- It is shown that behavior of interconnects on low-cost PCBs can be reliably predicted by electromagnetic analysis with the identified material properties
- Future work:
  - Practical methodology to identify conductor parameters (roughness), core dielectric parameters (vias and strip lines), effect of fibers,…
  - Investigate possibilities of extraction without de-embedding of launch to create simple on board coupons

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Dielectric properties of composite materials

- Multiple researches show considerable decline of DK and slight increase of LT with the frequency from DC to 20 GHz

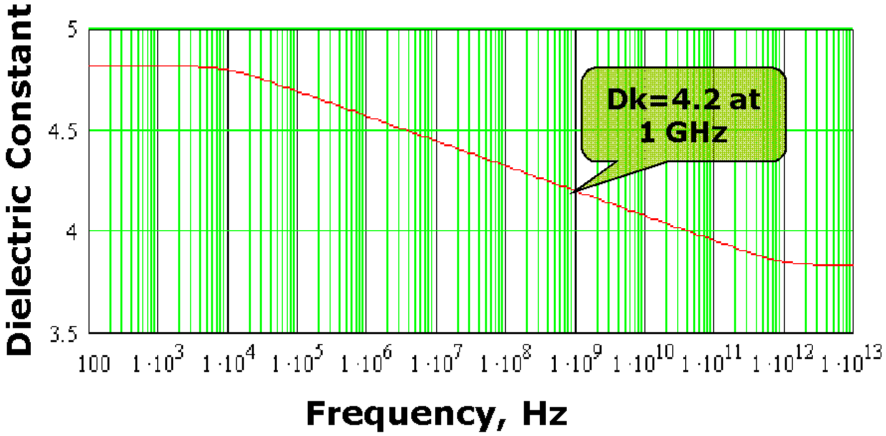
- A.R. Djordjevic at al. (**UB+SU**), Wideband frequency domain characterization of FR-4 and time-domain causality, IEEE Trans. on EMC, vol. 43, N4, 2001, p. 662-667.
- A. Deutsch at al. (**IBM**), Extraction of eps(f) and tand(f) for Printed Circuit Board Insulators Up to 30 GHz Using the Short-Pulse Propagation Technique, – IEEE Trans. on Adv. Packaging, v. 28 N 1, 2005, p. 4-12
- E.L. Holtzman (**Northrop**), Wideband Measurement of the Dielectric Constant of an FR4 Substrate Using a Parallel-Coupled Microstrip Resonator, IEEE Trans. on MTT, v. 54, N7, 2006, p. 3127-3130
- Z. Zhang at al. (**UMR-Apple**), Signal Link-Path Characterization Up To 20 GHz Based On A Stripline Structure, - in Proc. of EMC symposium, 2006
- H. Shi, G. Liu, A. Liu (**Altera**), Accurate Calibration and Measurement of Non-Insertable Fixtures in FPGA and ASIC Device Characterization, - DesignCon2006
- W. Kim at al. (**Rambus)**, Implementation of Broadband Transmission Line Models with Accurate Low-Frequency Response for High-Speed System Simulations, - DesignCon2006
- D.-H. Han at al. (**Intel**), Frequency-Dependent Physical-Statistical Material Property Extraction for Tabular W-element Model Based on VNA Measurements, - DesignCon2006
- A. E. Engin at al. (**GaTech**), Dielectric constant and loss tangent characterization of thin high-K dielectric using corner-to-corner plane probing, Proc. of EPEP 2006, p. 29-32.
- J. Miller at al. (**Sun**), Impact of PCB Laminate Parameters on Suppressing Modal Resonances – DesignCon2008
- B.O. McCoy at al. (**Mayo**), Broadband Resonant-Plate Permittivity Measurement Technique for Printed Wiring Boards Aided by Electromagnetic Simulations – DesignCon2008
- C. Morgan (**Tyco**), Solutions for Causal Modeling and A Technique for Measuring Causal, Broadband Dielectric Properties – DesignCon2008

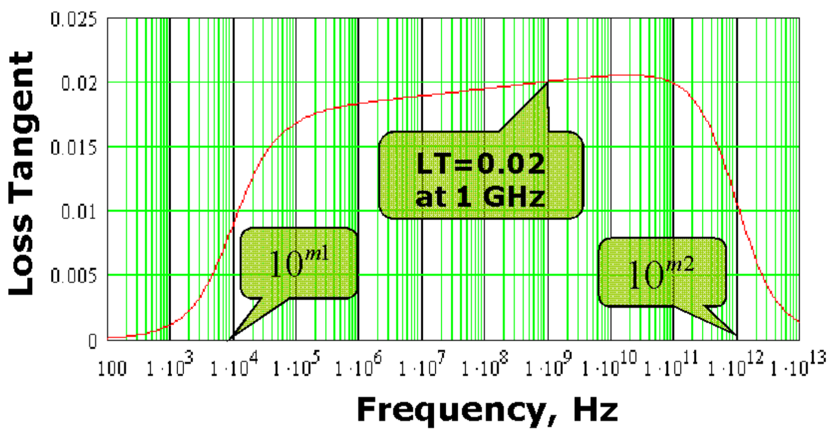
De-embedding methods

- Aditya P. Goswami, Implementation of Microwave Measurements Using Novel Calibration Techniques, Masters Thesis, NC State University, May 2003

Wideband Debye dielectric model

$$\varepsilon_{wd}(f) = \varepsilon_r(\infty) + \varepsilon_{rd} \cdot F_d(f) \qquad F_d(f) = \frac{1}{(m_2 - m_1)\cdot \ln(10)} \cdot \ln\left[\frac{10^{m2} + if}{10^{m1} + if}\right]$$





- Suggested in two papers independently and confirmed by multiple researchers
  - Djordjevic, R.M. Biljic, V.D. Likar-Smiljanic, T.K. Sarkar, Wideband frequency-domain characterization of FR-4 and time-domain causality, IEEE Trans. on EMC, vol. 43, N4, 2001, p. 662-667.
  - C. Svensson, G.E. Dermer, Time domain modeling of lossy interconnects, IEEE Trans. on Advanced Packaging, May 2001, N2, Vol. 24, pp.191-196.
- Can be specified with DK and LT at one frequency only!
  - Reproduces causal frequency-dependent dielectric loss and dispersion
  - Very convenient for measurements and fitting the experimental data

3D full-wave analysis with Simbeor software

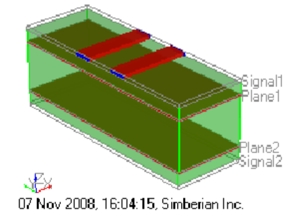
Solve Maxwell's equations in 3D to find frequency-dependent matrix RLGC per unit length parameters for transmission lines and S-parameters for discontinuities:

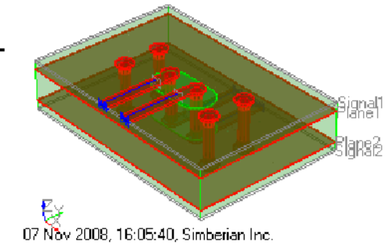
$$\nabla \times \vec{E} = -i\omega\mu\vec{H}$$

$$\nabla \times \vec{H} = i\omega\varepsilon\vec{E} + \sigma\vec{E} + \vec{J}$$

Plus additional boundary conditions at the metal and dielectric surfaces

$$\Rightarrow \quad R(\omega),\ L(\omega) \quad G(\omega),\ C(\omega) \qquad S(\omega)$$





- Method of Lines (MoL) for multilayered media
  - High-frequency dispersion in multilayered dielectrics
  - Losses in metal planes including roughness
  - Causal wideband Debye dielectric polarization loss and dispersion models
- Trefftz Finite Elements (TFE) for metal interior
  - Metal interior and surface roughness models to simulate proximity edge effects, transition to skin-effect and skin effect in rough and plated conductors
- Method of Simultaneous Diagonalization (MoSD) for lossy multiconductor line and multiport S-parameters extraction
  - Advanced 3-D extraction of modal and RLGC(f) p.u.l. parameters of lossy multi-conductor lines
  - Precise numerical de-embedding of extracted S-parameters