DesignCon® 2014

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SANTA CLARA CONVENTION CENTER

Lessons learned: How to Make Predictable PCB Interconnects for Data Rates of 50 Gbps and Beyond

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Outline

- Introduction
- Board Design
- Material models
- Validation
- Conclusion

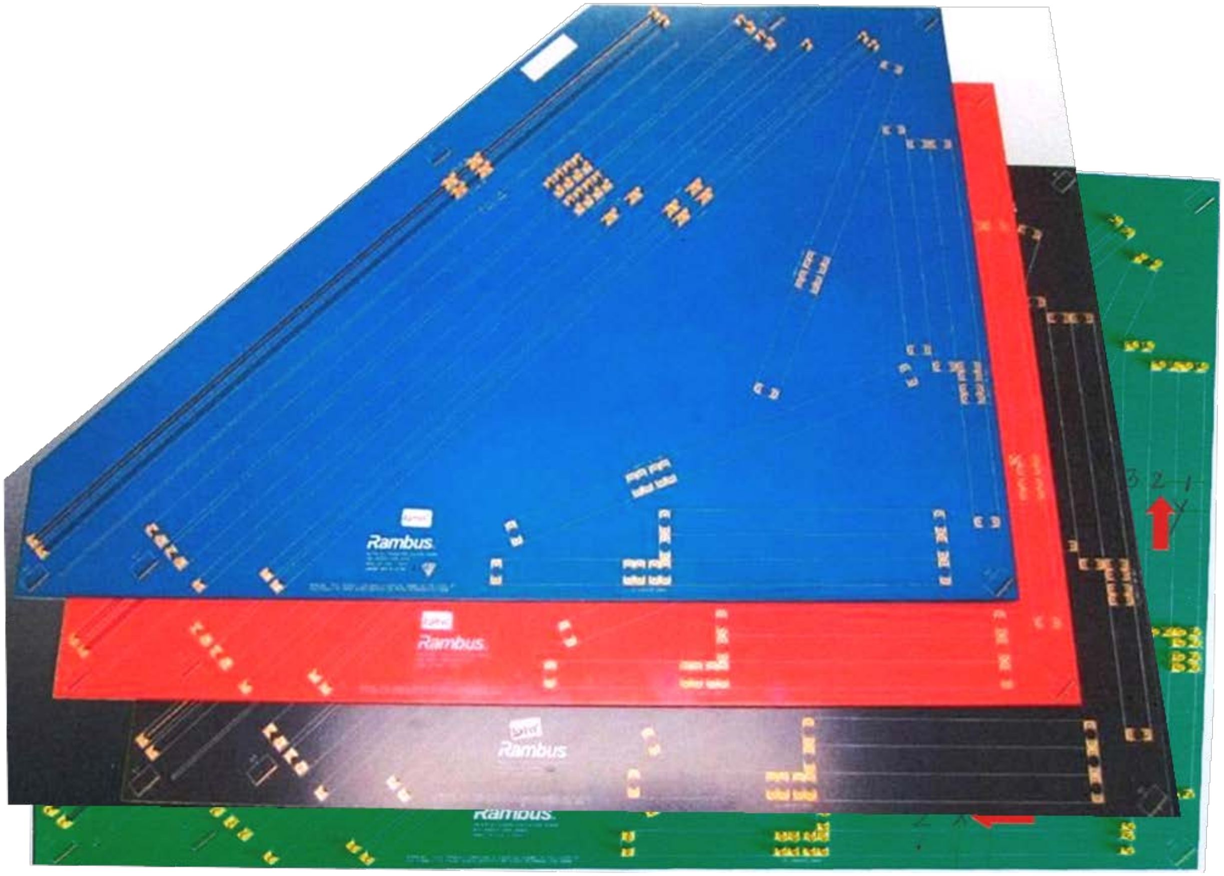
Introduction

- Demands for bandwidth continue to grow
- High bandwidth necessitates increase in data rate
- Growth of data rate has been sustained by increasing the performance of I/O circuits
- Electronic and I/O power consumption increases with increasing the interface speed
  - ⇨ Data rate increase cannot only come from I/O circuit
- Optical interconnects are not currently adopted for backplane links due to cost, manufacturability and power efficiency

Introduction Cont'd

- Proposals for next generation standards of electrical signaling to run at *50 Gbps*
- Copper based interconnect systems utilizing advanced connectors, packages, and boards
- To minimize the loss in long traces, board and packages with low-loss laminates are required
- It is essential to accurately model the board loss
- The models of the traces have to be broadband
  - Dielectric dispersion : dielectric constant and loss tangent
  - Conductor loss : skin effects and surface roughness

Photo of the Four Boards

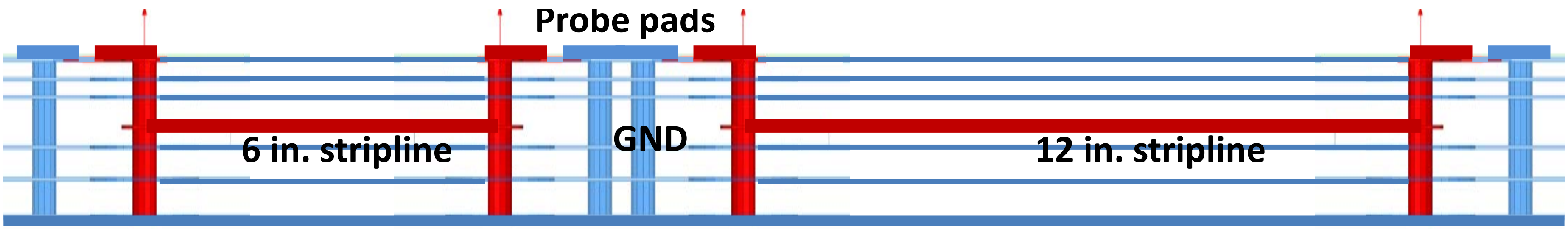


- Several boards and structures designed for material characterization
  - Isola FR408HR and Nelco 4000-13 EPSI with RTF copper foil and standard glass weave
  - Megtron 6 with finish and Reverse-Treated Foil finish and Hyper Very Low Profile

Board Stackups

Stackup	Segment	Glass type			Dielectric Constant			Thickness (mil)		
		MEG 6	EPSI	FR408HR	MEG 6	EPSI	FR408HR	MEG 6	EPSI	FR408HR
	Mask							0.8	0.8	0.8
L1	Foil							1.6	1.6	1.6
	Prepreg	1035(70)	1080(65)	1080(65)	3.35	3.2	3.46	5.37	5.12	5.52
		1078(72)	1080(65)	1080(65)	3.3	3.2	3.46			
L2								1.2	1.2	1.2
	Core	1-3313	1-2116	1-2116	3.71	3.38	3.7	3.9	5.00	5.00
L3								1.2	1.2	1.2
	Prepreg	3313(54)	106(75)	2116(55)	3.71	3.11	3.68	6.56	5.88	9.08
		3313(54)	2116(55)	2116(55)	3.71	3.31	3.68			
L4								1.2	1.2	1.2
	Core	2-3313	2-1080	1-1652	3.71	3.25	3.8	7.8	6.0	6.0
L5								1.2	1.2	1.2
	Prepreg	3313(54)	2116(55)	2116(55)	3.71	3.31	3.68	7.4	6.72	9.92
		3313(54)	106(75)	2116(55)	3.71	3.11	3.68			
L6								1.2	1.2	1.2
	Core	1-3313	1-2116	1-2116	3.71	3.38	3.7	3.9	5.0	5.0
L7								1.2	1.2	1.2
	Prepreg	1078(72)	1080(65)	1080(65)	3.30	3.2	3.46	5.37	5.12	5.52
		1035(70)	1080(65)	1080(65)	3.35	3.2	3.46			
L8	Foil							1.6	1.6	1.6
	Mask							0.8	0.8	0.8

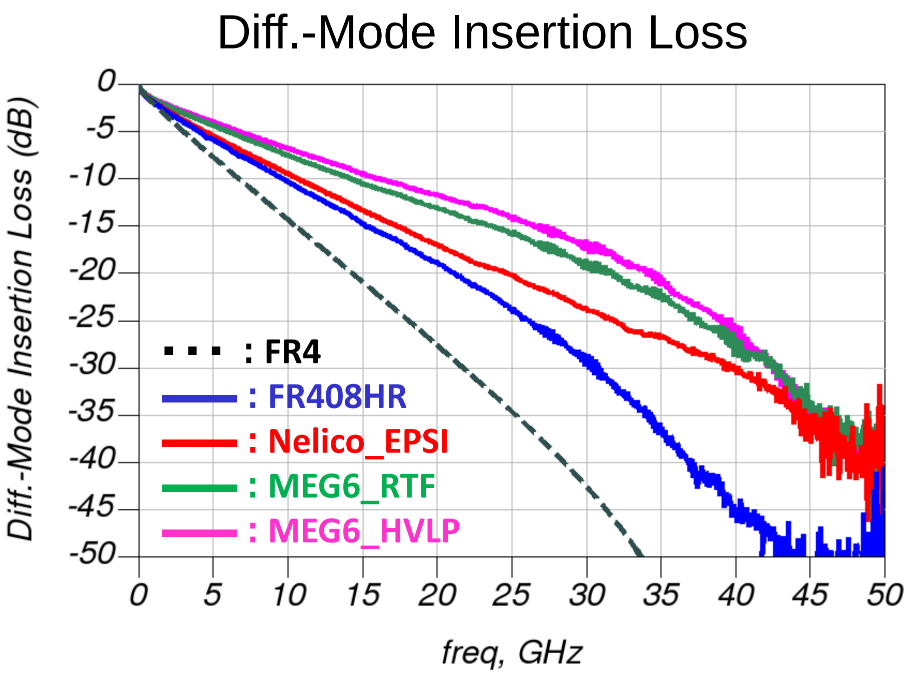
Structures and Typical Models

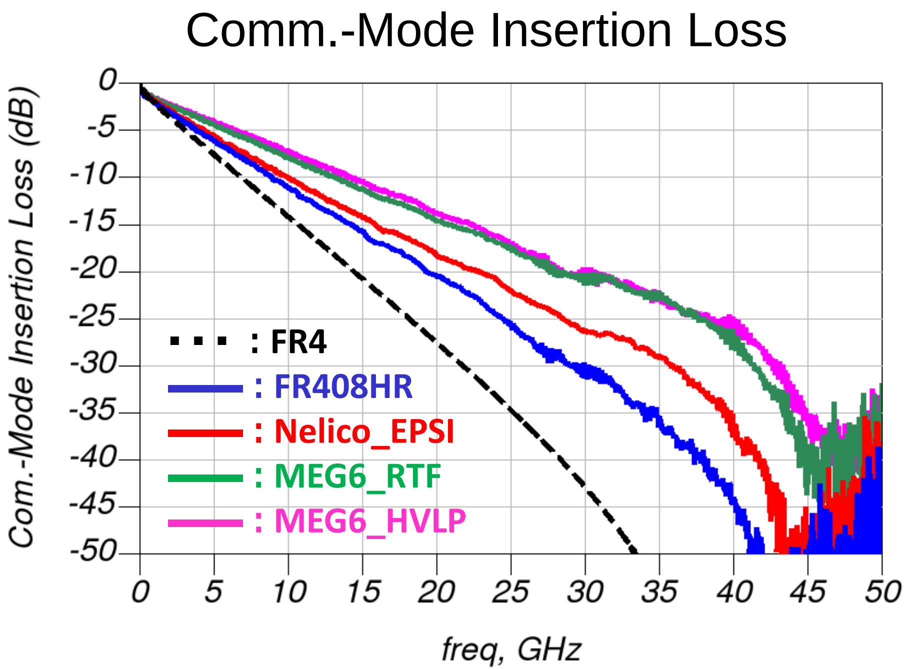


Laminate Types	Dielectric Constant	Dissipation Factor	Amplitude of Surface Roughness
Megtron 6 HVLP	3.6	0.004	1.5 – 2.0 um
Megtron 6 RTF	3.6	0.004	7.0 – 8.0 um
Nelco N4000-13 EPSI	3.2	0.008	7.0 – 8.0 um
FR408HR	3.65	0.0095	7.0 – 8.0 um
Typical FR-4	4.3	0.02	7.0 – 8.0 um

- The striplines with two different lengths : 6 in and 12 in.
- The four boards have different laminates and surface roughness

Frequency-Domain Responses

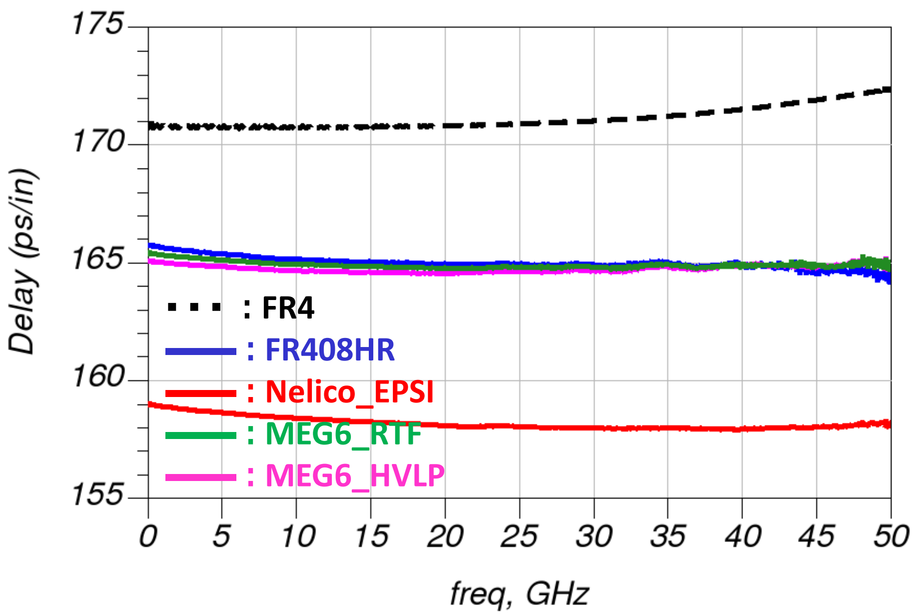




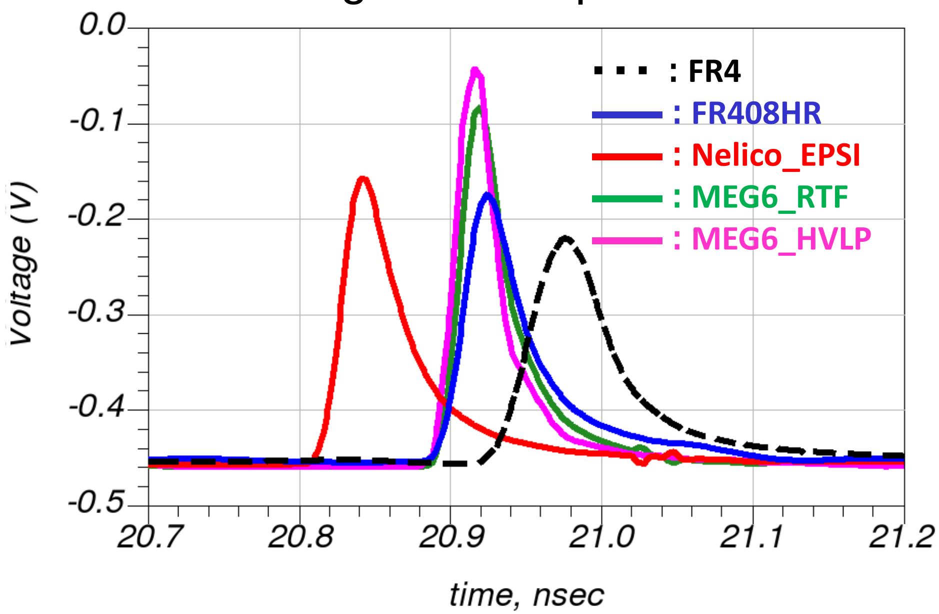
- Magnitude of differential and common-mode insertion loss for 12-in striplines
  - Measured loss of the four laminates
  - Response of FR4 is from simulation

Time-Domain Responses

Group Delay (ps/in.)



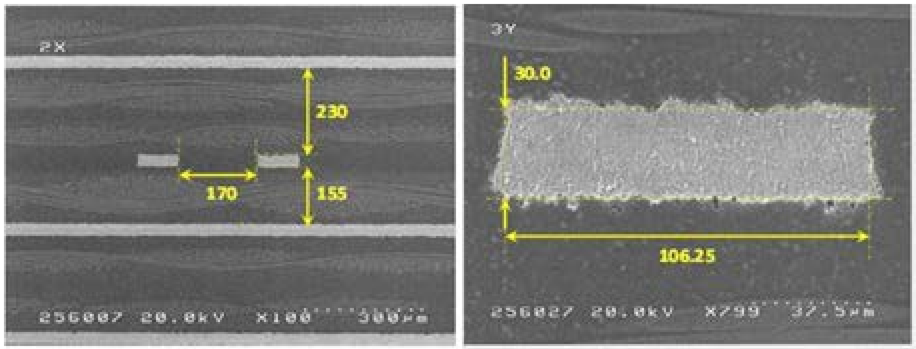
Single-Bit Response



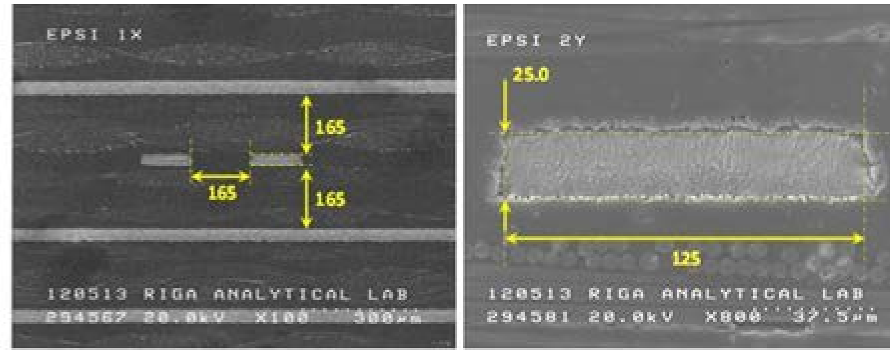
- Based on the measured S-parameters
  - Group delay per in. from measured S-parameters
  - Single-bit (pulse with width = *20 ps*) responses

Board Cross-Sections

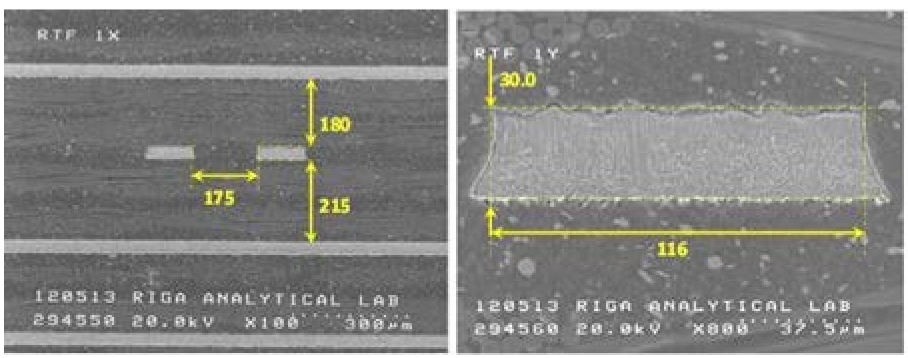
FR408 HR



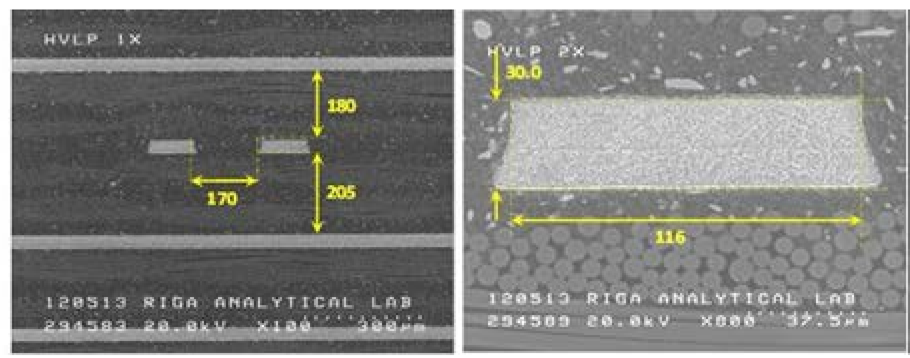
Nelco N4000-13EPSI



Megtron 6 RTF



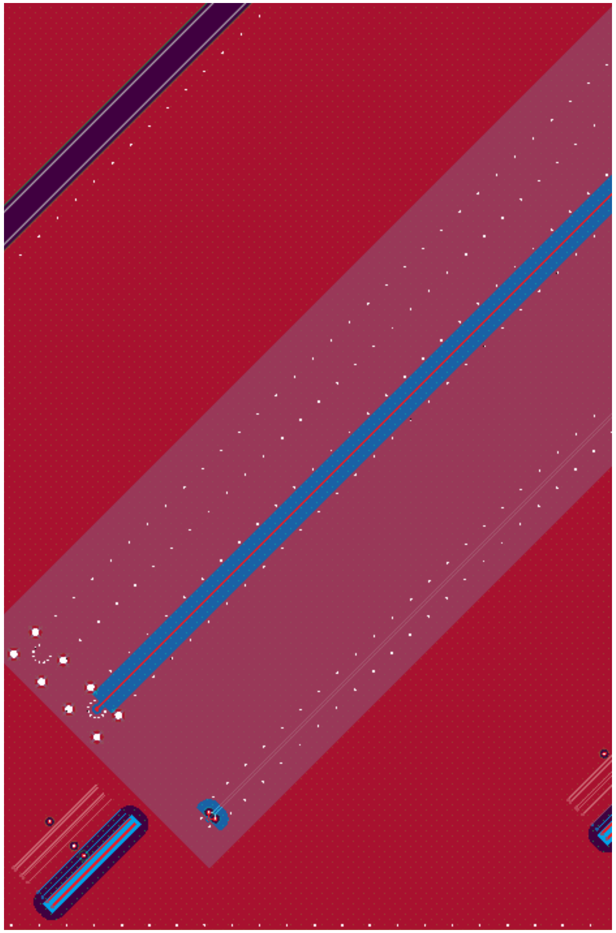
Megtron 6 HLVP



- Cross-sectioned of the four boards
  - Finding accurate dimensions are critical to modeling

Material Models

- The largest part of interconnects are transmission line segments
- Models for transmission lines are usually constructed with a quasi-static or electromagnetic field solvers
- Accuracy of transmission line models is mostly defined by availability of broadband dielectric and conductor roughness models
- This is one of the most important elements for design success



Broadband material models

- **Dielectric models:**

Wideband Debye (aka Djordjevic-Sarkar):

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

Continuous-spectrum model
Requires specification of DK and LT at one frequency point (2 parameters)

Multi-pole Debye:

$$\varepsilon(f) = \varepsilon(\infty) + \sum_{n=1}^{N} \frac{\Delta\varepsilon_n}{1 + i\frac{f}{fr_n}}$$

Requires specification of value at infinity and poles/residues or DK and LT at multiple frequency points (more than 2 parameters)

- **Conductor surface roughness models:**

Modified Hammerstad (2 parameters):

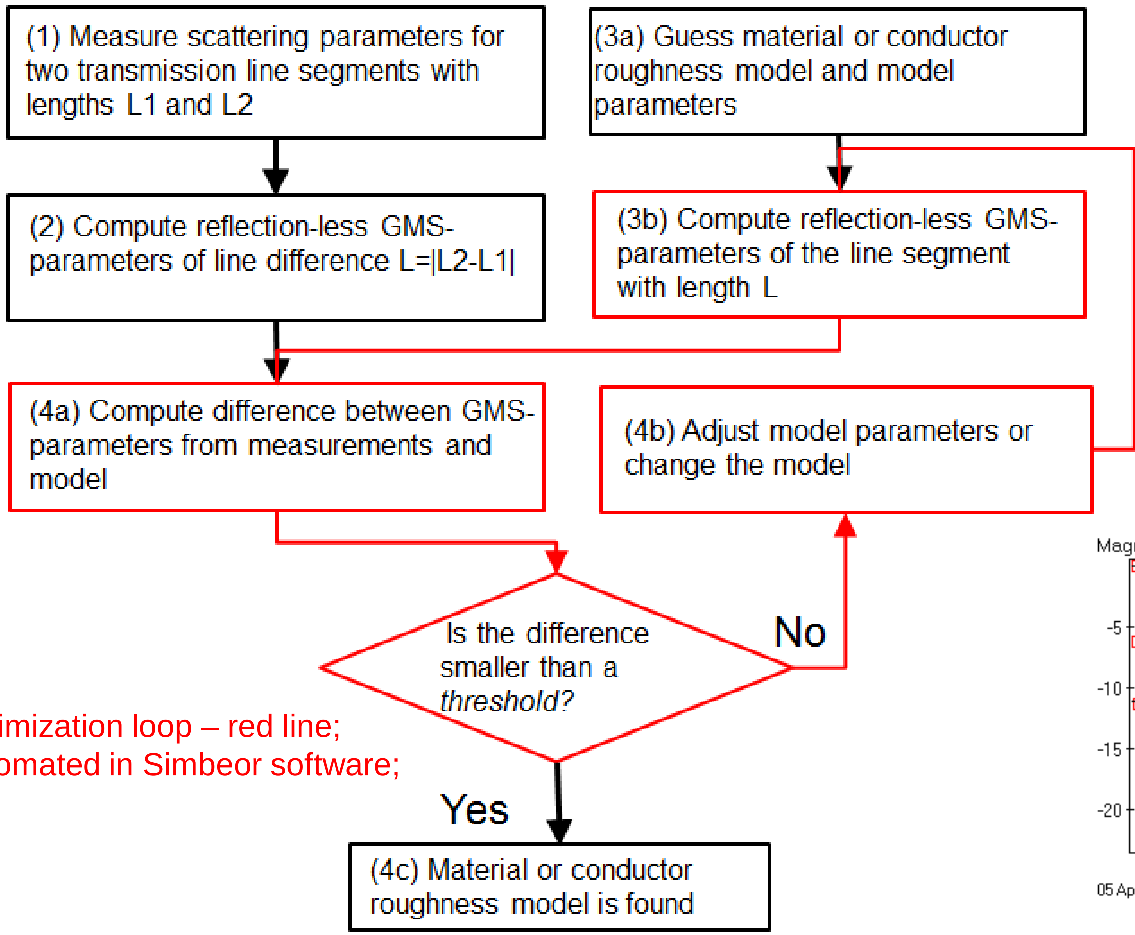
$$K_{rh} = 1 + \left(\frac{2}{\pi} \cdot \arctan\left[1.4\left(\frac{\Delta}{\delta}\right)^2\right]\right) \cdot (RF - 1)$$

Huray snowball (1-ball, 2 parameters):

$$K_{rhu} = 1 + \left(\frac{N \cdot 4\pi \cdot r^2}{A_{hex}}\right) \Big/ \left(1 + \frac{\delta}{r} + \frac{\delta^2}{2 \cdot r^2}\right)$$

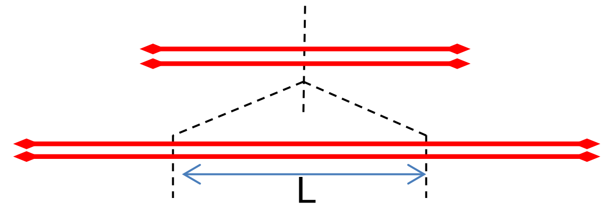
- Parameters for the models are not available and must be identified

Material Model Identification with GMS-Parameters

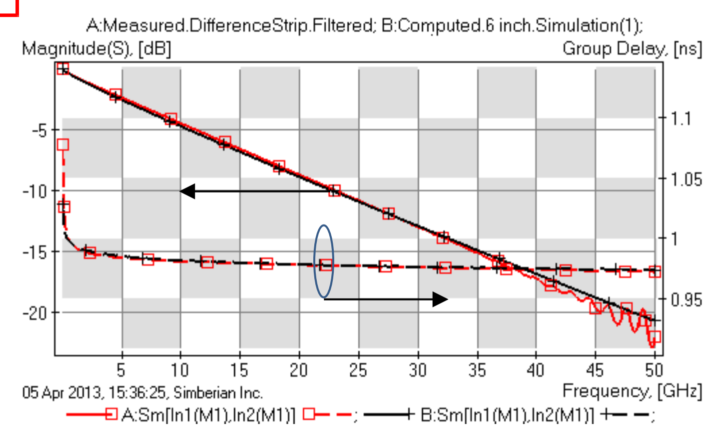


Optimization loop – red line;
Automated in Simbeor software;

Use 6 and 12 inch differential line segments:



Applicable to dielectric and conductor roughness models;



Simberian's USA patent #8577632 and patent pending #14/045,392

Measured S-Parameters (Pre-Qualification)

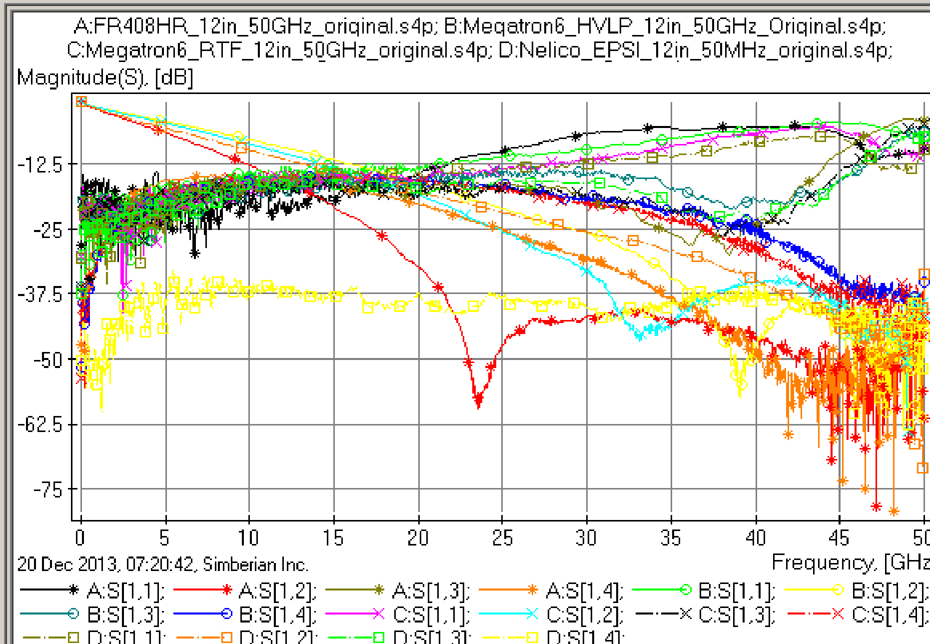
- Final quality metric is acceptable:

Board Analyzer | Graph(1) | Touchstone Analyzer

File name	Quality	Passivity	Reciprocity
C:\Repository\Simbeor\Support\Rambus\DesignCon2014\Nov22_2013_Id			
FR408HR_12in_50GHz_original.s4p	95.5	100	96.7
FR408HR_6in_50GHz_original.s4p	94.9	100	94.2
Megatron6_HVLP_12in_50GHz_Original.s4p	96.2	100	95.4
Megatron6_HVLP_6in_50GHz_Original.s4p	96.1	100	90.8
C:\Repository\Simbeor\Support\Rambus\DesignCon2014\Nov28_2013_Id			
Megatron6_RTF_12in_50GHz_original.s4p	95.1	100	96.8
Megatron6_RTF_6in_50GHz_original.s4p	95.9	100	94.6
Nelico_EPSI_12in_50MHz_original.s4p	96.9	100	96.5
Nelico_EPSI_6in_50MHz_original.s4p	96.8	100	95.9

Computed with the rational approximation of measured S-parameters (Y. Shlepnev, Reflection on S-parameters quality, IBIS summit 2011)

Ready



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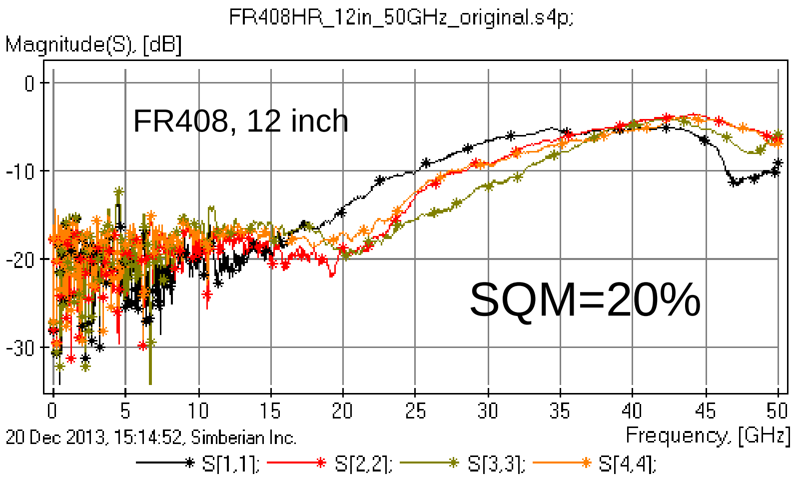
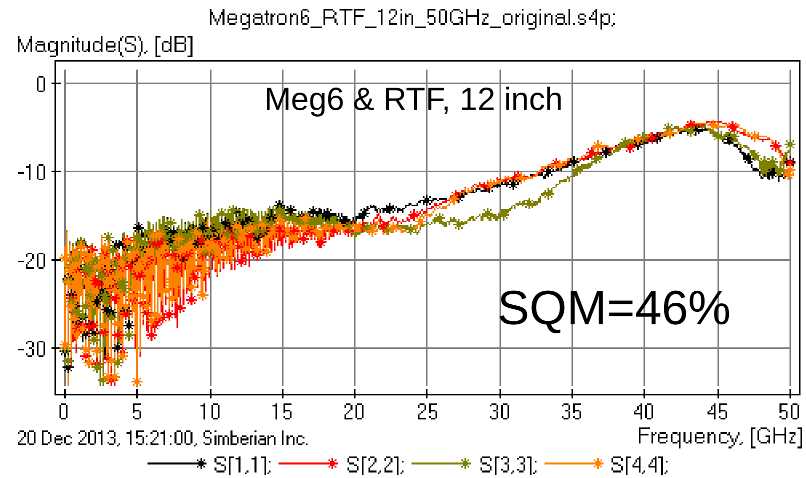
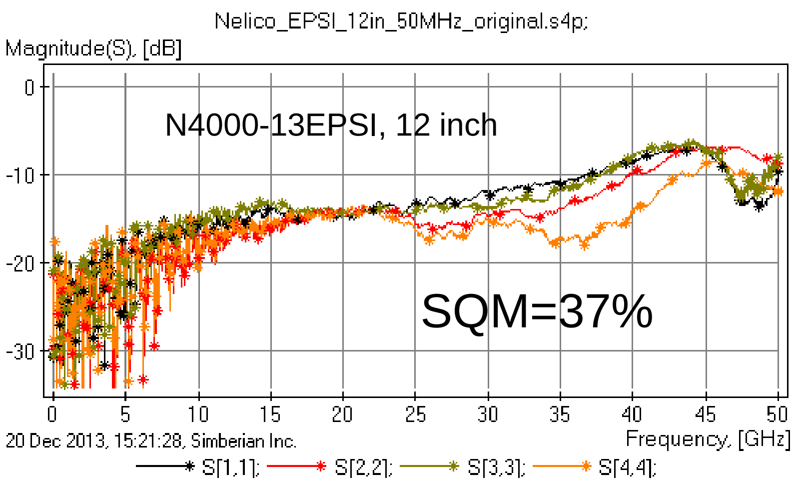
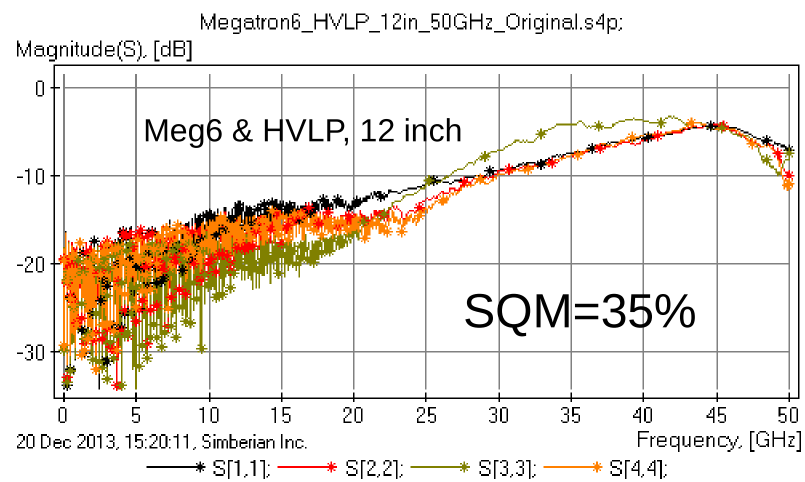
Reflection Loss (Single-Ended)

geometrical symmetry: S11=S22=S33=S44, S12=S34, S13=S24, S14=S23 => SQM=100%



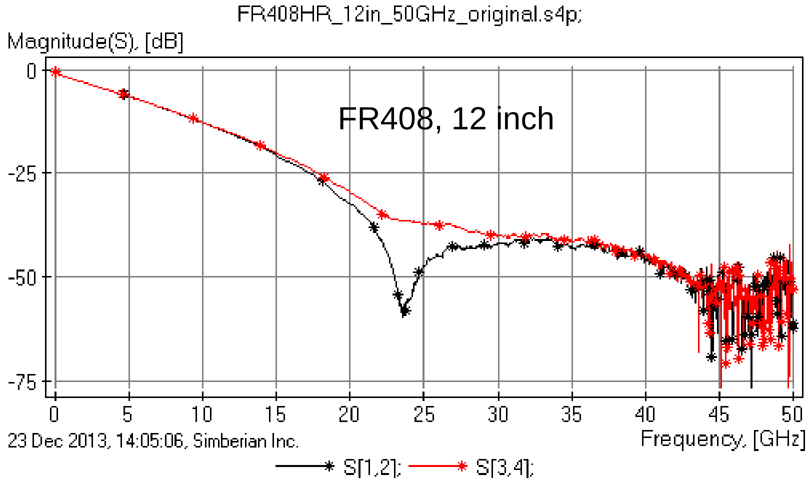


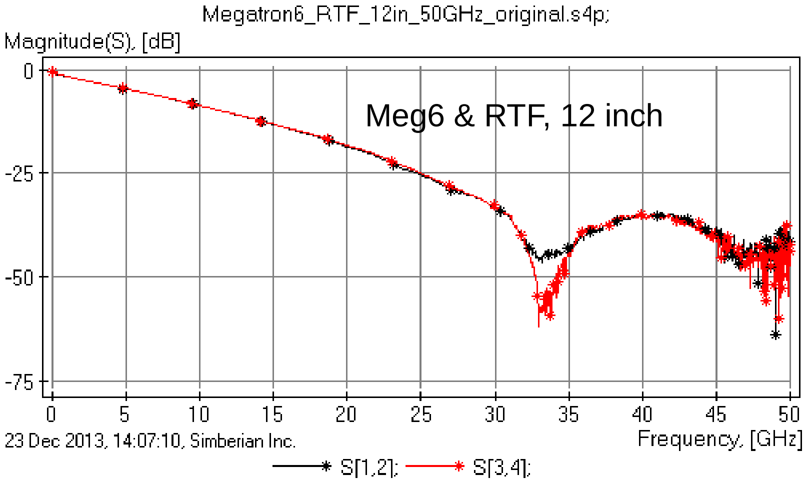


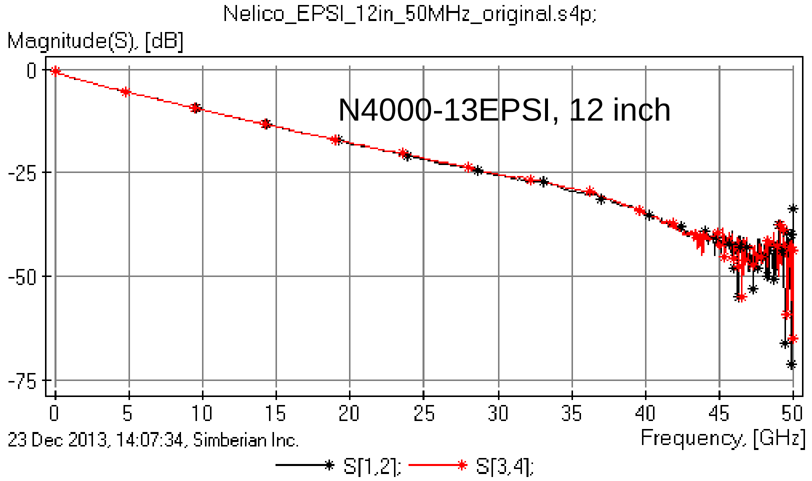


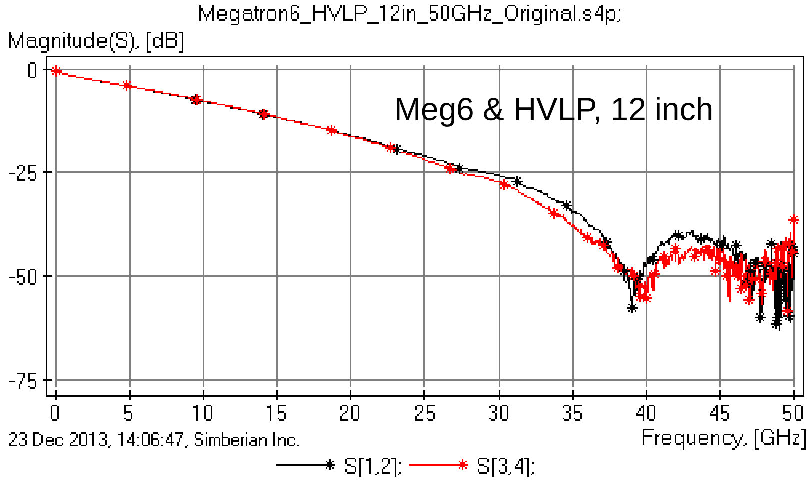
Insertion Loss (Single-Ended)

geometrical symmetry: S12=S34



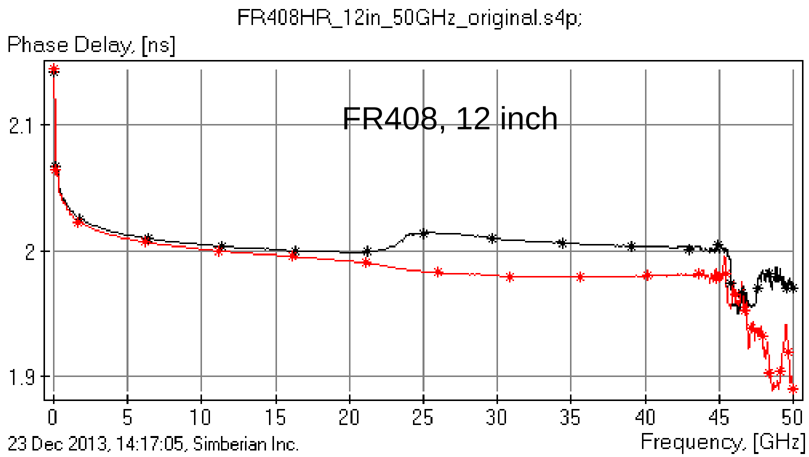


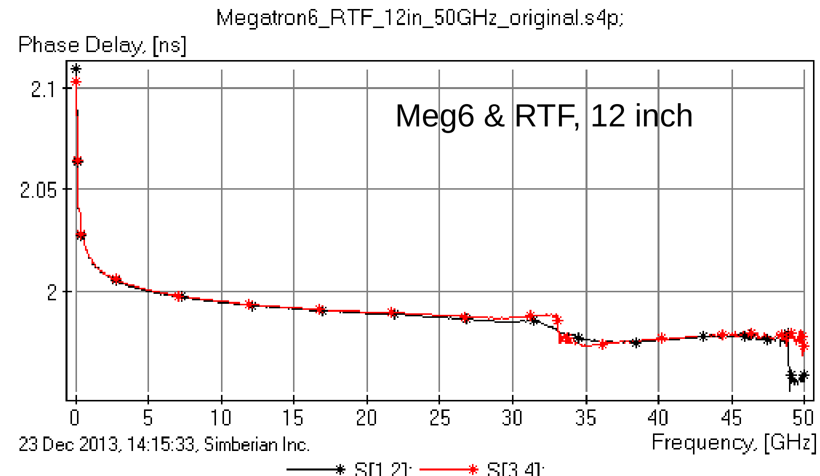


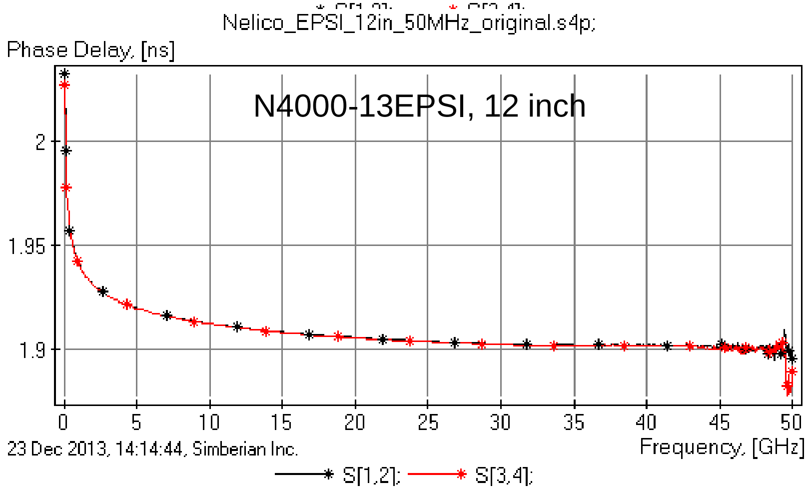


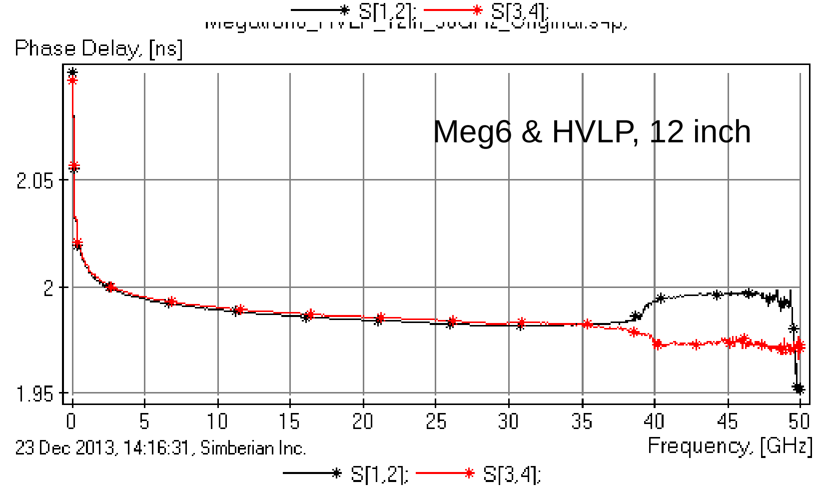
Phase Delay (Single-Ended)

geometrical symmetry: S12=S34



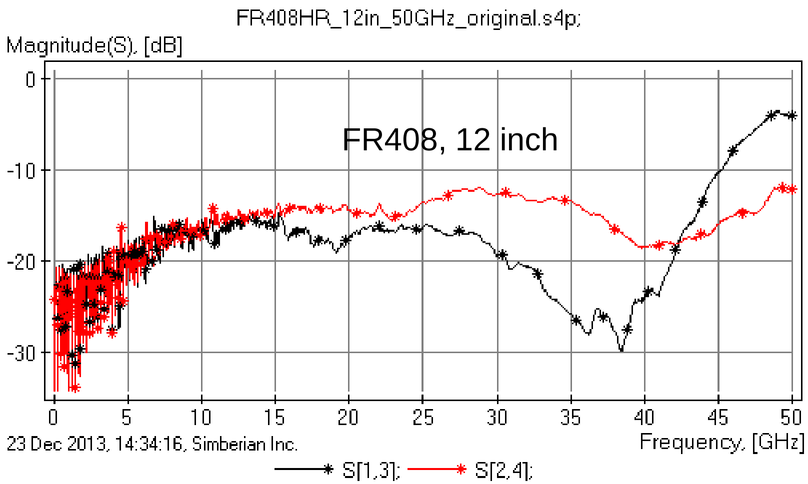


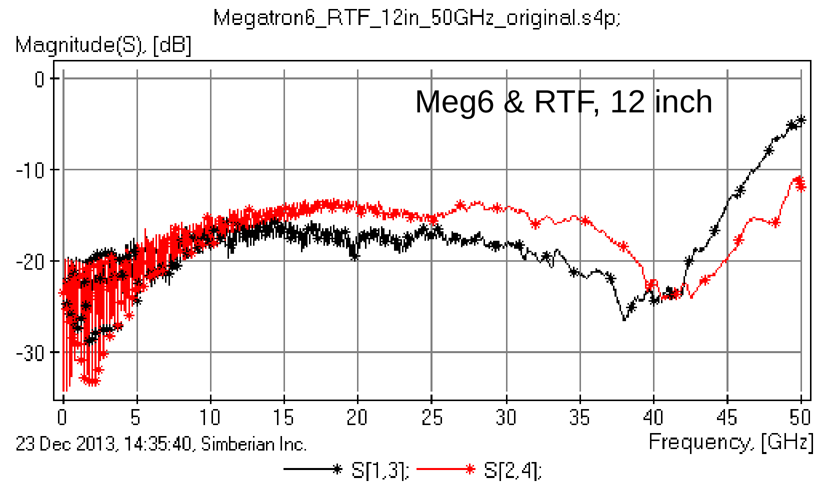


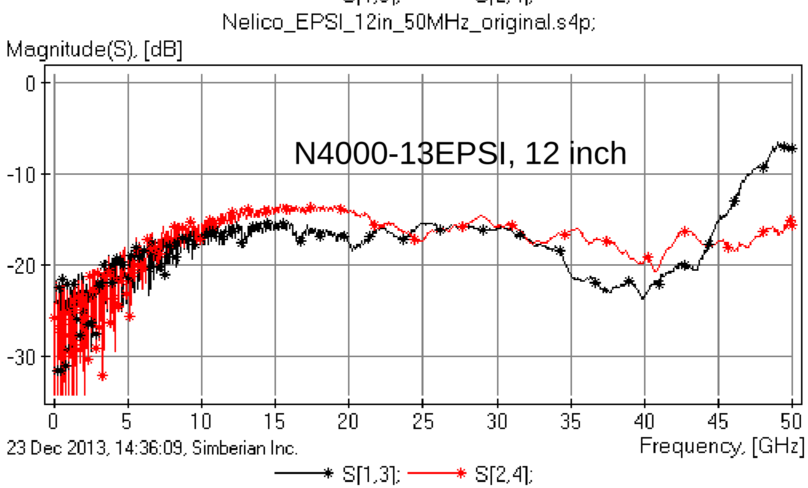


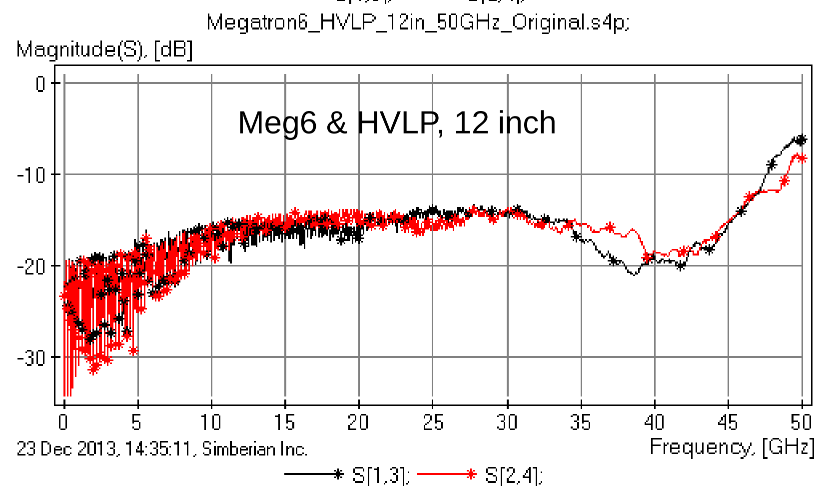
NEXT (Single-Ended)

geometrical symmetry: S13=S24



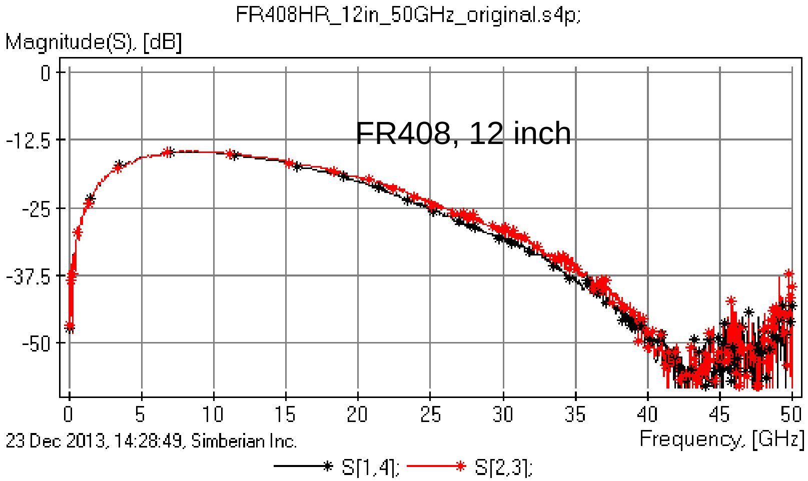


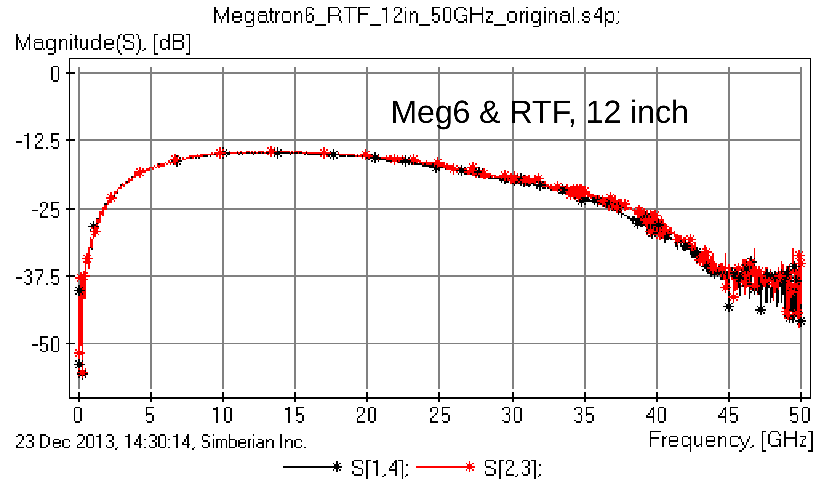


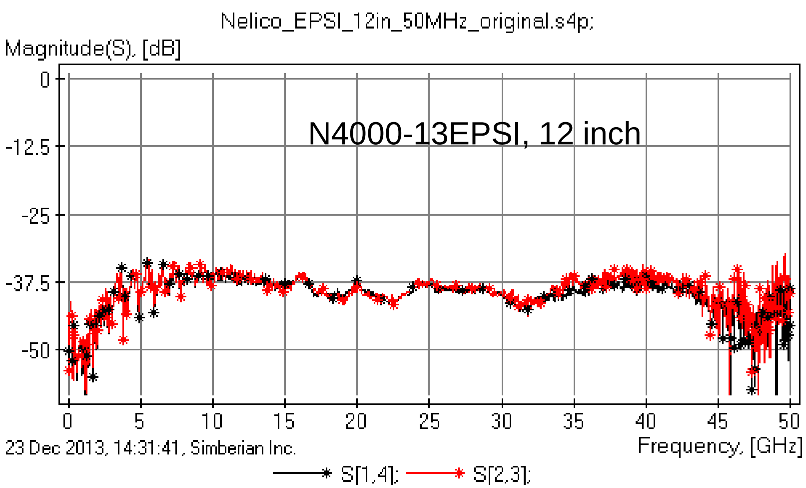


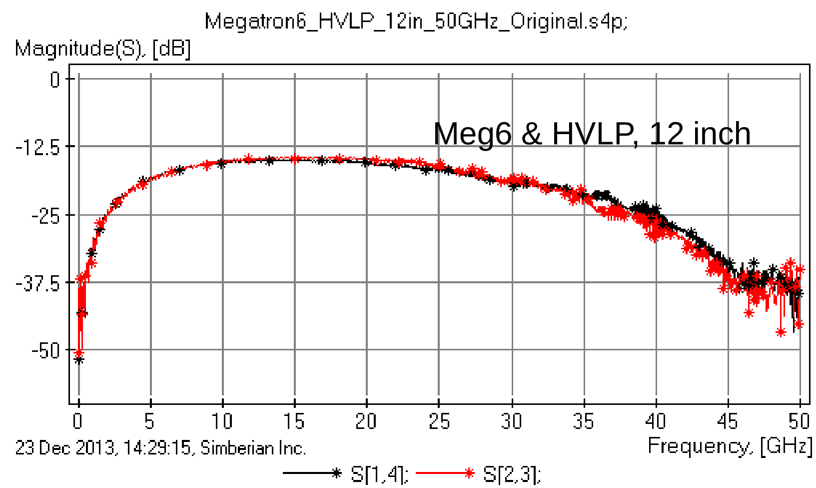
FEXT (Single-Ended)

geometrical symmetry & homogeneity: S14=S23=0



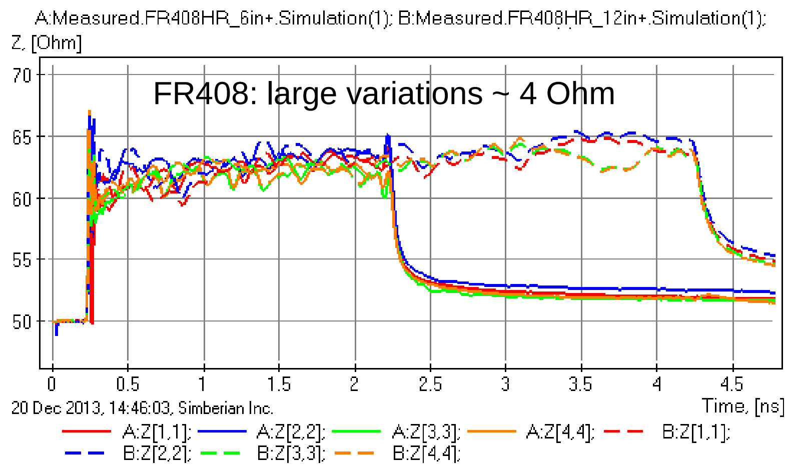


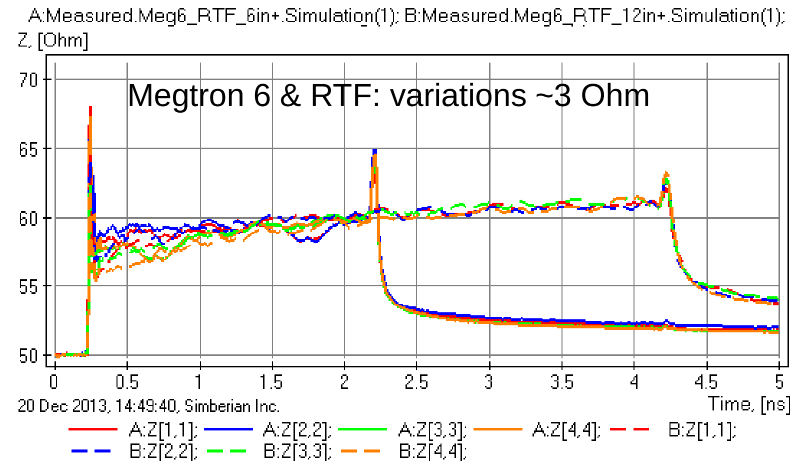


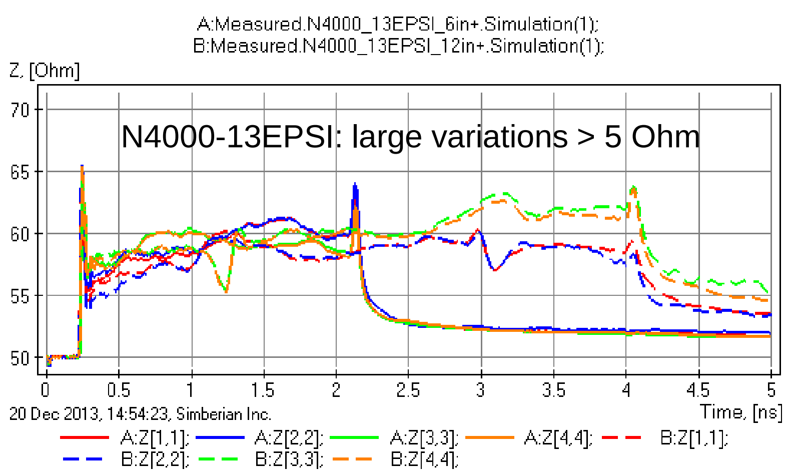


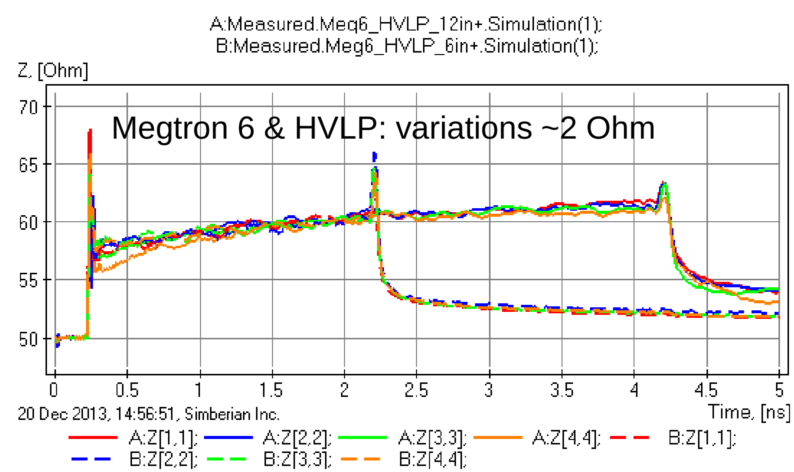
TDR Pre-Qualification

Computed with measured S-parameters and 20-ps Gaussian step (100 ps delay added)

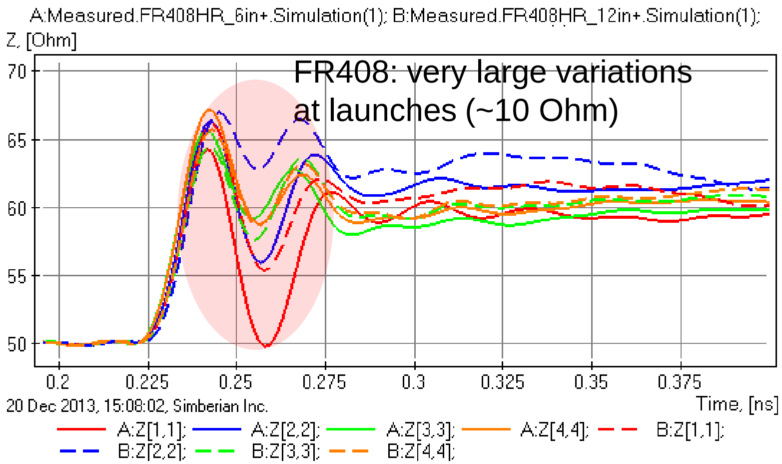


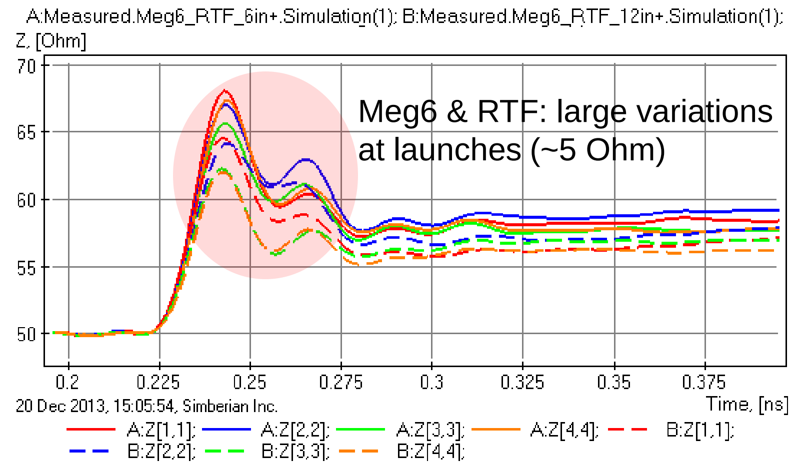


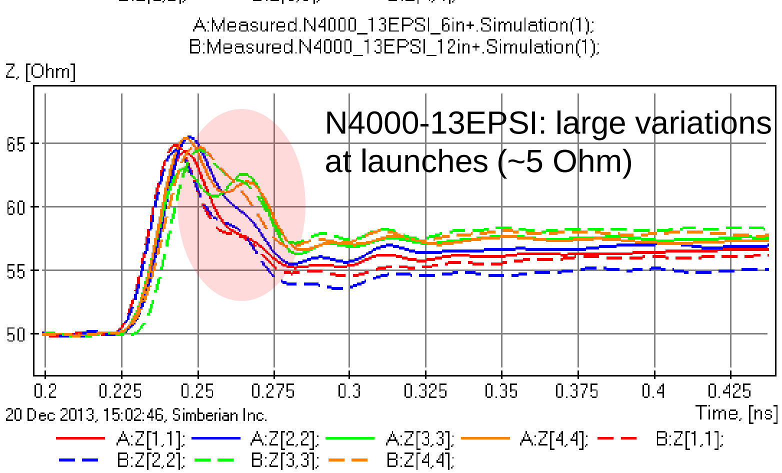


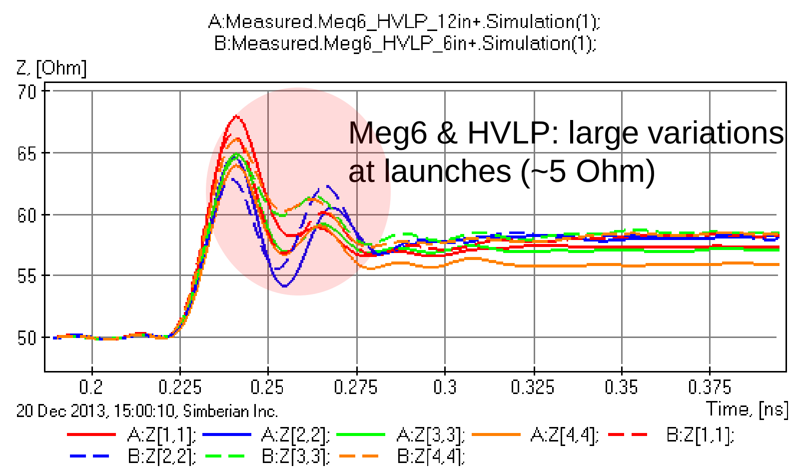


Closer Look at TDR of Launches



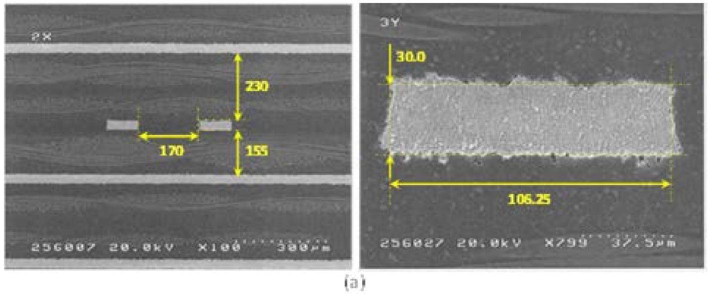




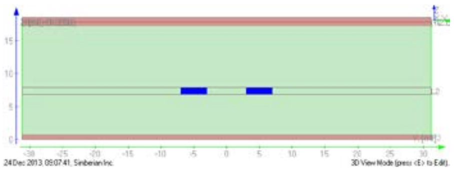


Not promising – see more at "Sensitivity of PCB Material Identification with GMS-Parameters to Variations in Test Fixtures", Simberian App. Note #2010_03 – www.simberian.com

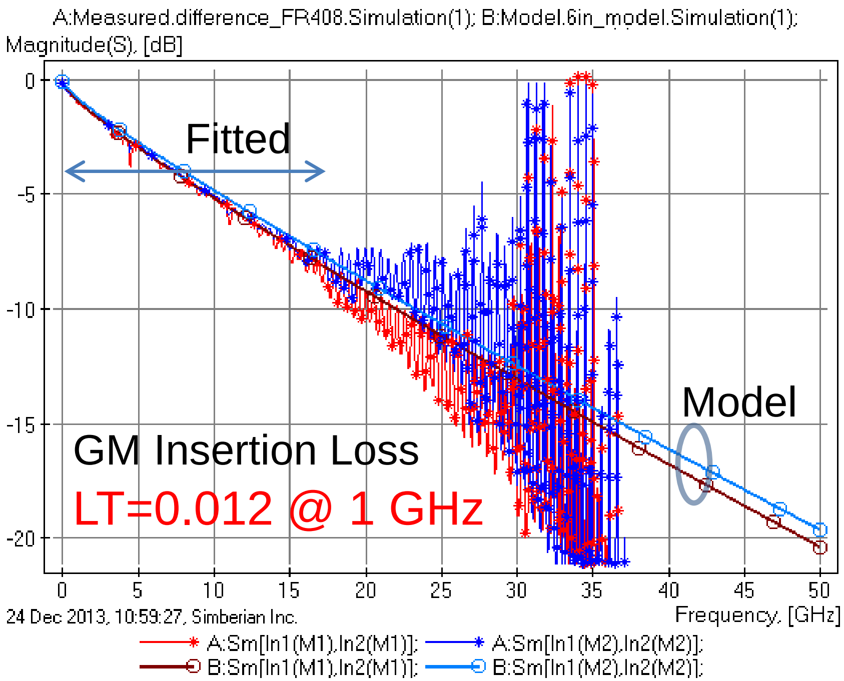
Model Identification for FR408 with RTF

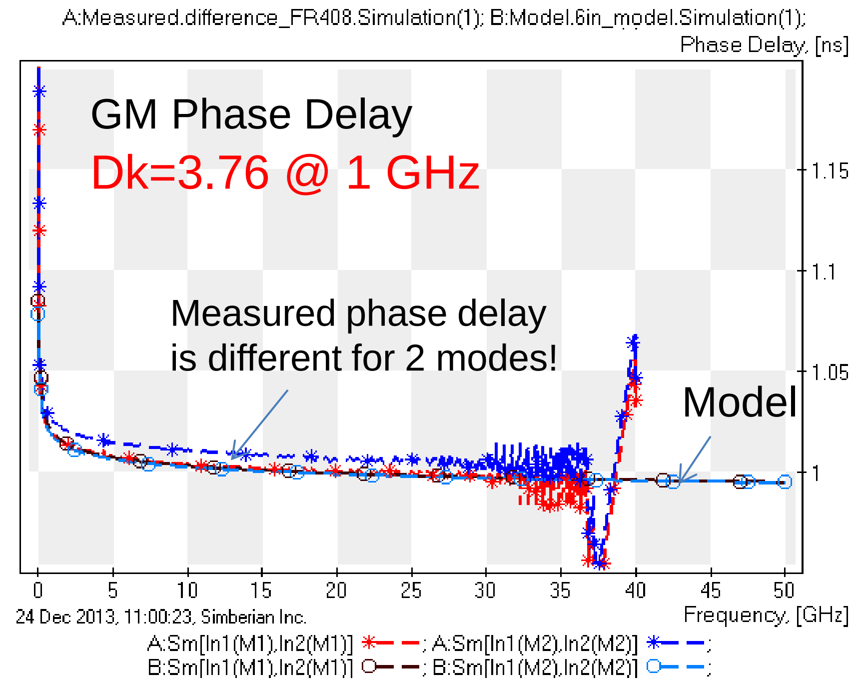


6.15 inch segment model with **homogeneous** dielectric



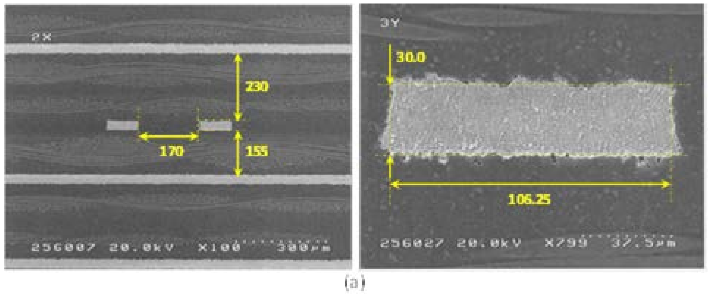
Wideband Debye model identified with reduced bandwidth GMS-parameters @ 1 GHz



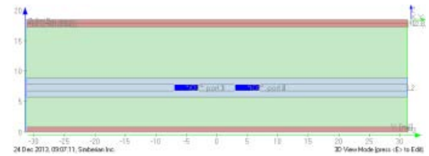


Odd modes – red and brown lines; Even modes – blue lines;

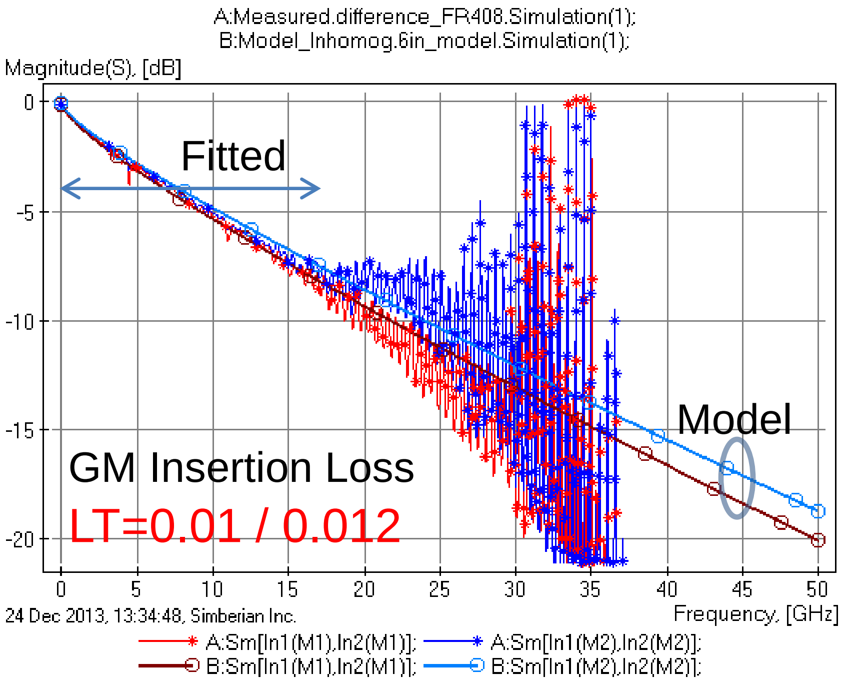
Model for FR408 with RTF Copper

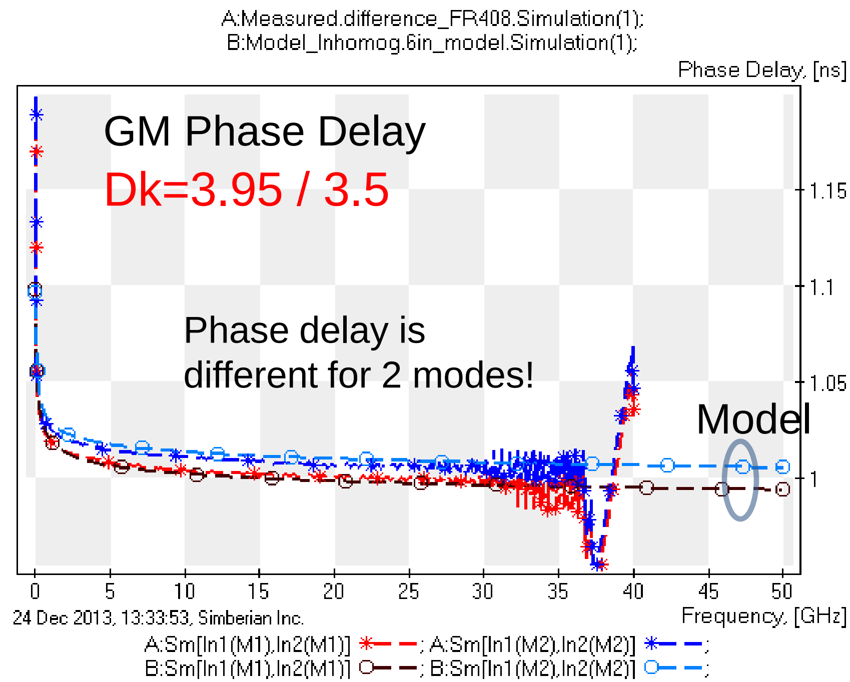


6.15 inch segment model with **inhomogeneous** dielectric



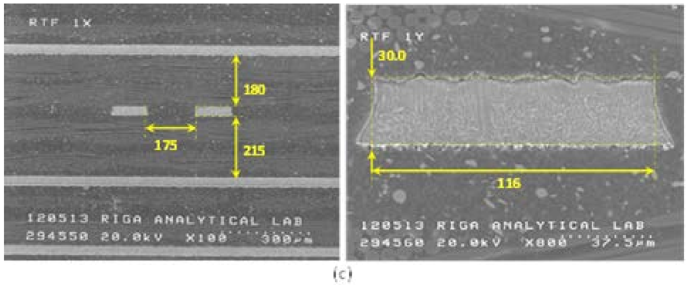
Wideband Debye model identified with reduced-bandwidth GMS-parameters: composite/resin @ 1 GHz



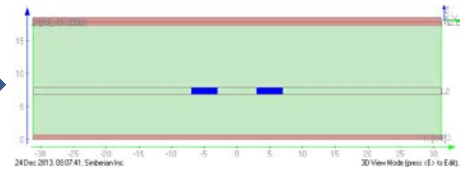


Odd modes – red and brown lines; Even modes – blue lines;

Model for Megtron 6 with RTF Copper

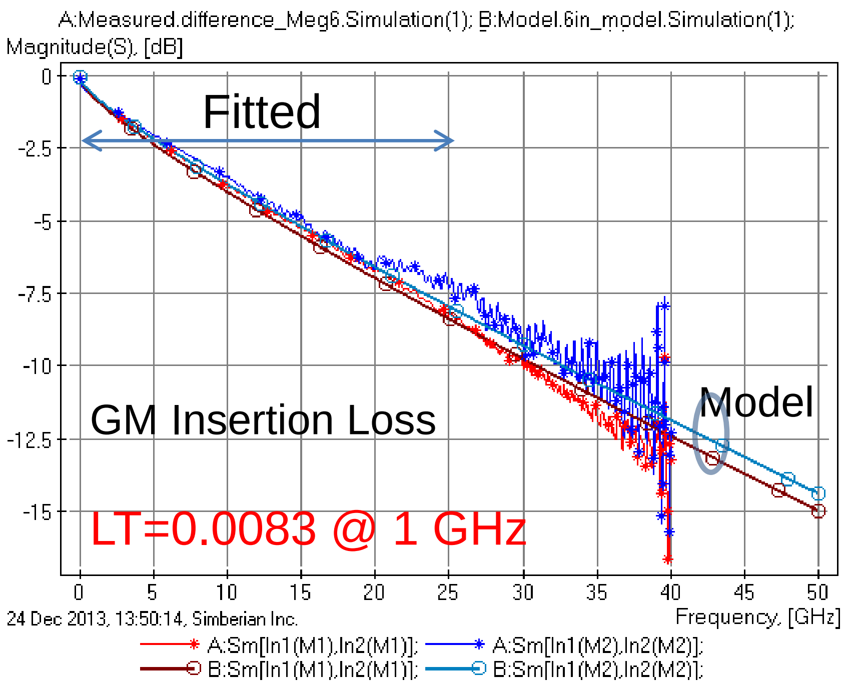


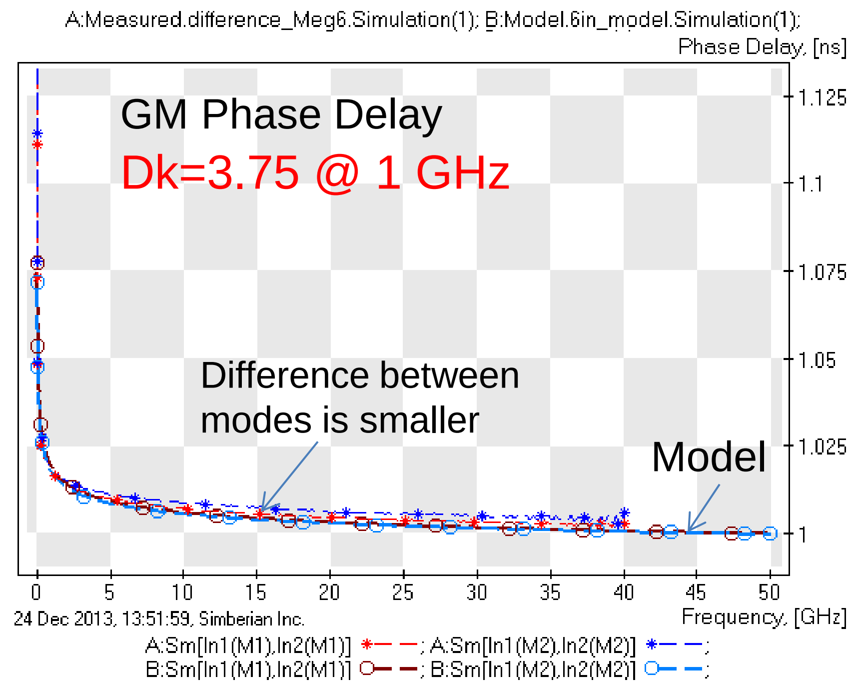
6.15 inch segment model with **homogeneous** dielectric



Strips modeled as trapezoidal

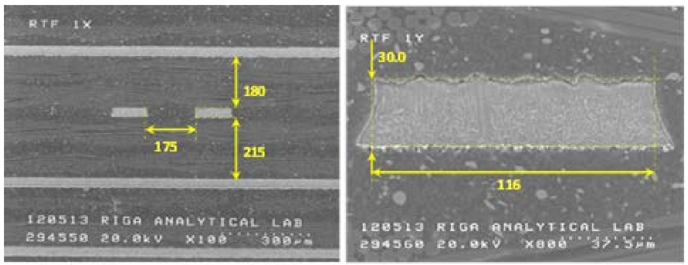
Wideband Debye model **includes all losses** @ 1 GHz





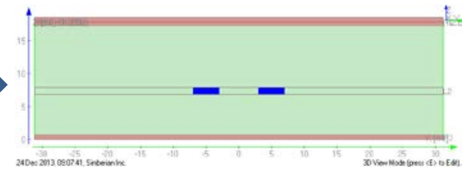
Odd modes – red and brown lines; Even modes – blue lines;

Model for Megtron 6 with RTF Copper



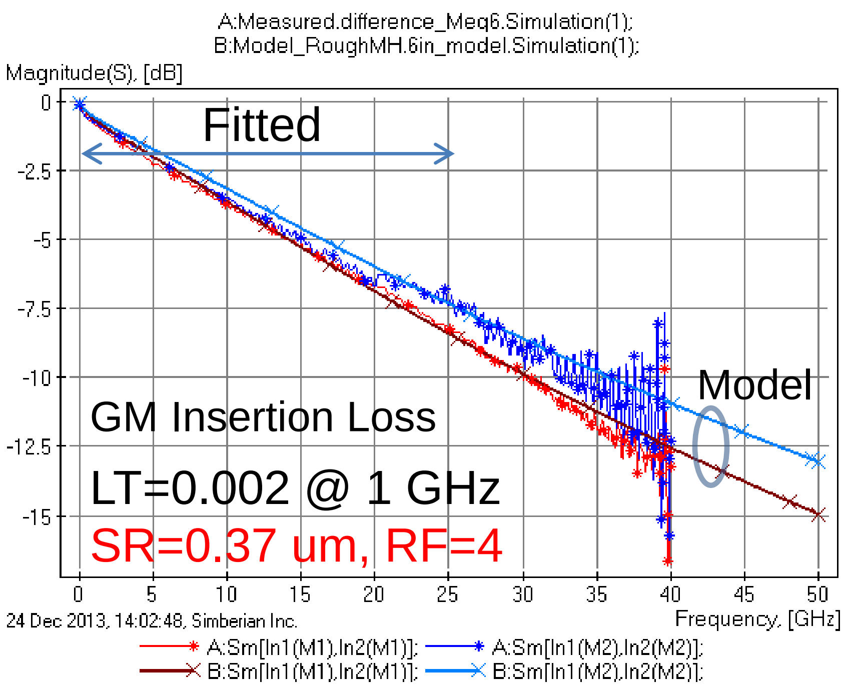
(c)

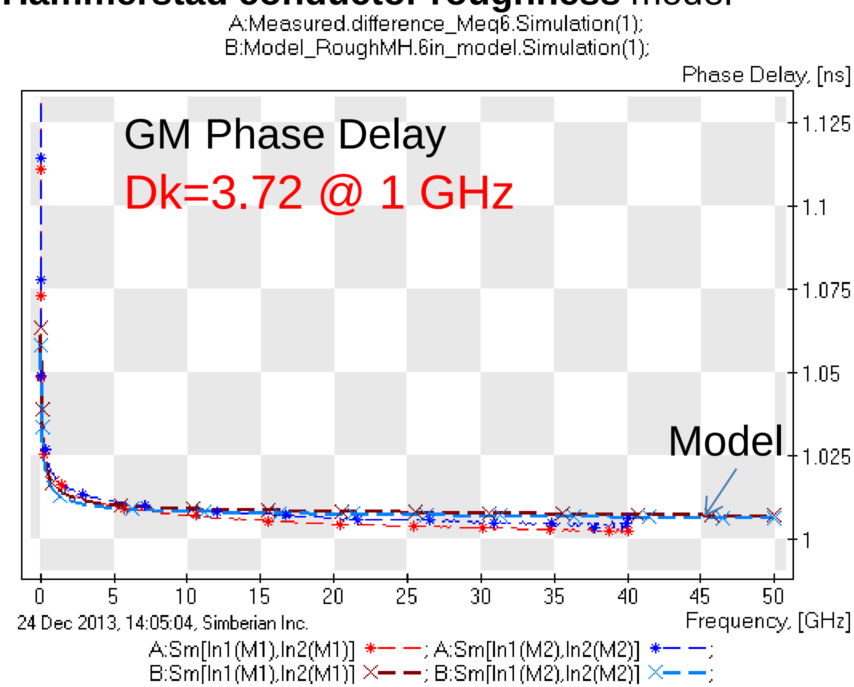
6.15 inch segment model with **homogeneous** dielectric



Strips modeled as trapezoidal

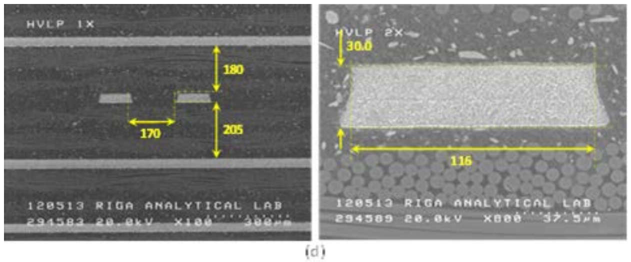
Wideband Debye model @ 1 GHz and **Modified Hammerstad conductor roughness** model



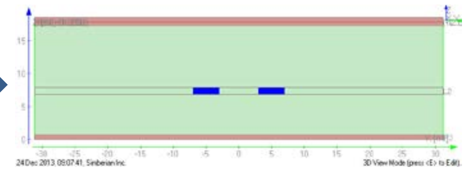


Odd modes – red and brown lines; Even modes – blue lines;

Model for Megtron 6 with HVLP Copper

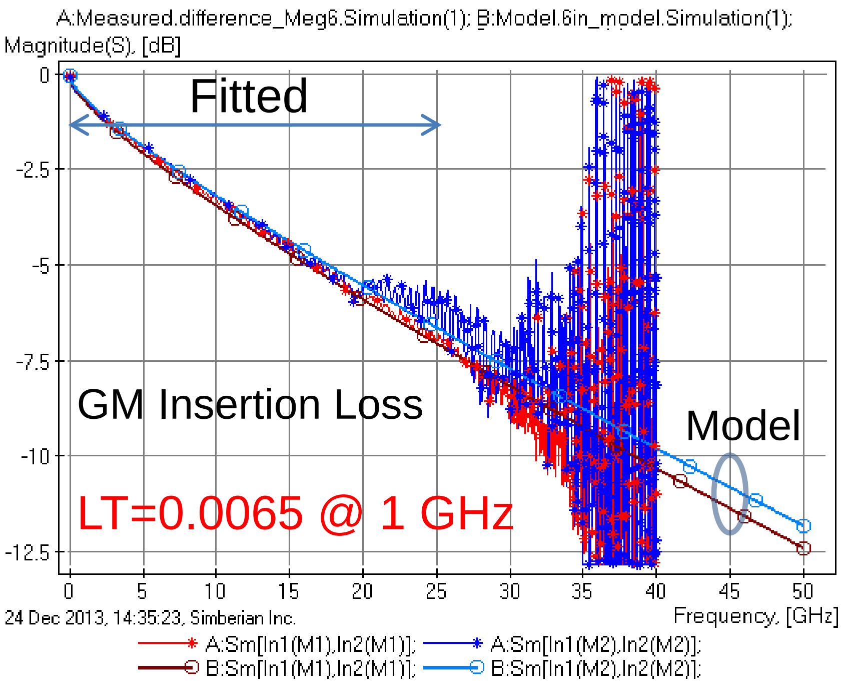


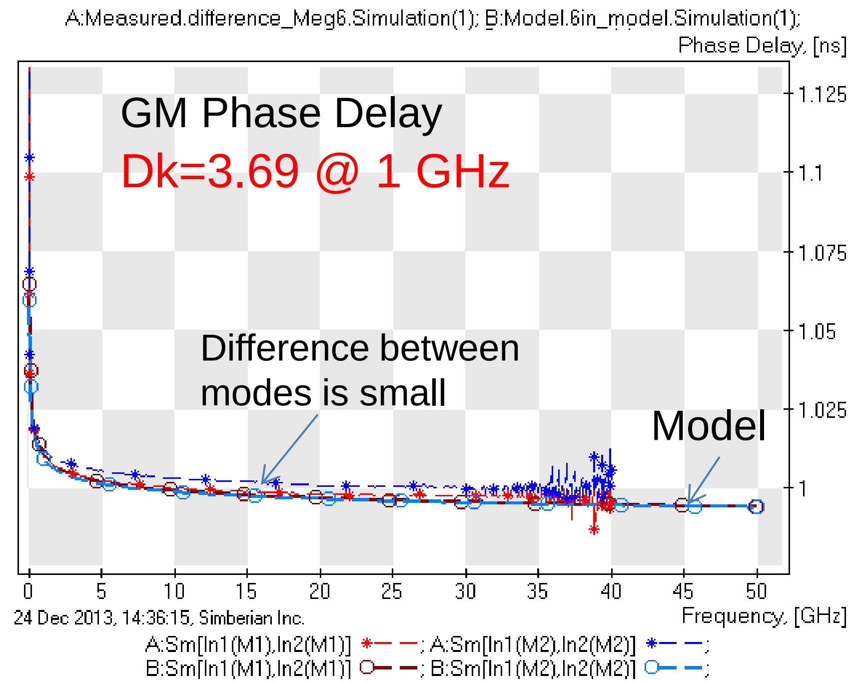
6.15 inch segment model with **homogeneous** dielectric



Strips modeled as trapezoidal

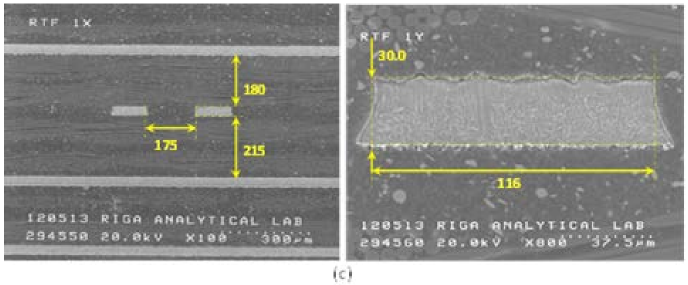
Wideband Debye model **includes all losses** @ 1 GHz



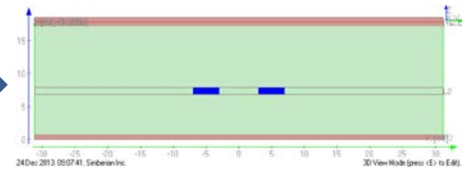


Odd modes – red and brown lines; Even modes – blue lines;

Model for Megtron 6 with HVLP Copper

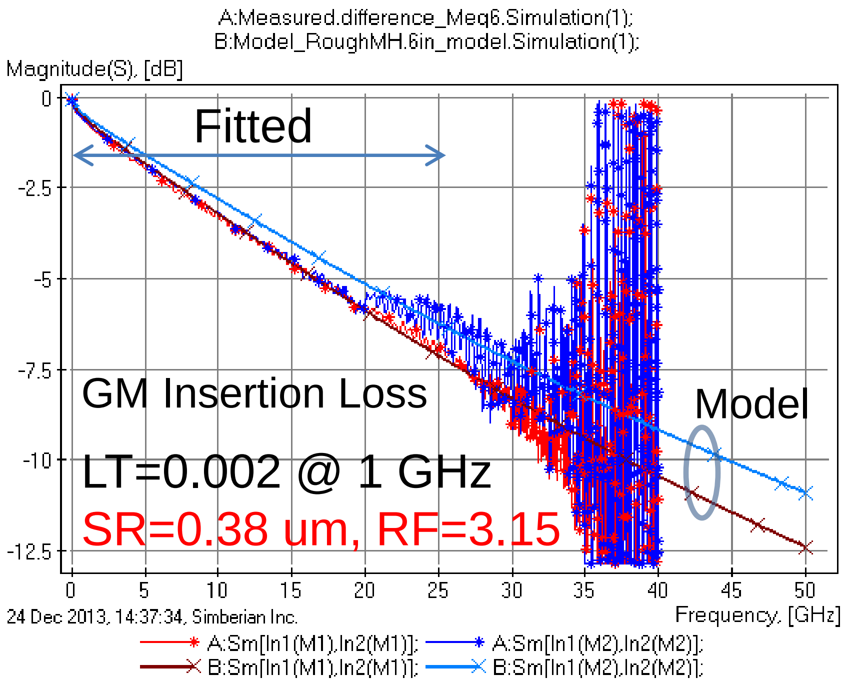


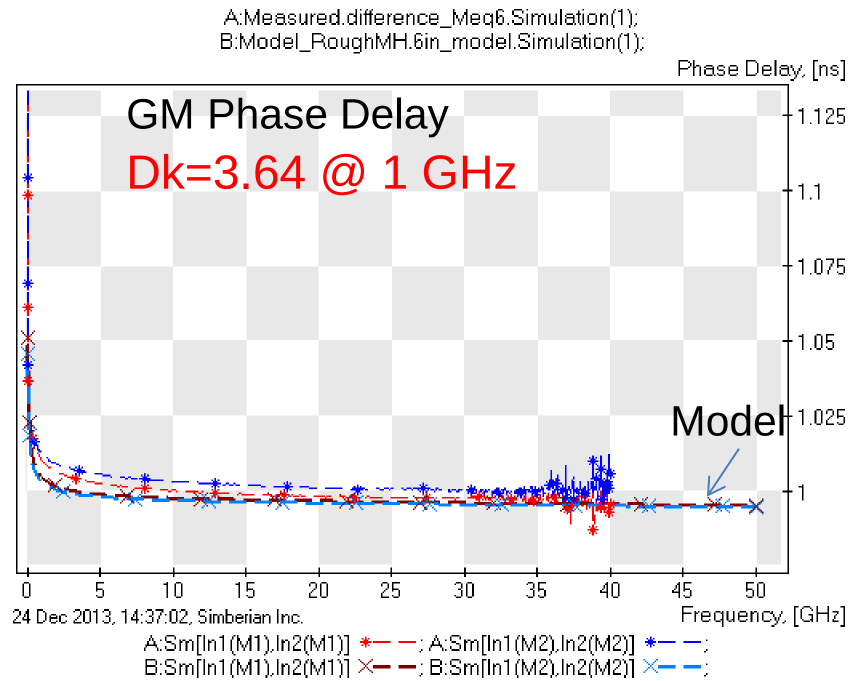
6.15 inch segment model with **homogeneous** dielectric



Strips modeled as trapezoidal

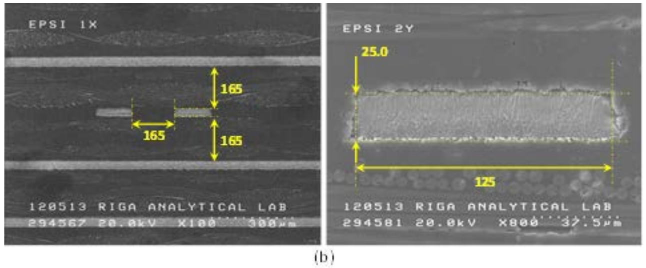
Wideband Debye model @ 1 GHz and **Modified Hammerstad conductor roughness** model



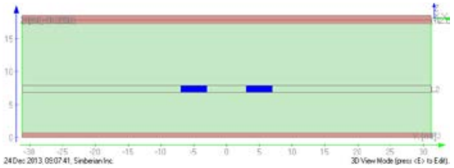


Odd modes – red and brown lines; Even modes – blue lines;

Model for N4000-13EPSI with RTF Copper

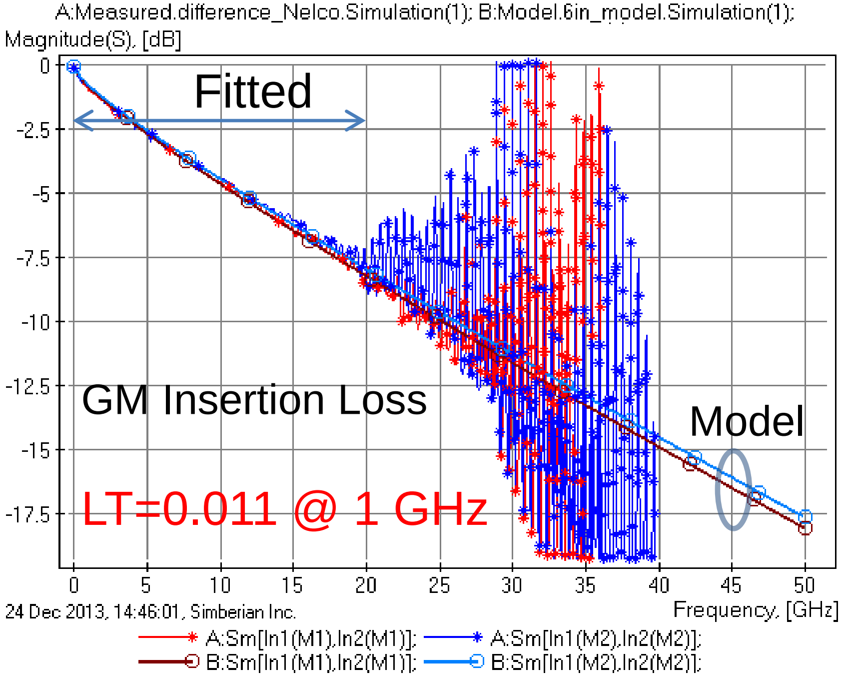


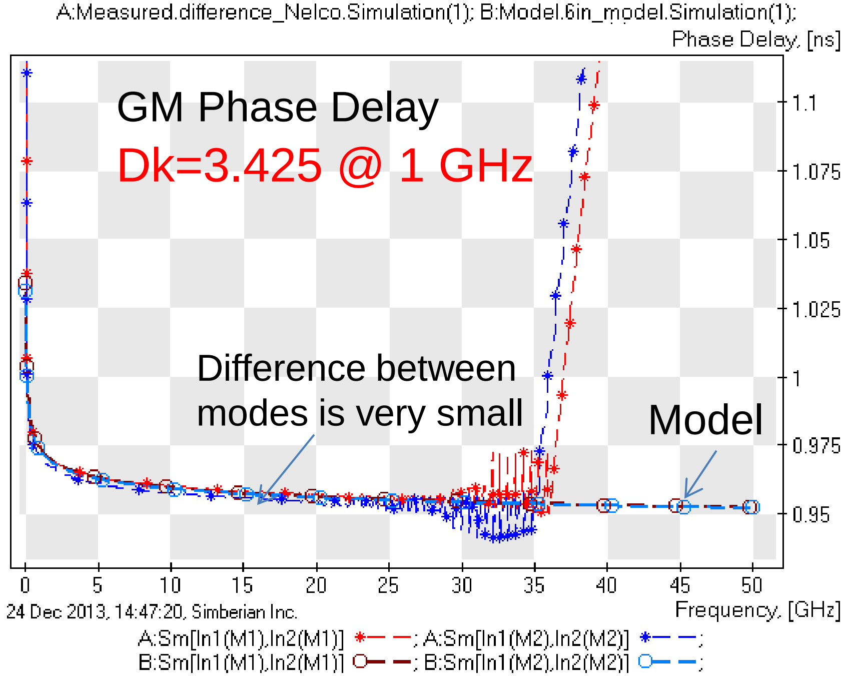
6.15 inch segment model with **homogeneous** dielectric



Strips modeled as trapezoidal

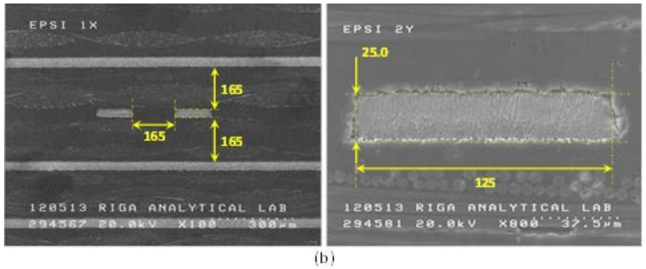
Wideband Debye model **includes all losses** @ 1 GHz



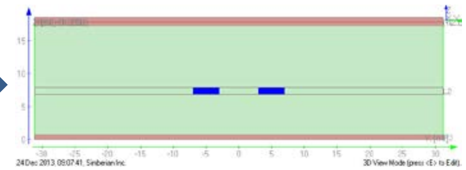


Odd modes – red and brown lines; Even modes – blue lines;

Model for N4000-13EPSI with RTF Copper

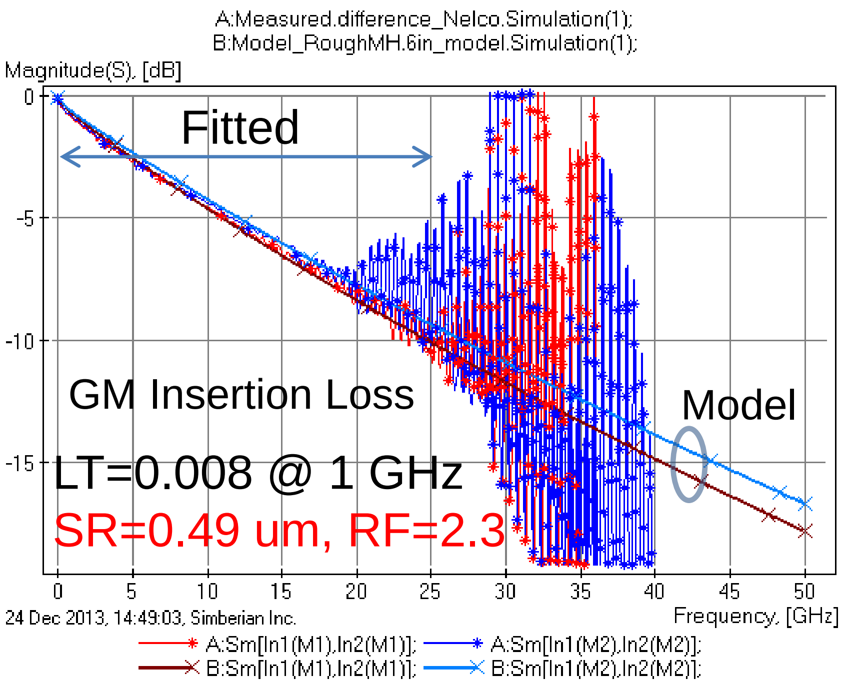


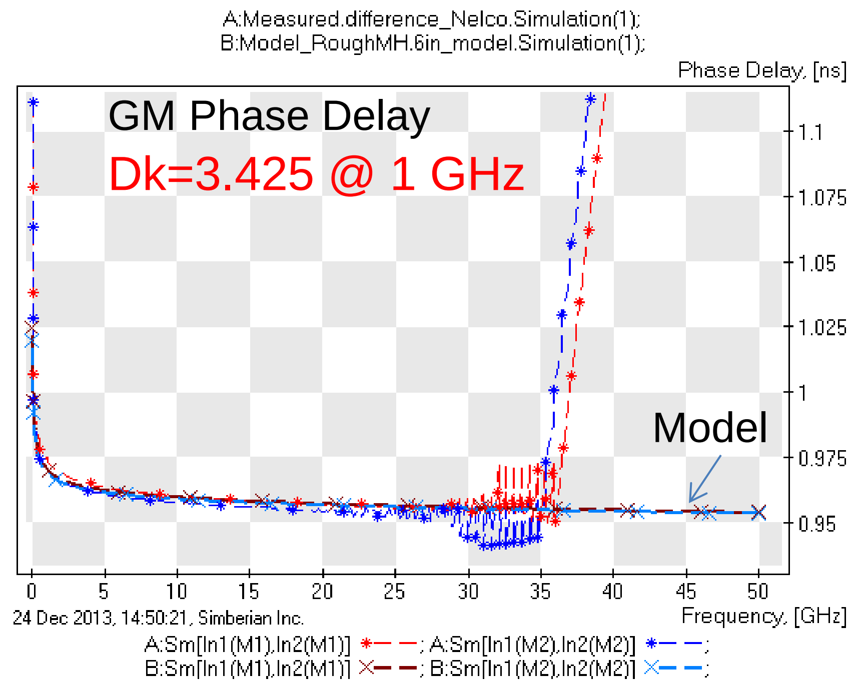
6.15 inch segment model with **homogeneous** dielectric



Strips modeled as trapezoidal

Wideband Debye model @ 1 GHz and **Modified Hammerstad conductor roughness** model





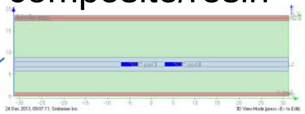
Odd modes – red and brown lines; Even modes – blue lines;

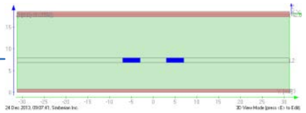
Identified Material Models

- Wideband Debye (WD) with dielectric and roughness losses:

Model Parameters Board Types	WD Dielectric Constant @ 1 GHz	WD Loss Tangent @ 1 GHz
FR408HR with RTF copper, inhomogeneous	3.95/3.5 (3.66)	0.01/0.012 (0.0117)
FR408HR with RTF copper	3.76 (3.66)	0.012 (0.0117)
Megtron-6 with HVLP copper	3.69 (3.6)	0.0065 (0.002)
Megtron-6 with RTF copper	3.75 (3.6)	0.0083 (0.002)
Nelco N4000-13EPSI with RTF copper	3.425 (3.4)	0.011 (0.008)

composite/resin



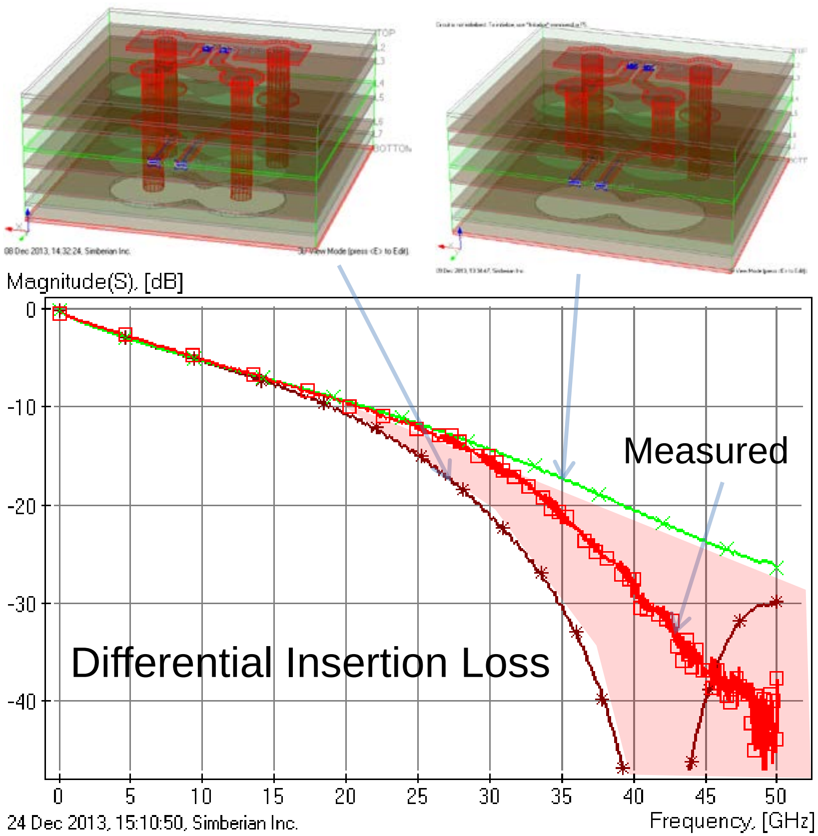


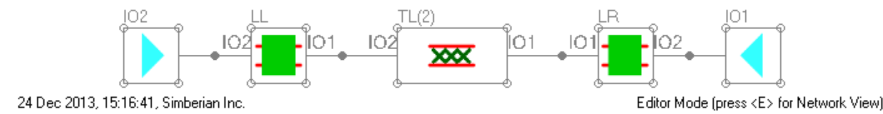
- Wideband Debye (WD) dielectric with loss tangent from specs and Modified Hammerstad model (MH) for conductor roughness losses:

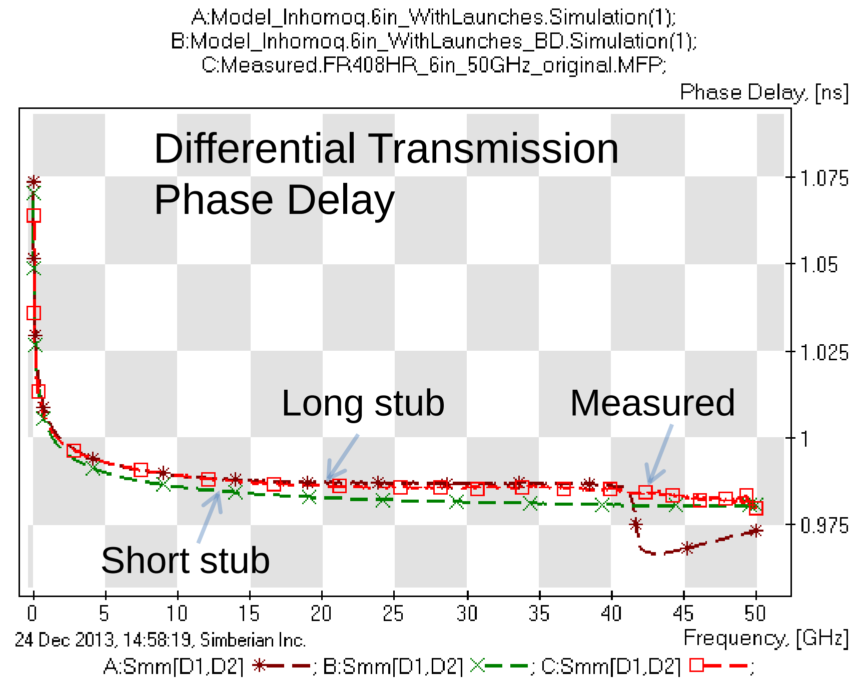
Model Parameters Board Types	WD Dielectric Constant @ 1 GHz	WD Loss Tangent @ 1 GHz	MH Roughness (SR,rms) (um)	MH Roughness Factor (RF)
Megtron-6 with HVLP copper	3.64 (3.6)	0.002	0.38	3.15
Megtron-6 with RTF copper	3.72 (3.6)	0.002	0.37	4
Nelco N4000-13EPSI with RTF copper	3.425 (3.4)	0.008	0.49	2.3

Values from specifications are provided in brackets for comparison

Preliminary 6-inch Link Analysis

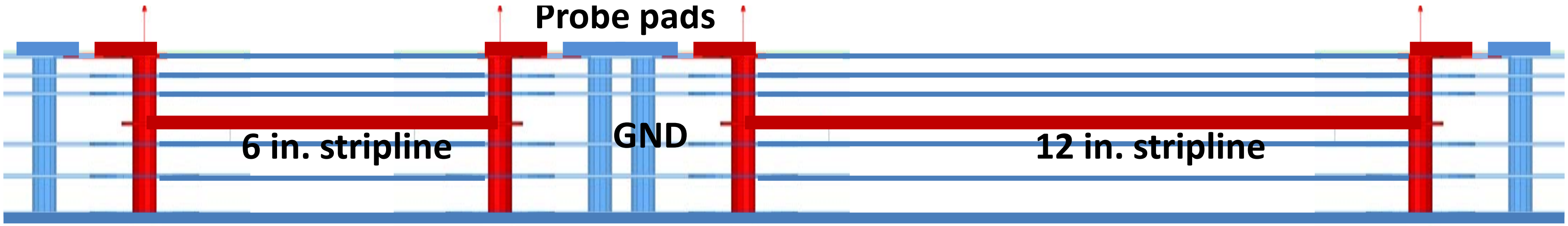


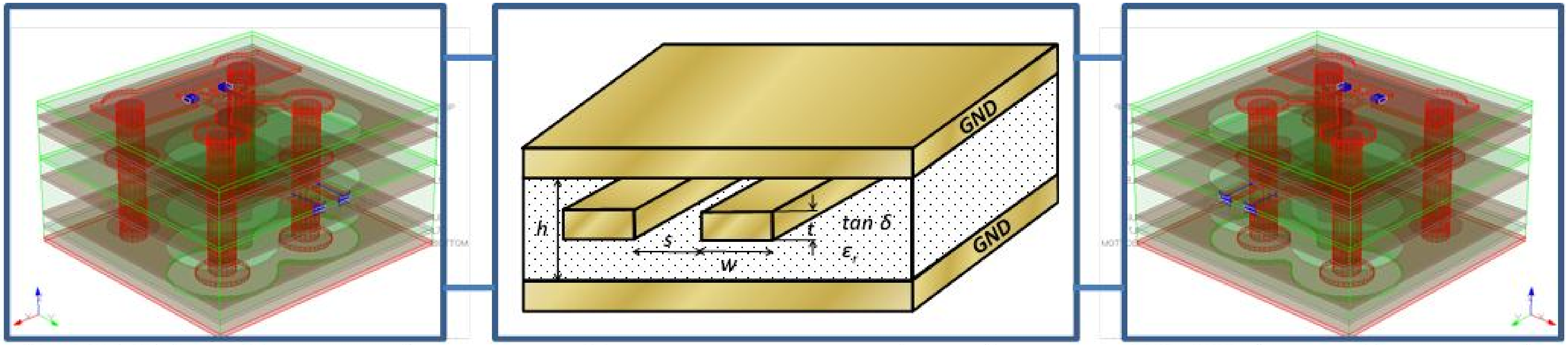




Measured – red lines; Model with long via stubs - brown lines; Model with short via stubs – green lines;

Measured Structures





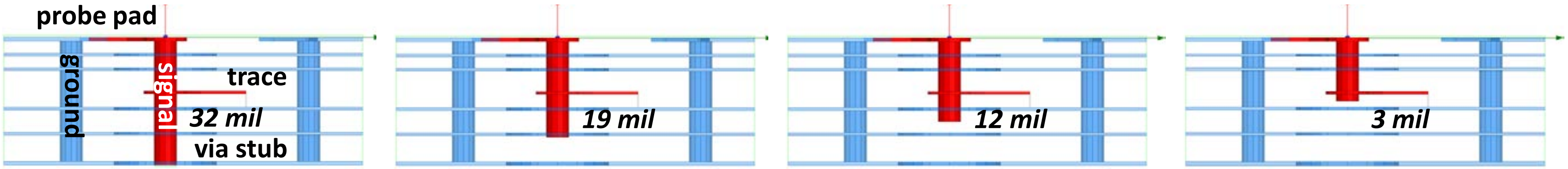
3D EM Solver Generated Via and Pad S parameter

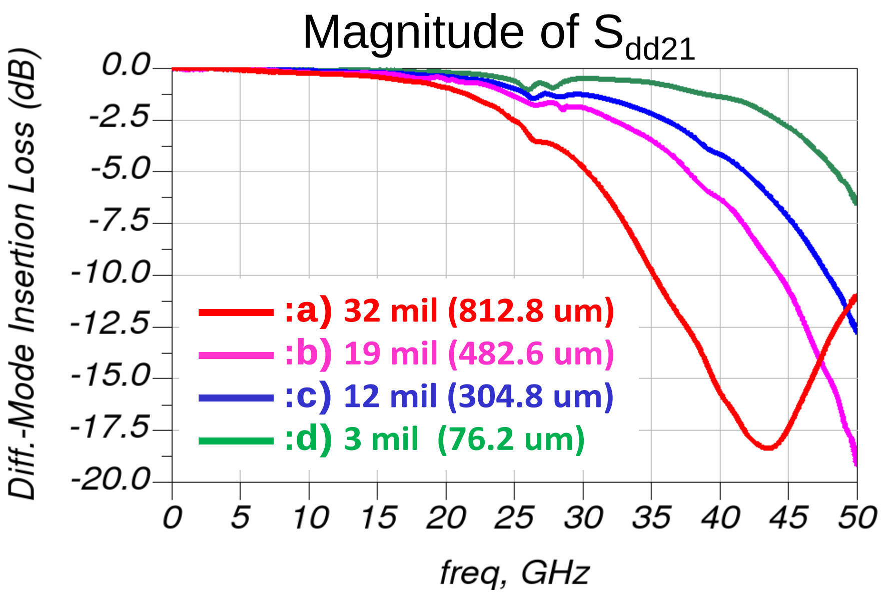
Extract parameters-based Transmission Line Model

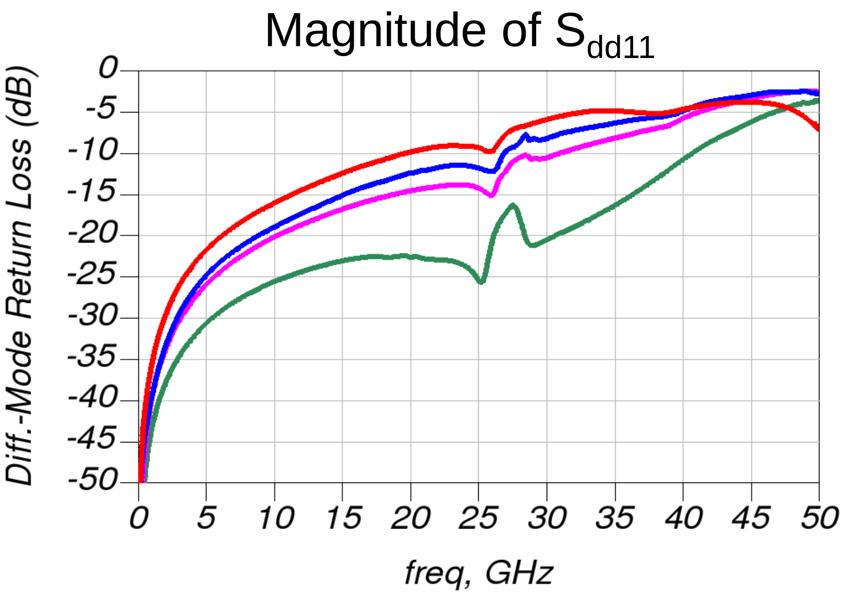
3D EM Solver Generated Via and Pad S parameter

- Eight-layer board and the striplines are on layer four
- Extracting frequency-dependent model requires stripline-only measurement
  - The S-parameters of the via and pad structures are obtained from field solvers

Via Stub Impact vs. Length

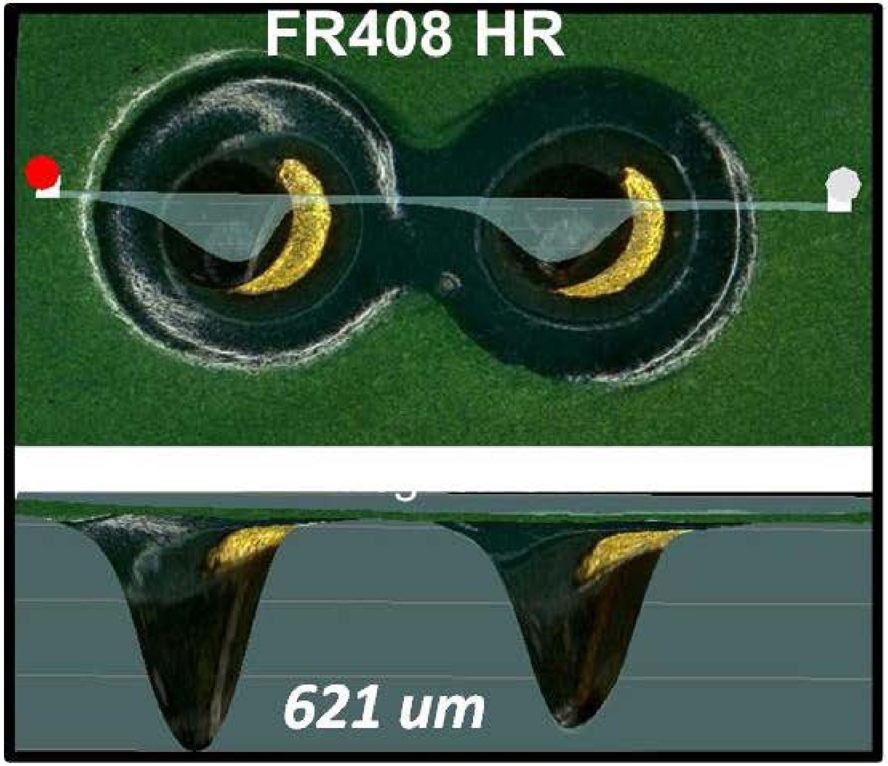


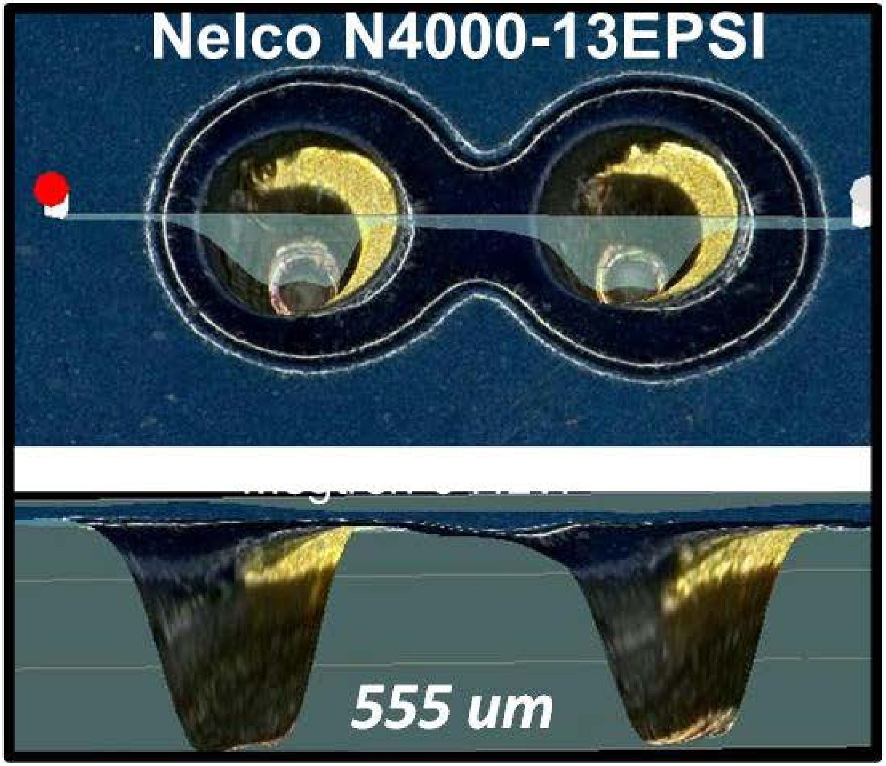




- The reflection and band-limiting impacts of the vias and pads need to be considered
  - Back drilling is necessary to minimize the impacts of via stubs
  - The via stub length need to be accurately measured

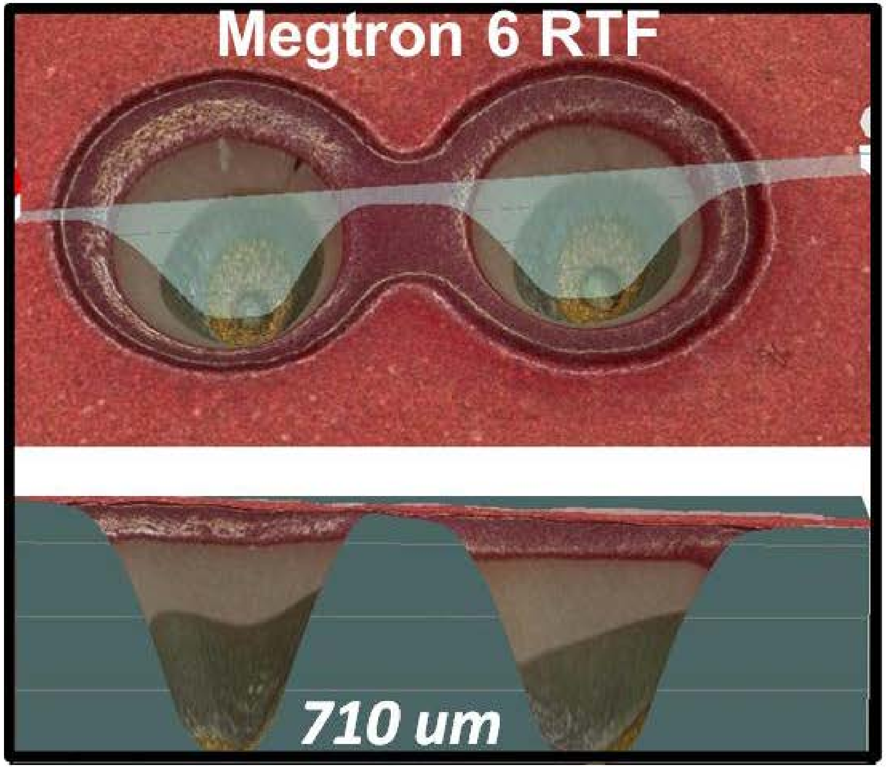
Back Drilling in FR408 & Nelico Boards

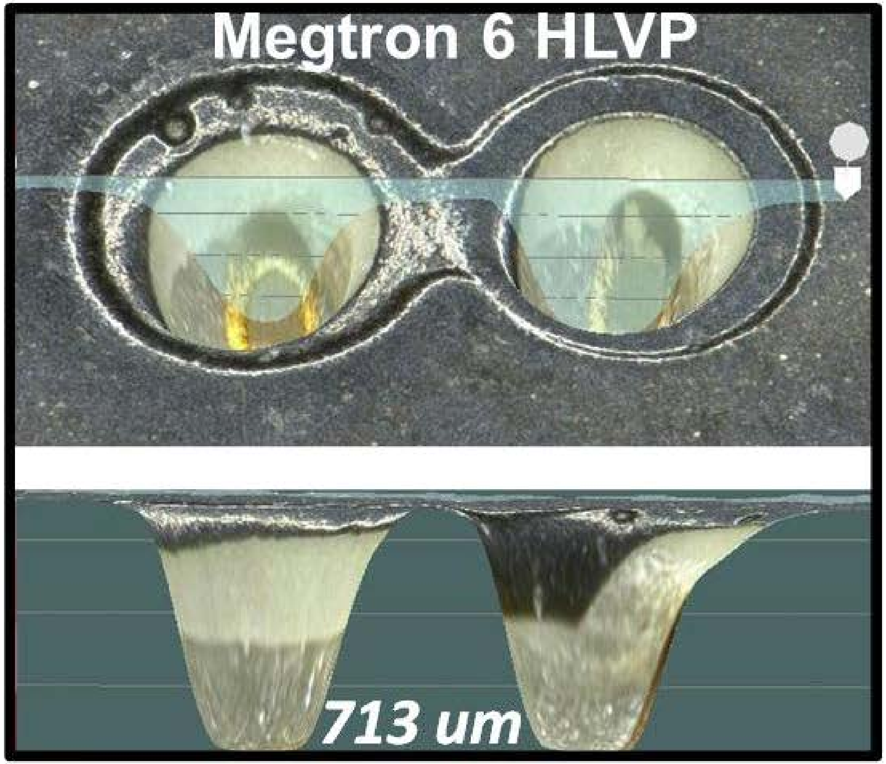




- Significant variations in the back-drilled holes
  – from board to board
  – from via to via within a board (differential pairs)

Back Drilling in Megtron 6 Boards





- For example, the Megtron 6 board
  - Range of the back-drilled depth
    - 748.10 um – 680.90 um = 67.2 um

	Depth (um)
Average	712.45
Max	748.10
Min	680.90
Std. Dev.	25.17

Model and Correlation

Via Stub Length (um)

Board Type	Board Thickness	Pad to trace Via length	Back drill depth	Via stub length
FR 408HR	1470	600	620	250
Nelco N4000 EPSI	1360	540	555	265
Megtron 6 RTF	1400	560	710	130
Megtron 6 HVLP	1400	560	713	127

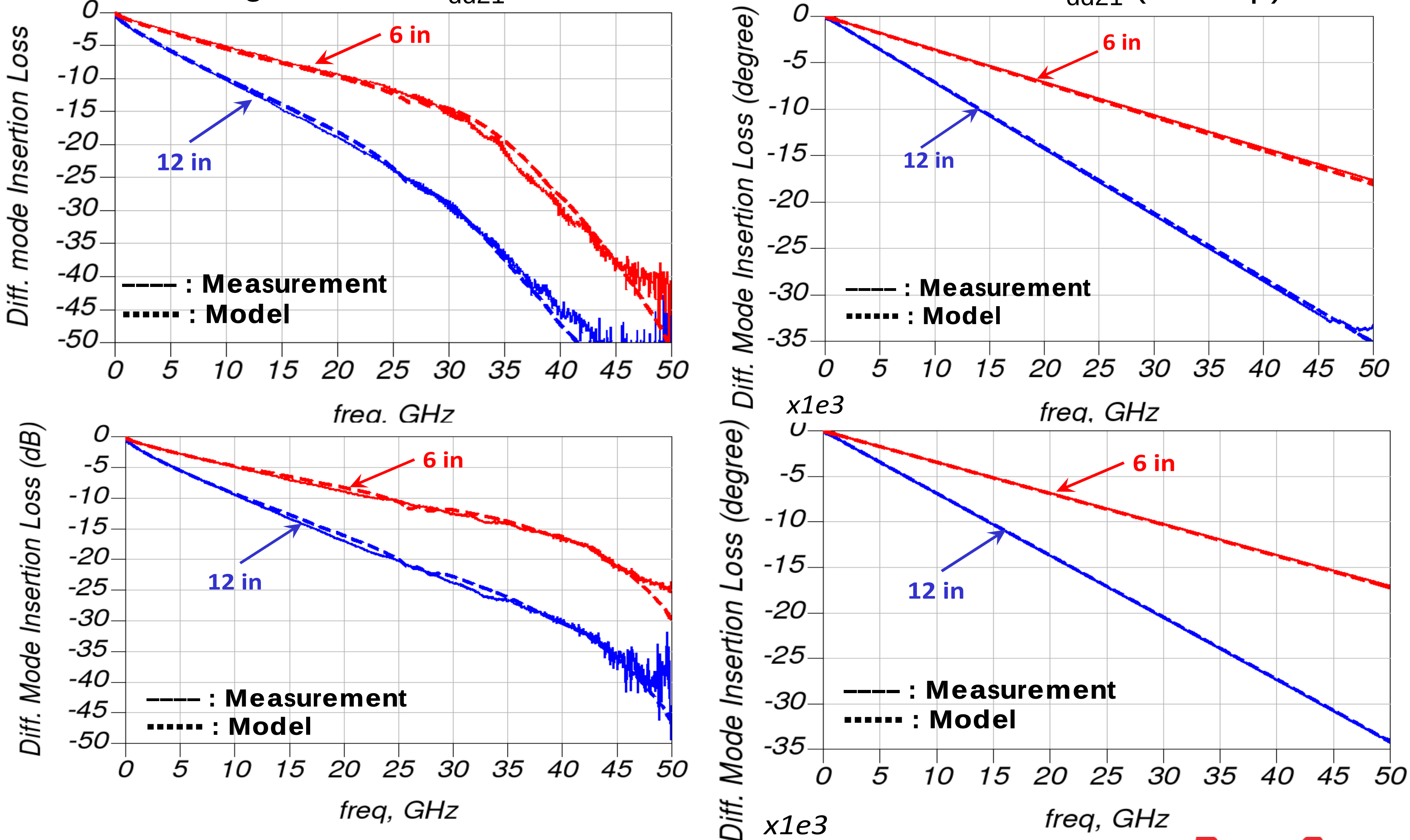
Board Parameters

Model Parameters / Board Types	WD Dielectric Constant @ 1 GHz	WD Loss Tangent @ 1 GHz	MH Roughness (SR,rms) (um)	MH Roughness Factor (RF)
FR408HR with RTF copper	3.76 (3.66)	0.012	2.0	5.0
Nelco N4000-13EPSI with RTF copper	3.425 (3.4)	0.008	0.49	2.3
Megtron-6 with RTF copper	3.64 (3.6)	0.002	0.37	4
Megtron-6 with HVLP copper	3.72 (3.6)	0.002	0.38	3.15

- The parameters are used along the S-parameters of via, pad, and remaining stub structure

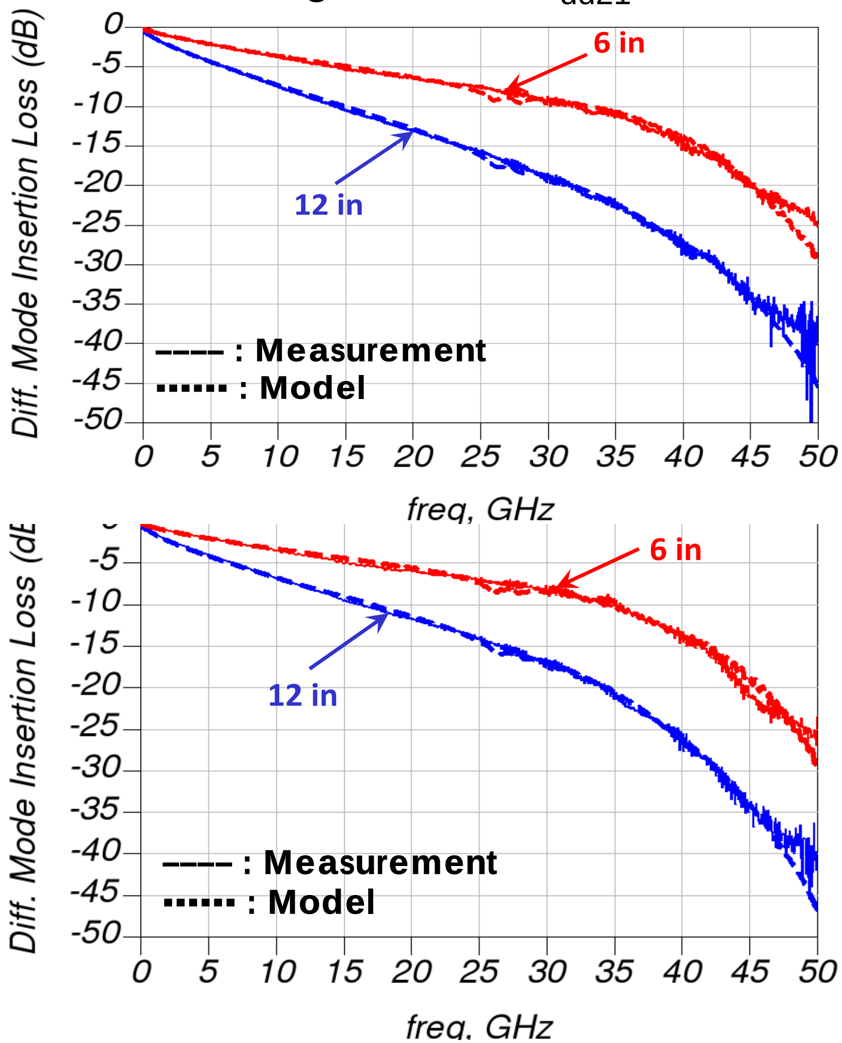
FR408 and Nelco with RTF

Magnitude of S_{dd21} — Phase of S_{dd21} (unwrap)

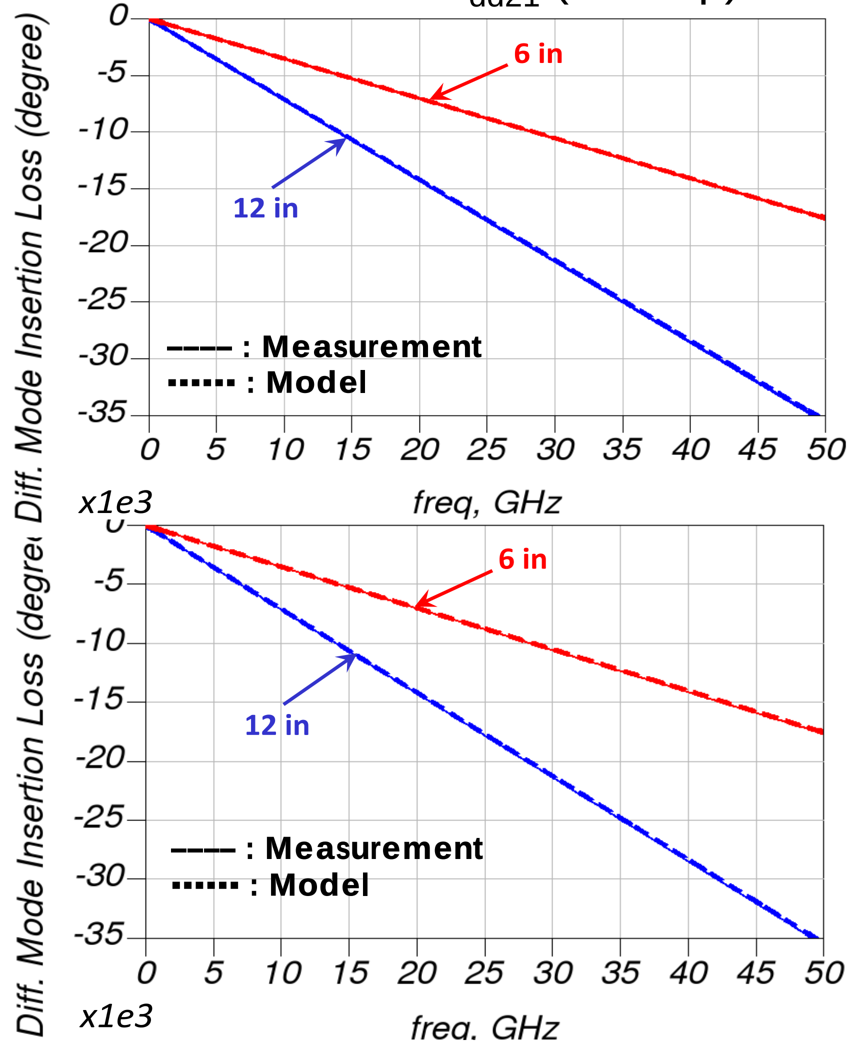


Megtron 6 with RTF and HVLP

Magnitude of S_{dd21}



Phase of S_{dd21} (unwrap)



Conclusions: Lessons Learned

- Formal quality metrics are useful for pre-qualification of measured S-parameters
- Expected symmetry of manufactured test fixtures was violated by:
  - Fiber weave effect (FR408HR)
  - Manufacturing tolerances (back-drilling on all boards)
  - Probes positioning (or de-embedding? on some boards)
  - Loss of localization by vias at higher frequencies (dependence on stub length)
- These non-idealities reduced bandwidth of GMS-parameters for model identification
- Frequency-continuous models for dielectrics and conductor roughness can be extracted with the reduced-bandwidth GMS-parameters to 50 GHz and beyond
- Inhomogeneity of FR408 and Megtron 6 dielectrics has to be accounted for to increase accuracy and to account for FEXT (not needed for N4000-13EPSI)
- With separate roughness models and loss tangents from specs, identified dielectric constants are closer to specs