Decompositional Electromagnetic Analysis of Digital Interconnects

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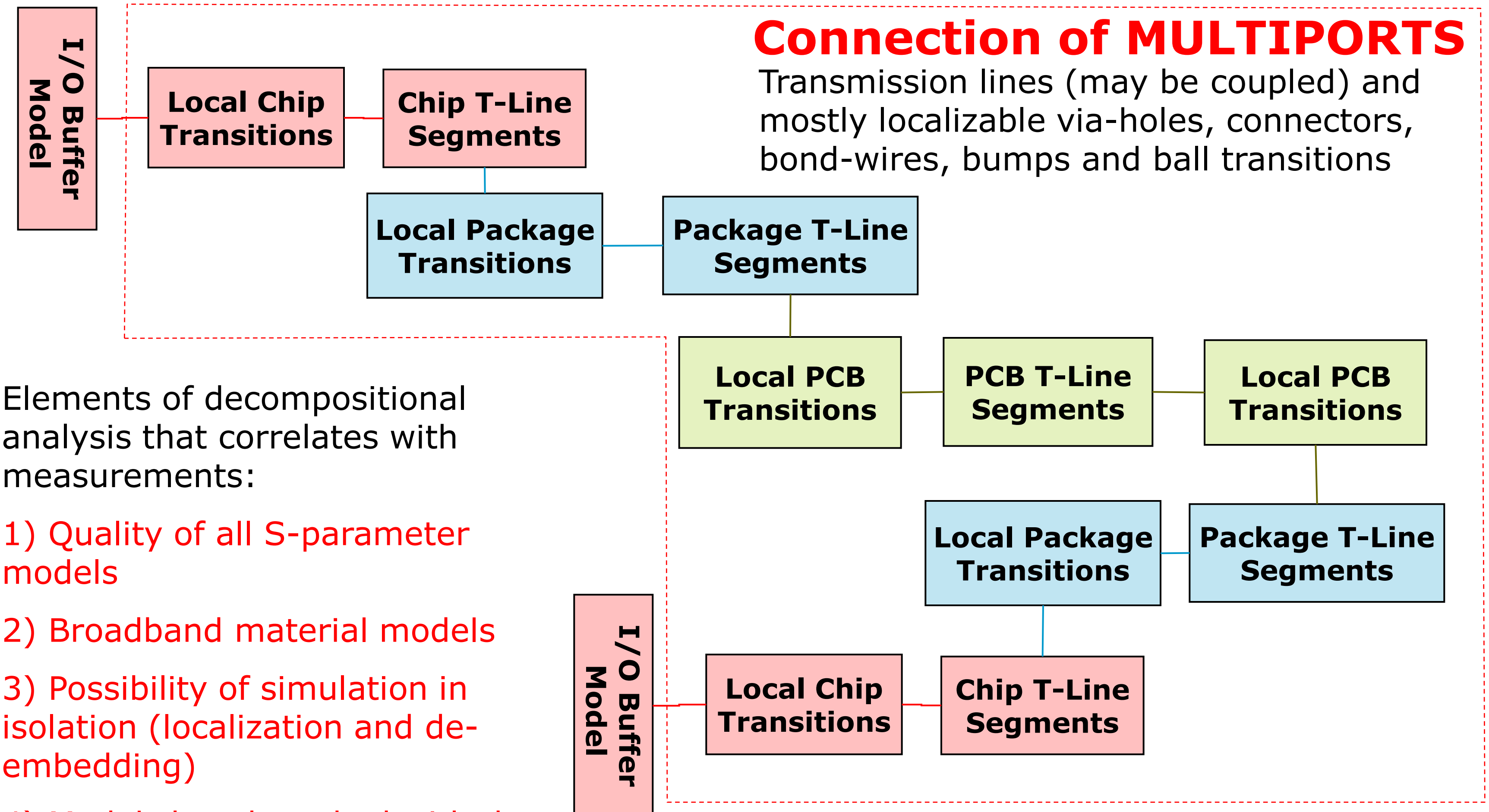
Outline

- Introduction
- Quality of S-parameter models
- Broadband material models
- Modeling discontinuities in isolation
- Validation and benchmarking
- Conclusion
- References and contacts

Introduction

- 10G Ethernet is practically mainstream now, 25-50 G is coming out…
  - Spectrum of signals ranges from DC or MHz frequencies up to 20-50 GHz and beyond – no established methodologies to design predictable interconnects
  - Improper interconnect modeling may result in multiple re-spins or complete failure due to interconnects
- What is the best way to analyze such interconnects?
  - Electromagnetic analysis as a whole
    - Suitable for EMC/EMI (radiation)
    - Inefficient for signal integrity analysis due to problem size and fine details
  - Decompositional electromagnetic analysis is the alternative
    - Divide into elements, build or get element models and unite
    - 2D, 3D, quasi-static or full-wave models can be used for the elements
    - Much faster and more accurate, but only if some conditions satisfied…

Decompositional analysis of a channel



Elements of decompositional analysis that correlates with measurements:

1) Quality of all S-parameter models

2) Broadband material models

3) Possibility of simulation in isolation (localization and de-embedding)

4) Models benchmarked with the measurements

(1) Quality of S-parameter models

- Multiports are usually described with S-parameter models
  - Produced by circuit or electromagnetic simulators, VNAs and TDNAs in forms of Touchstone or BB SPICE models
- Very often such models have issues and may be not suitable for consistent frequency and time domain analyses
  - S-parameter models must have sufficient bandwidth and satisfy passivity, reciprocity and causality conditions
- How to make sure that a model is suitable for analysis?
- The answer is the key element for design success

Good models of interconnects …

- Must have sufficient bandwidth matching signal spectrum
- Must be appropriately sampled to resolve all resonances
- Must be passive (do not generate energy)

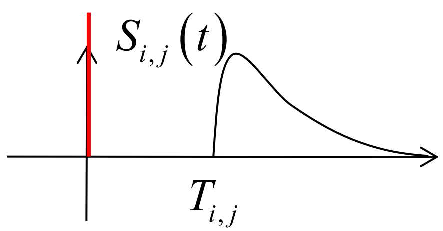
$$P_{in} = \overline{a}^* \cdot \left[U - S^* S \right] \cdot \overline{a} \ \geq 0 \quad \Rightarrow \quad eigenvals\left[S^* \cdot S \right] \leq 1$$ from DC to infinity!

- Must be reciprocal (linear reciprocal materials used in PCBs)

$$S_{i,j} = S_{j,i} \quad or \quad S = S^t$$

- Must be causal (have causal step or impulse response or satisfy KK relations)

$$S_{i,j}(t) = 0, \ \ t < T_{ij}$$



$$S(i\omega) = \frac{1}{i\pi} PV \int_{-\infty}^{\infty} \frac{S(i\omega')}{\omega - \omega'} \cdot d\omega'$$

Model bandwidth and sampling

- If no DC point, the lowest frequency in the sweep should be
  - Below the transition to skin-effect (1-50 MHz for PCB applications)
  - Below the first possible resonance in the system (important for cables, L is physical length)

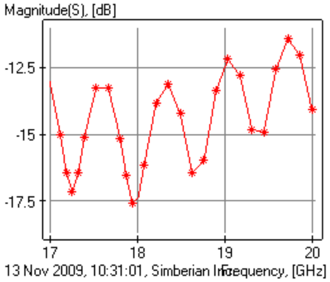
$$L < \frac{\lambda}{4} = \frac{c}{4 f_l \cdot \sqrt{\varepsilon_{eff}}} \Rightarrow f_l < \frac{c}{4L \cdot \sqrt{\varepsilon_{eff}}}$$

- The highest frequency in the sweep must be defined by the required resolution in time-domain or by spectrum of the signal (by rise time or data rate)

$$f_h > \frac{1}{2t_r} \qquad f_h > K \cdot f_{s1}$$

- The sampling is very important for DFT and convolution-based algorithms, but not so for algorithms based on fitting
  - There must be 4-5 frequency point per each resonance
  - The electrical length of a system should not change more than quarter of wave-length between two consecutive points

$$df < \frac{c}{4L \cdot \sqrt{\varepsilon_{eff}}}$$



Model quality metrics (0-100%)

First introduced at IBIS forum at DesignCon 2010

- Passivity Quality Measure:

$$PQM = \max\left[\frac{100}{N_{total}}\left(N_{total} - \sum_{n=1}^{N_{total}} PW_n\right), 0\right]\%$$

$$PW_n = 0 \ if \ \ PM_n < 1.00001; \ otherwise \ PW_n = \frac{PM_n - 1.00001}{0.1}$$

$$PM_n = \sqrt{\max\left[eigenvals\left(S^*(f_n)\cdot S(f_n)\right)\right]}$$

should be >99%

- Reciprocity Quality Measure:

$$RQM = \max\left[\frac{100}{N_{total}}\left(N_{total} - \sum_{n=1}^{N_{total}} RW_n\right), 0\right]\%$$

$$RW_n = 0 \ if \ \ RM_n < 10^{-6}; \ otherwise \ RW_n = \frac{RM_n - 10^{-6}}{0.1}$$

$$RM_n = \frac{1}{N_s}\sum_{i,j}\left|S_{i,j}(f_n) - S_{j,i}(f_n)\right|$$

should be >99%

- Causality Quality Measure: Minimal ratio of clockwise rotation measure to total rotation measure in % (should be >80% for numerical models)

Preliminary quality estimation metrics

- Preliminary Touchstone model quality can be estimated with Passivity, Reciprocity and Causality quality metrics (PQM, RQM, CQM)

Metric/Model Icon	- good	- acceptable	- inconclusive	- bad
Passivity	[100, 99.9]	(99.9, 99]	(99, 80]	(80, 0]
Reciprocity	[100, 99.9]	(99.9, 99]	(99, 80]	(80, 0]
Causality	[100, 80]	(80, 50]	(50, 0]	-----

Color code	Passivity (PQM)	Reciprocity (RQM)	Causality (CQM)
Green – good	[99.9, 100]	[99.9, 100]	[80, 100]
Blue – acceptable	[99, 99.9)	[99, 99.9)	[50, 80)
Yellow – inconclusive	[80, 99)	[80, 99)	[20, 50)
Red - bad	[0, 80)	[0, 80)	[0, 20)

Example of preliminary quality estimation

Small passivity & reciprocity violations in most of the models
Low causality in some measured data due to noise at high frequencies

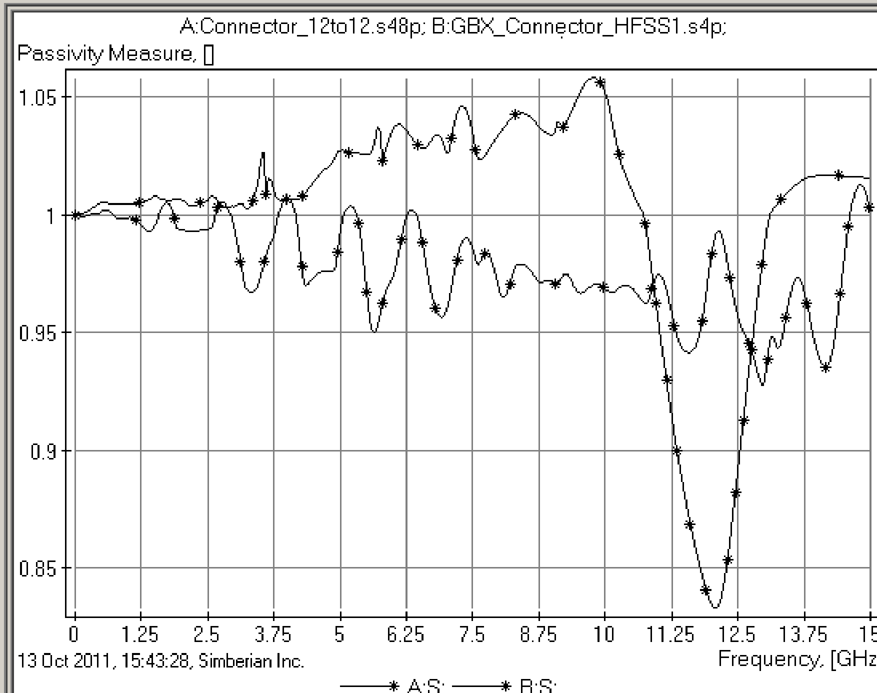
Simbeor - [Touchstone Analyzer]

Touchstone Analyzer

Refresh | Tree-view | Table-view

File name	Quality	Passivity	Reciprocity	Causality
3coupleddiffpairJ74J76toJ7...	-	95.9	99.3	0
3coupleddiffpairJ74J76toJ8...	-	96	99.2	0
beattystandard25ohm.S2P	-	100	95.5	12.7
beattystandard80ohm.S2P	-	100	95.6	0
Connector_12to12.s48p	-	82.6	100	80.5
crosstalkstriptobroadsidec...	-	96.4	99.2	0
crosstalkstriptobroadsidec...	-	96.3	99.2	0
crosstalkstriptobroadsidec...	-	96.1	99.3	0
crosstalkstriptobroadsidec...	-	96.1	99	0
crsstalkstriplinedpair.S4P	-	97.3	99.2	35.2
example calibration.S2P	-	99.2	99.5	0
GBX_Connector_HFSS1.s4p	-	99.5	91	96.2
IConect.s2p	-	99.4	52.6	73.4
J104J94-J105J95.s4p	-	99.8	100	97.7
J104J94-J97J99.s4p	-	100	100	98
J20J24-J21J25-6in.s4p	-	99.4	100	94.3
J20J24-J21J25.s4p	-	99.4	100	94.3
J26J30-J27J31-3in.s4p	-	99.5	99.9	92.7
J26J30-J27J31.s4p	-	99.5	99.9	92.7

Ready



Good S-parameter models must allow accurate approximation with frequency-continuous model

$$\bar{b} = S \cdot \bar{a}, \quad S_{i,j} = \left. \frac{b_i}{a_j} \right|_{a_k=0\ k\neq j} \Rightarrow S_{i,j}(i\omega) = \left[d_{ij} + \sum_{n=1}^{N_{ij}} \left(\frac{r_{ij,n}}{i\omega - p_{ij,n}} + \frac{r_{ij,n}^*}{i\omega - p_{ij,n}^*} \right) \right] \cdot e^{-s \cdot T_{ij}}$$

$$s = i\omega,\ d_{ij} - values\ at\ \infty,\ N_{ij} - number\ of\ poles,$$

$$r_{ij,n} - residues,\ p_{ij,n} - poles\,(real\ or\ complex), T_{ij} - optional\ delay$$

Continuous functions of frequency defined from DC to infinity

- Impulse response is analytical, real and delay-causal:

$$S_{i,j}(t) = 0,\ t < T_{ij}$$

$$S_{i,j}(t) = d_{ij}\delta(t - T_{ij}) + \sum_{n=1}^{N_{ij}} \left[r_{ij,n} \cdot \exp\left(p_{ij,n} \cdot (t - T_{ij})\right) + r_{ij,n}^* \cdot \exp\left(p_{ij,n}^* \cdot (t - T_{ij})\right) \right],\ t \geq T_{ij}$$

- Stable $\mathrm{Re}\left(p_{ij,n}\right) < 0$
- Passive if $eigenvals\left[S(\omega) \cdot S^*(\omega)\right] \leq 1\ \forall \omega,\ from\ 0\ to\ \infty$
- Reciprocal if $S_{i,j}(\omega) = S_{j,i}(\omega)$

May require enforcement

We can use it for final quality estimation with rational approximation

- Accuracy of discrete S-parameters approximation with frequency-continuous macro-model, passive from DC to infinity

$$RMSE = \max_{i,j}\left[\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left|S_{ij}(n) - S_{ij}(\omega_n)\right|^2}\right]$$

original tabulated data

$$S_{i,j}(i\omega) = \left[d_{ij} + \sum_{n=1}^{N_{ij}}\left(\frac{r_{ij,n}}{i\omega - p_{ij,n}} + \frac{r_{ij,n}^*}{i\omega - p_{ij,n}^*}\right)\right]\cdot e^{-s\cdot T_{ij}}$$

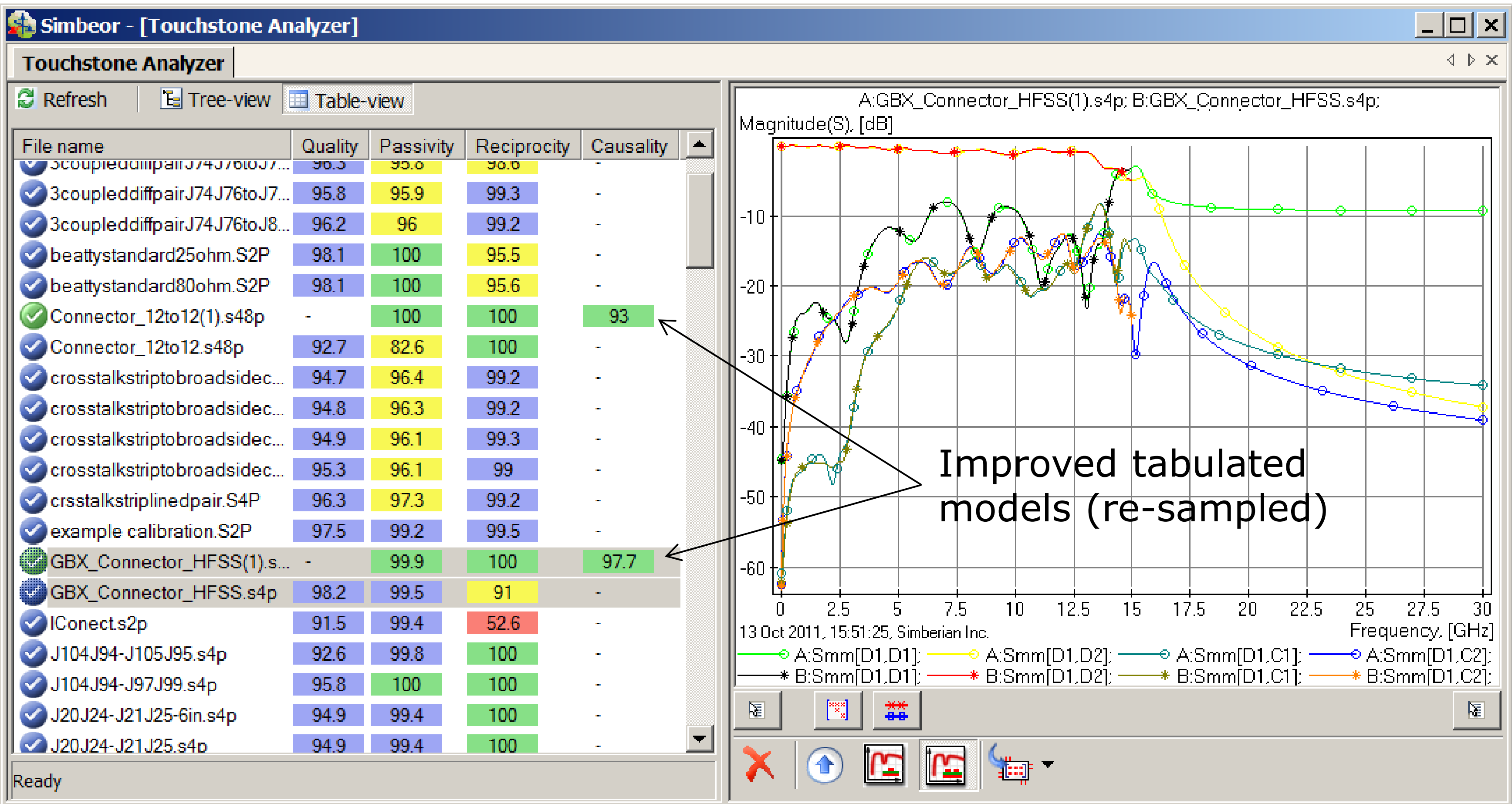
- Can be used to estimate quality of the original data

$$Q = 100\cdot\max\left(1 - RMSE, 0\right)\%$$

Model Icon/Quality	Quality Metric	RMSE
- good	[99, 100]	[0, 0.01]
- acceptable	[90, 99)	(0.01, 0.1]
- inconclusive	[50, 90)	(0.1, 0.5]
- bad	[0, 50)	> 0.5
- uncertain	[0,100], not passive or not reciprocal	

Example of final quality estimation

All rational macro-models are passive, reciprocal, causal and have acceptable accuracy (acceptable quality of original models)



File name	Quality	Passivity	Reciprocity	Causality
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3coupleddiffpairJ74J76toJ8...	96.2	96	99.2	-
beattystandard25ohm.S2P	98.1	100	95.5	-
beattystandard80ohm.S2P	98.1	100	95.6	-
Connector_12to12(1).s48p	-	100	100	93
Connector_12to12.s48p	92.7	82.6	100	-
crosstalkstriptobroadsidec...	94.7	96.4	99.2	-
crosstalkstriptobroadsidec...	94.8	96.3	99.2	-
crosstalkstriptobroadsidec...	94.9	96.1	99.3	-
crosstalkstriptobroadsidec...	95.3	96.1	99	-
crsstalkstriplinedpair.S4P	96.3	97.3	99.2	-
example calibration.S2P	97.5	99.2	99.5	-
GBX_Connector_HFSS(1).s...	-	99.9	100	97.7
GBX_Connector_HFSS.s4p	98.2	99.5	91	-
IConect.s2p	91.5	99.4	52.6	-
J104J94-J105J95.s4p	92.6	99.8	100	-
J104J94-J97J99.s4p	95.8	100	100	-
J20J24-J21J25-6in.s4p	94.9	99.4	100	-
J20J24-J21J25.s4p	94.9	99.4	100	-

(2) Broadband 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
  - T-lines with homogeneous dielectrics (strip lines) can be effectively analysed with quasi-static field solvers
  - T-lines with inhomogeneous dielectric may require analysis with a full-wave solver to account for the high-frequency dispersion
- Accuracy of transmission line models is mostly defined by **availability of broadband dielectric and conductor roughness models**
- This is another most important elements for design success

Causal dielectric models for PCB and PKG

- Multi-pole Debye-Lorentz (real and complex poles)

$$\varepsilon(f) = \varepsilon(\infty) + \sum_{n=1}^{N} \frac{\Delta\varepsilon_n}{1 + i\frac{f}{fr_n}} + \sum_{k=1}^{K} \frac{\Delta\varepsilon_k \cdot fr_k^2}{fr_k^2 + 2i \cdot f \cdot \frac{\delta_k}{2\pi} - f^2}$$

Requires specification of value at infinity and poles/residues/damping or DK and LT at multiple frequency points

- Wideband Debye (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

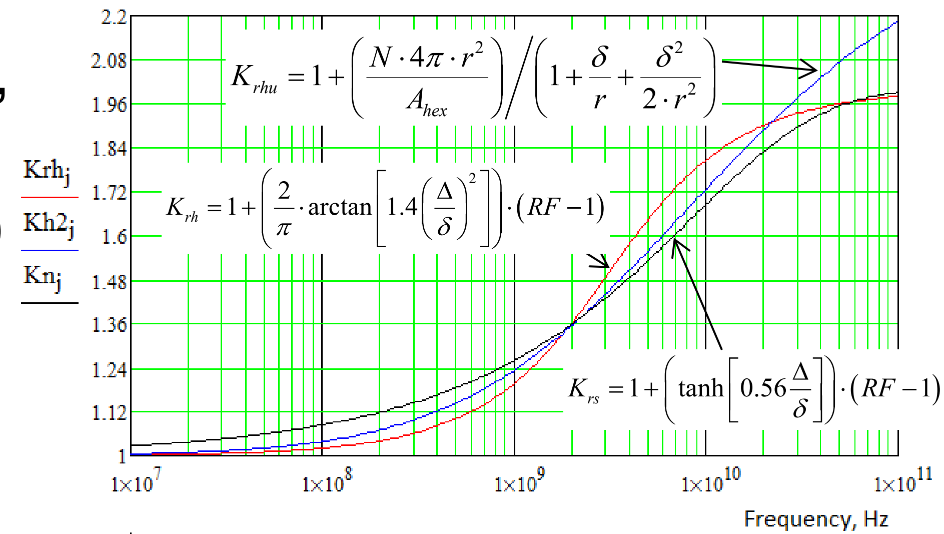
- Models for dielectric mixtures (Wiener, Maxwell-Garnet, …)

- Models for anisotropic dielectrics (separate definition of Z, and XY-plane components of permittivity tensor)

Parameters of the causal models are not available from manufacturers!

Causal roughness models

- Modified Hammerstad (red), Simbeor (black)
  and Huray's snowball (blue) models (RTF/TWS foil example)

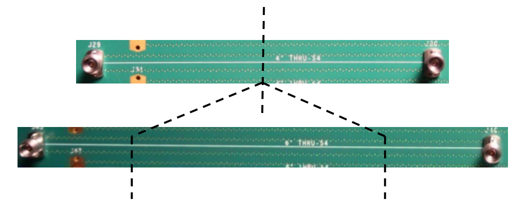


See references in the paper
(EMC2012 and DC2012)

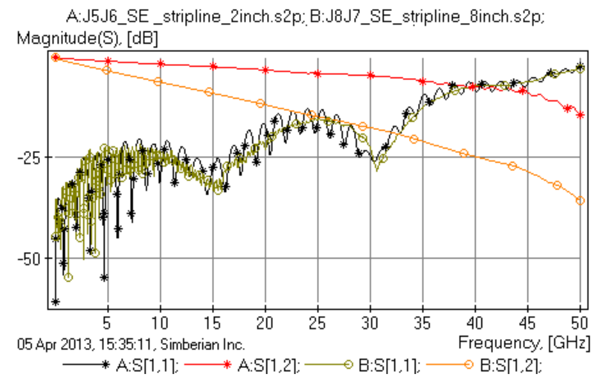
- Causal if correction is applied to conductor surface impedance operator
- Where to get the model parameters?
  - SR (delta) and RF for Simbeor and MHCC
  - Number of balls, ball size and tile area for Huray's model

Material parameters identification with generalized modal S-parameters (GMS-parameters)

1. Measure S-parameters of two test fixtures with different length of line segments S1 and S2



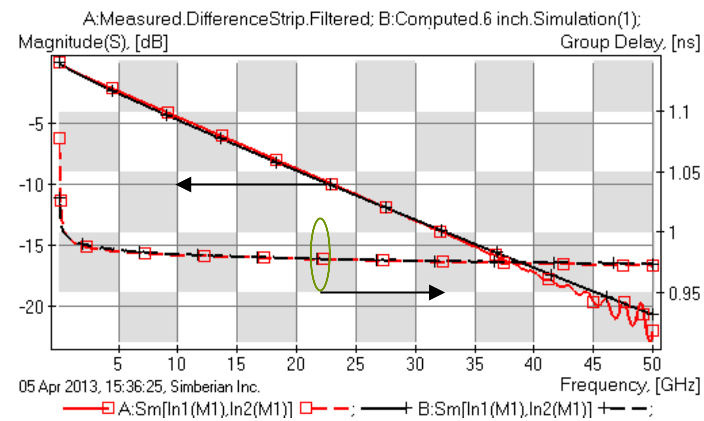
2. Extract Generalized Modal S-parameters of the line difference



3. Select material model and guess values of the model parameters

4. Compute GMS-parameters of the line difference segment by solving Maxwell's equation for t-line cross-section

5. Adjust material parameters until computed GMS parameters fit measured GMS-parameters with the computed



See references in the paper
Simberian's patent pending #**13/009,541**

Simberian
Electromagnetic Solutions

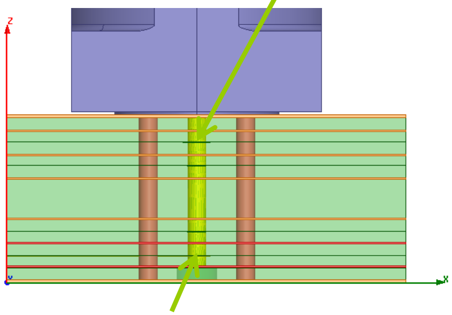
Example: Nelco N4000-13EP

- Example for the original board made with Nelco 4000-13EP investigated in:
  D. Dunham, J. Lee, S. McMorrow, Y. Shlepnev, 2.4mm Design/Optimization with 50 GHz Material Characterization, DesignCon2011

Test structures are pre-qualified for the identification up to 50 GHz in the paper

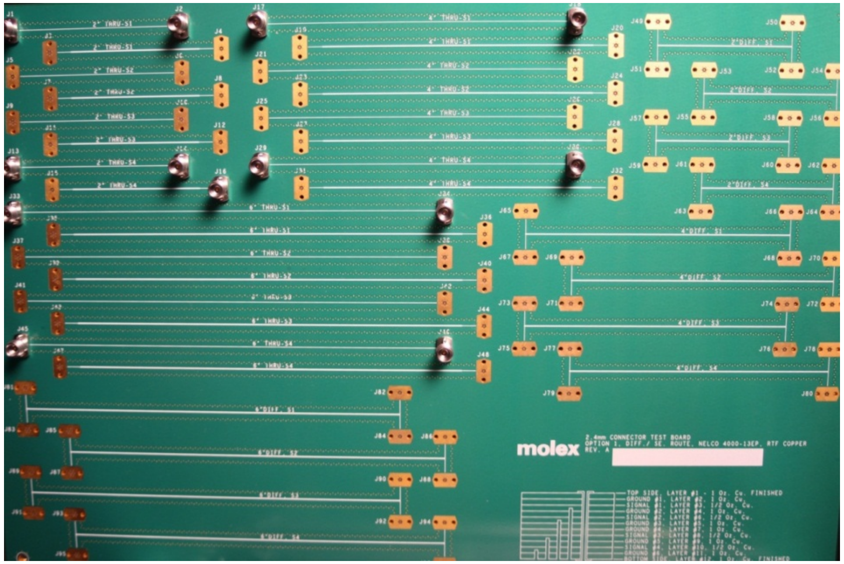
6 test fixtures with 2, 4 and 6 inch strip line segments in Layer 1 (S1) and Layer 4 (S4)

Signal Layer 1



Signal Layer 4

Scott McMorrow from Teraspeed Consulting Group designed launches for 2.4mm Molex connectors, board made by Molex and measurements done by David Dunham, Molex



Test board and cross-section

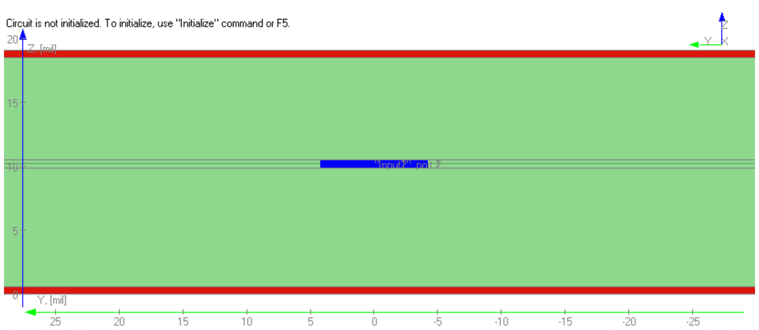
- Strip line segments in Nelco N4000-13EP
- 2 inch, 4 inch and 6 inch segments with launches and Molex 2.6 mm connectors to identify material parameters

ModeledWithRourhness
- Materials: T=20[°C],...
  - "Copper", RR=1.05, SR=0.27, RF=4, RM=MHCC
  - "Air"
  - "N400013EP", Dk=3.8, LT=0.008, PLM=WD
- StackUp: LU=[mil], NL=3, T=19.1[mil]
  - 1| Plane: "Plane1", Cond="Copper", T=0.6, Ins="N400013EP"
  - 2| Medium: T=8, Ins="N400013EP"
  - 3| Signal: "Signal1", T=0.6, Ins="N400013EP", Cond="Copper"
  - 4| Medium: T=9.3, Ins="N400013EP"
  - 5| Plane: "Plane2", Cond="Copper", T=0.6, Ins="N400013EP"

From datasheet Dk is 3.6-3.7 and LT 0.008-0.009

Electrical Properties					
Dielectric Constant (50% resin content)					
@ 1 GHz (RF Impedance)	3.7	3.4	3.7	3.4	IPC-TM-650 2.5.5.9
@ 2.5 GHz (Split Post Cavity)	3.7	3.2	3.7	3.2	
@ 10 GHz (Stripline)	3.6	3.2	3.6	3.2	IPC-TM-650 2.5.5.5
@ 10 GHz (Split Post Cavity)	3.7	3.3	3.7	3.3	
Dissipation Factor (50% resin content)					
@ 2.5 GHz (Split Post Cavity)	0.009	0.008	0.009	0.008	
@ 10 GHz (Stripline)	0.009	0.008	0.009	0.008	IPC-TM-650 2.5.5.5
@ 10 GHz (Split Post Cavity)	0.008	0.007	0.008	0.007	

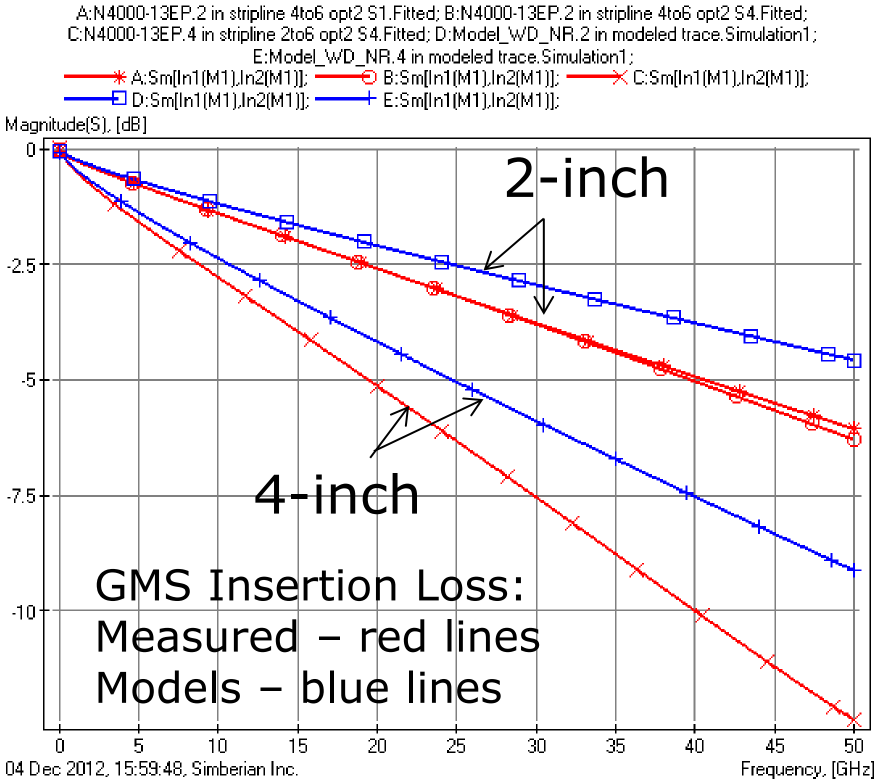
Strip width 8.5 mil (both S1 and S4)

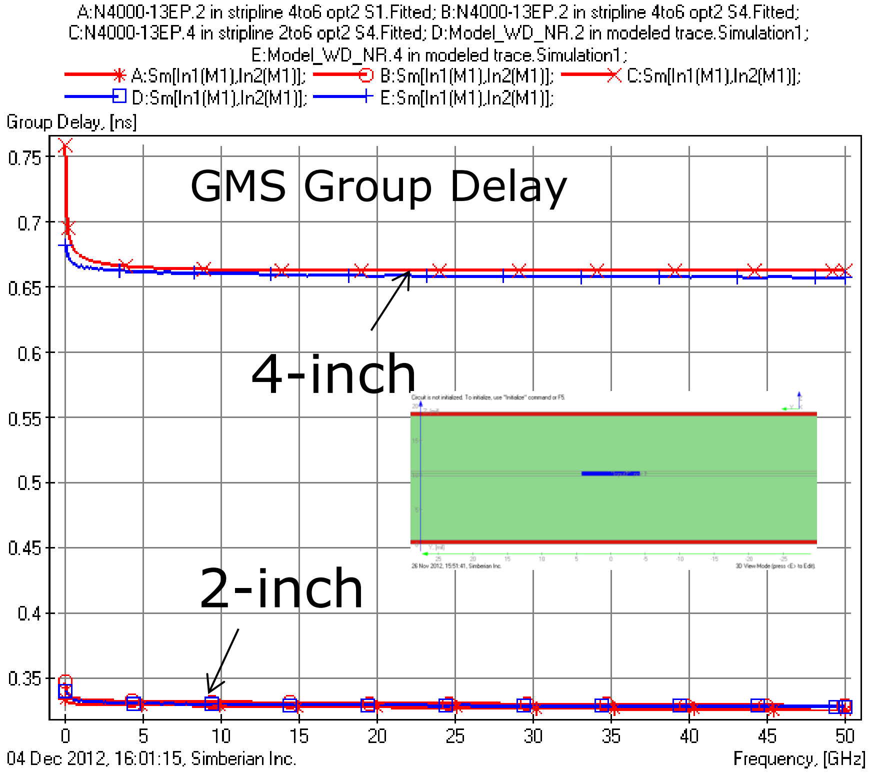


Different methods produce slightly different parameters
Which one is correct?
What causal model to use?

Wideband Debye model with parameters from specs

- Dk=3.8, LT=0.008 @ 10 GHz, WD model, no roughness



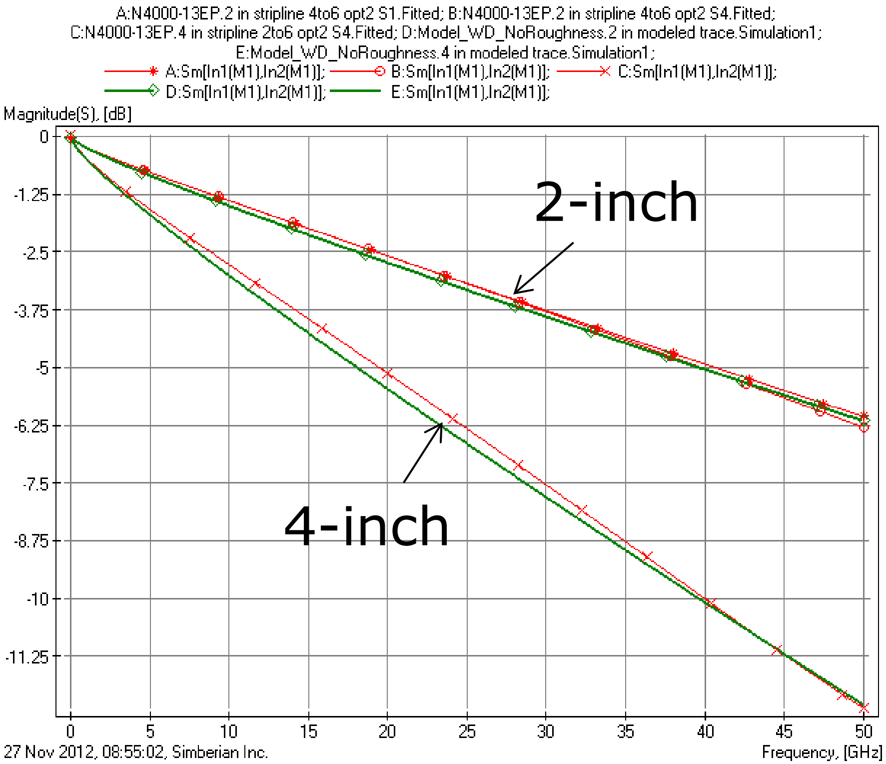


BIG DIFFERENCE IN THE INSERTION LOSS!!!

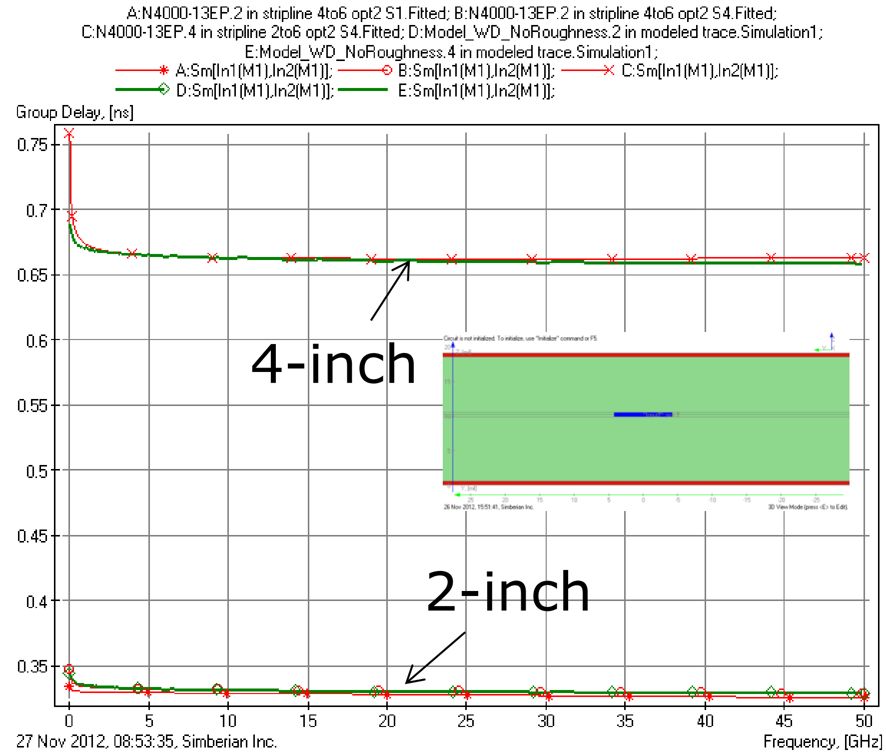
WD model with adjusted loss tangent No roughness

- Dk=3.8, LT=0.0115 @ 10 GHz, no adjustment for low frq. – acceptable fit (green lines) to measured GMS-parameters (red lines)

GMS Insertion Loss



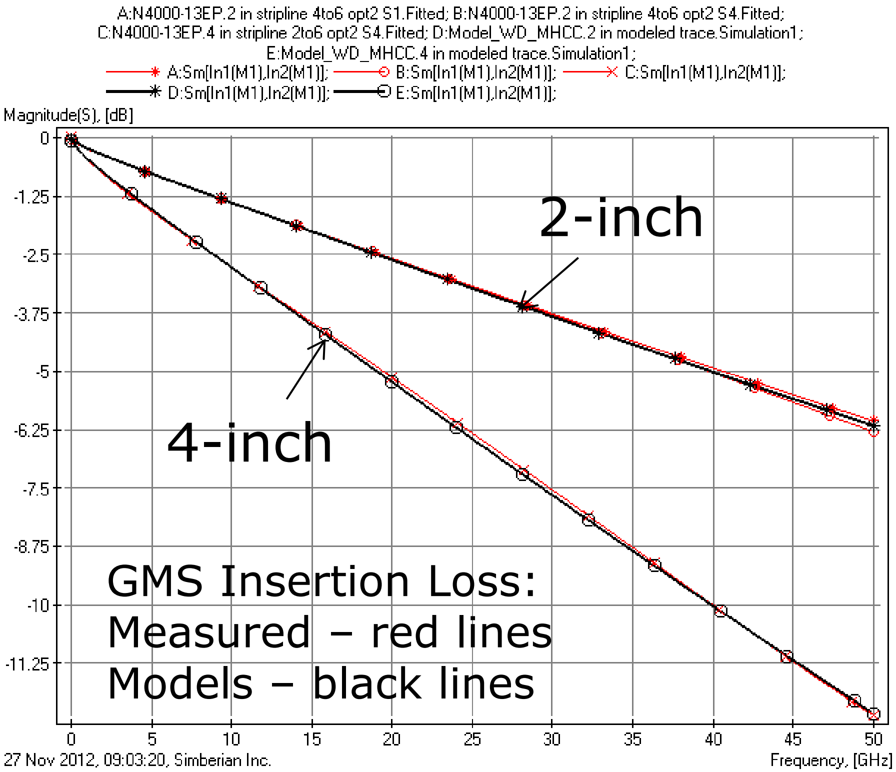
GMS Group Delay

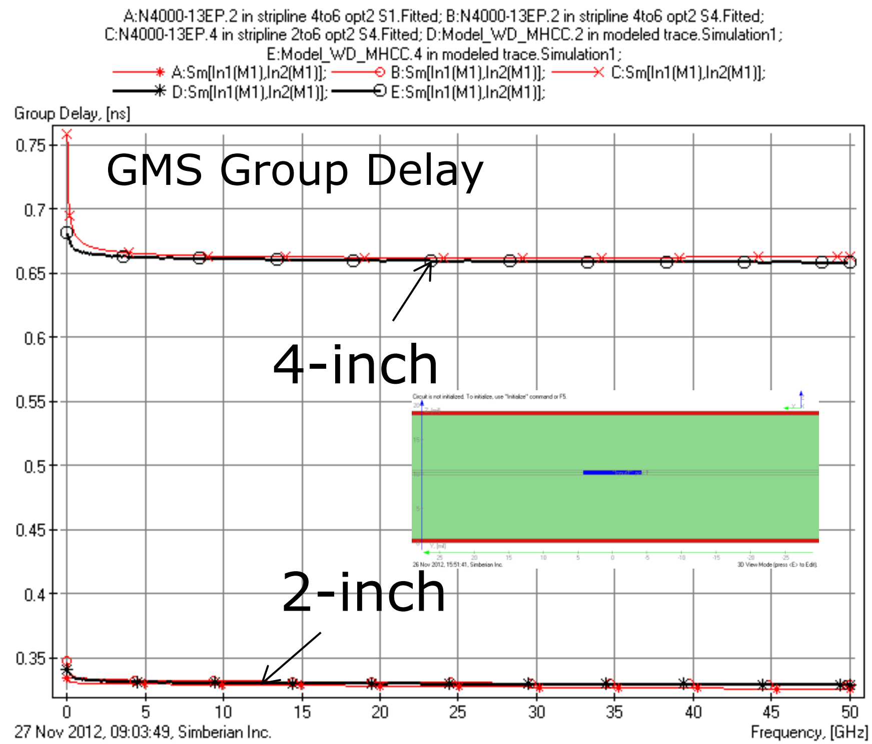


LOOKS LIKE SUITABLE MODEL?

WD model with parameters from specs and with MHCC roughness model

- Dk=3.8, LT=0.008 @ 10 GHz – as in specs, modified Hammerstadt correction coefficient SR=0.27, RF=4 (relative resistivity 1.05) produces good fit (black lines) to measured GMS-parameters (red lines)

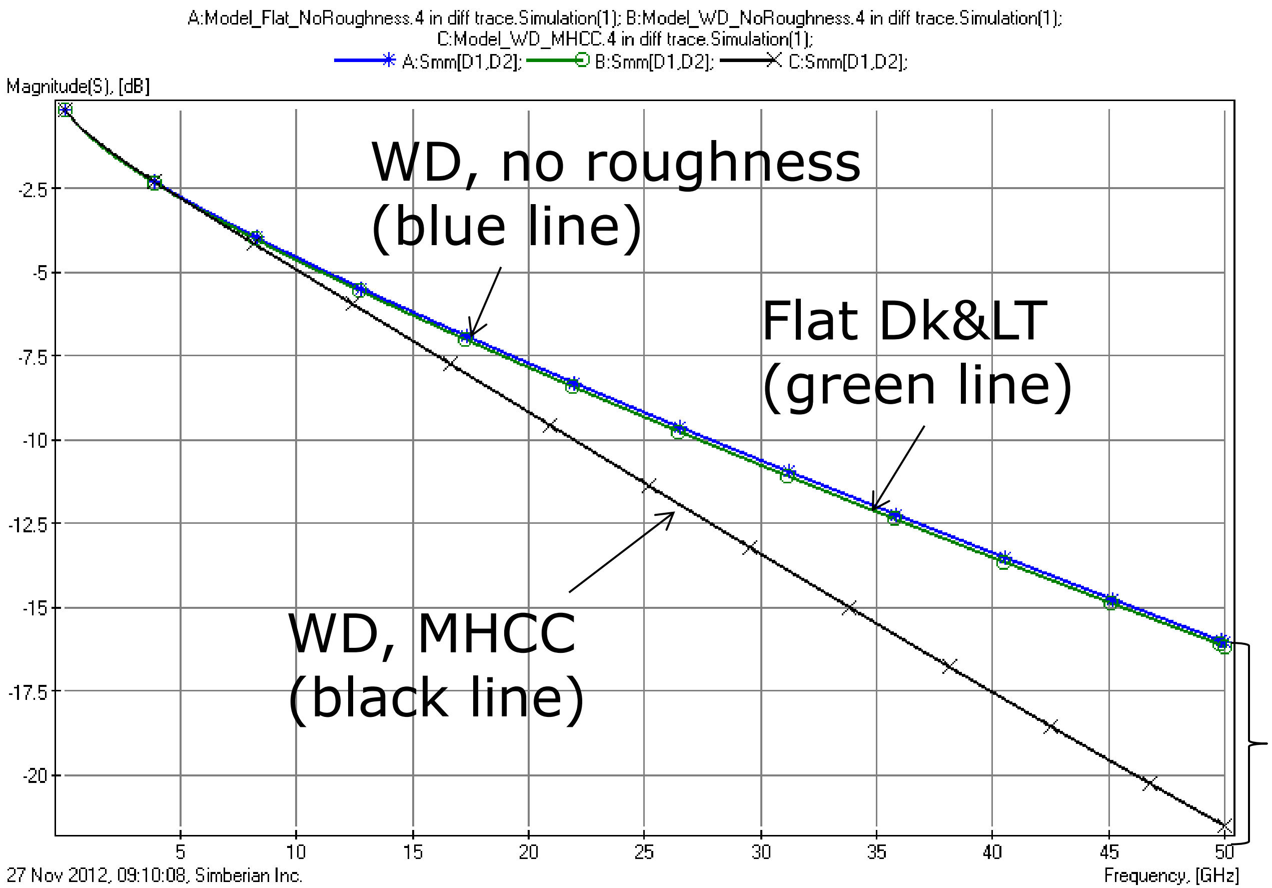


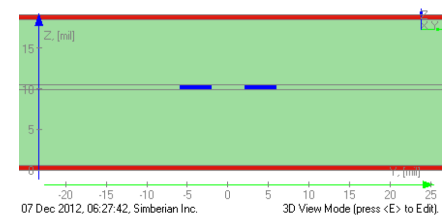


WICH MODEL IS ACCEPTABLE – WITH OR WITHOUT ROUGHNESS?

Models for differential strips (4 mil wide, 4 mil distance)

- Model with the roughness predict much more loss for a different cross-section then models with the increased loss tangent!!!





All models predict close phase and GD

Over 40% difference!!!

Summary on material models

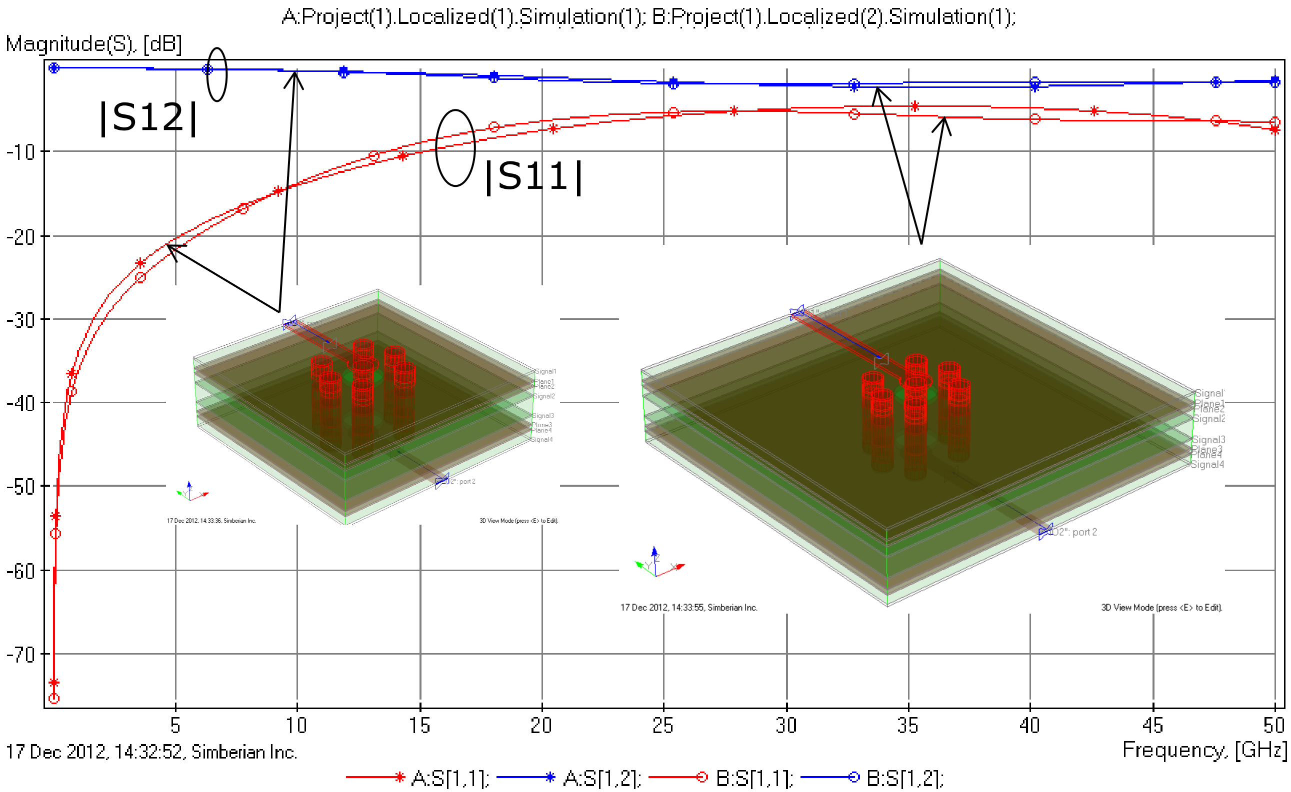
- Both dielectric and conductor roughness models require procedure to identify or confirm broadband models
- Provided example illustrates typical situation and importance of the dielectric and conductor roughness models identification
- Proper separation of loss and dispersion effects between dielectric and conductor models is very important, but not easy task
  - Without proper roughness model dielectric models become dependent on strip width and cross-section
- Another problem with the PCB materials is the layered structure and associated with that anisotropy
  - Difference between the vertical and horizontal components of the effective dielectric constant may be substantial and must be taken into account

(3) Modeling discontinuities in isolation

- A channel is typically composed with transmission lines of different types and transitions (vias, launches, connectors,…)
- The transitions may be reflective due to physical differences in cross-sections of the connected lines
  - The reflections cause additional losses and resonances and, thus, unwanted signal degradation
- The effect of the transitions can be accounted for with models built with a full-wave 3D analysis
- If such analysis is possible in isolation from the rest of the board up to a target frequency, the structure is called localizable
- **Only localizable transitions must be used to design predictable interconnects – this is one of the most important elements for design success**

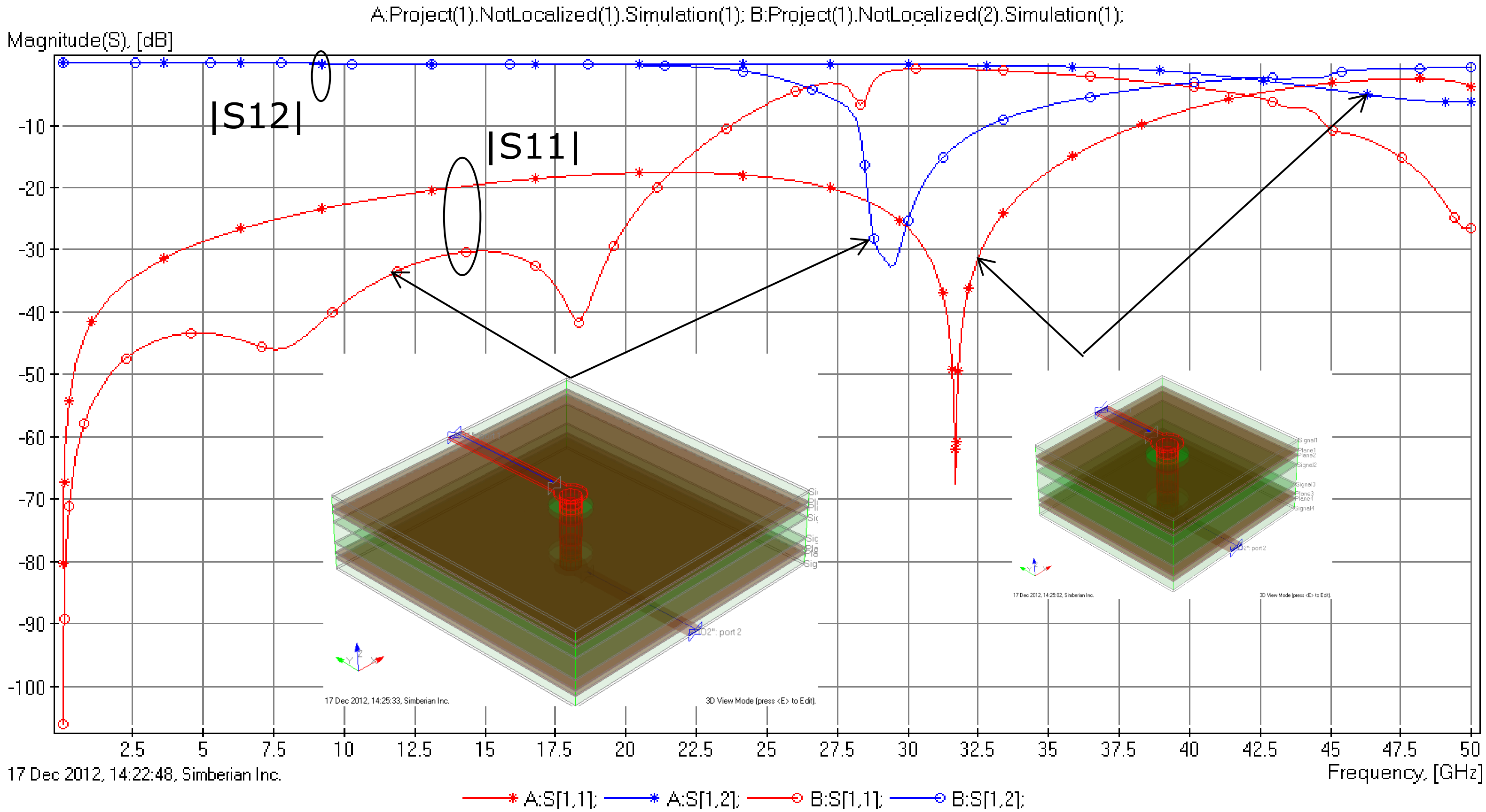
How estimate the localization?

- Change simulation area or simulate with different boundary conditions and observe changes
- Example of conditionally localized structure



Example of non-localizable via

- Change of simulation area size causes huge differences in reflection and insertion loss – unpredictable "pathological" structure



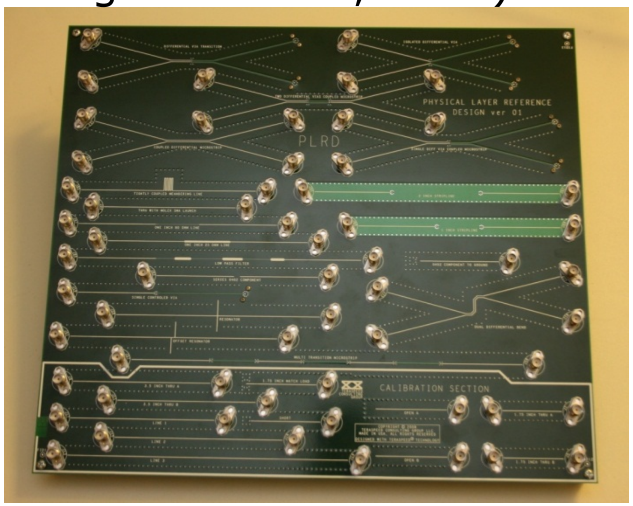
Simberian Electromagnetic Solutions

(4) Benchmarking or validation

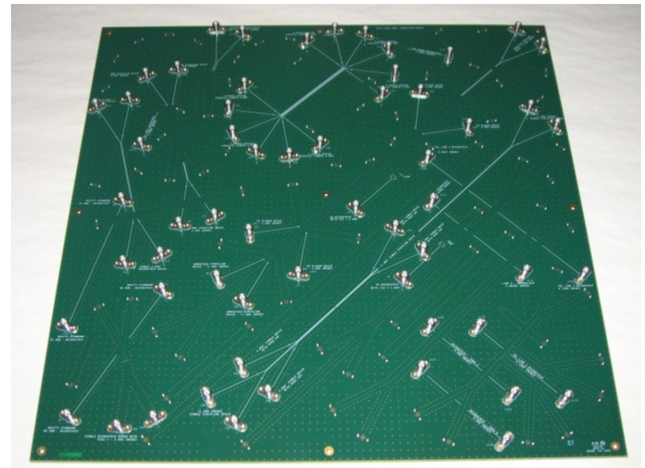
- How to make sure that analysis works? – Build validation boards!
- Controlled board manufacturing is the key for success
  - Fiber type, resin content, copper roughness must be strictly specified or fixed!!!
- Include a set of structures to identify one material model at a time
  - Solder mask, core and prepreg, resin and glass, roughness, plating,…
- Include a set of structures to identify accuracy for transmission lines and typical discontinuities
  - Use identified material models for all structures on the board consistently
  - No tweaking - discrepancies should be investigated
- Use VNA/TDNA measurements and compare both magnitude and phase (or group delay) of all S-parameters

Example of benchmarking boards

PLRD-1 (Teraspeed Consulting, DesignCon 2009, 2010)

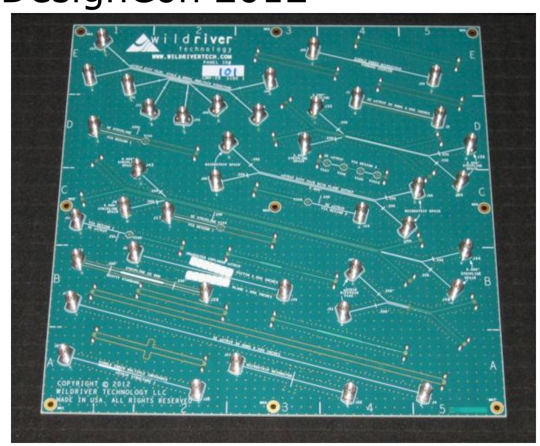


CMP-08 (Wild River Technology & Teraspeed Consulting, DesignCon 2011)



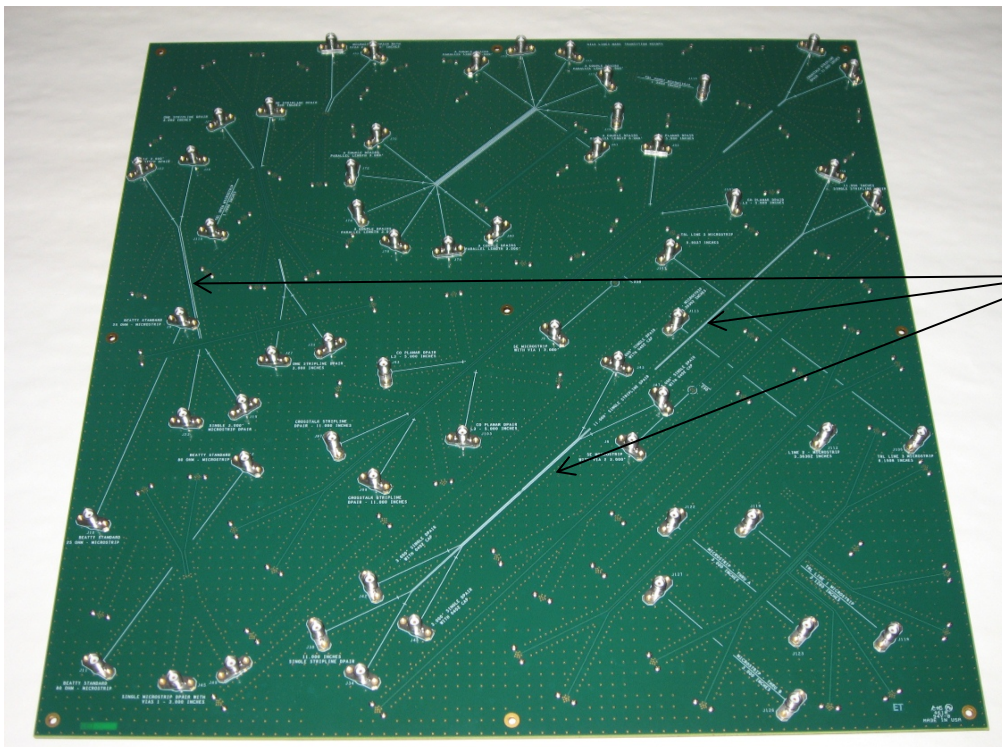
Isola, EMC 2011, DesignCon 2012

CMP-28, Wild River Technology, DesignCon 2012



Channel Modeling Platform CMP-08

- **Validation board with coupled microstrip and strip structures** designed with Simbeor software by Wild River Technology
  - J. Bell, S. McMorrow, M. Miller, A. P. Neves, Y. Shlepnev, Unified Methodology of 3D-EM/Channel Simulation/Robust Jitter Decomposition, DesignCon2011 (also App Note #2011_02 at www.simberian.com)

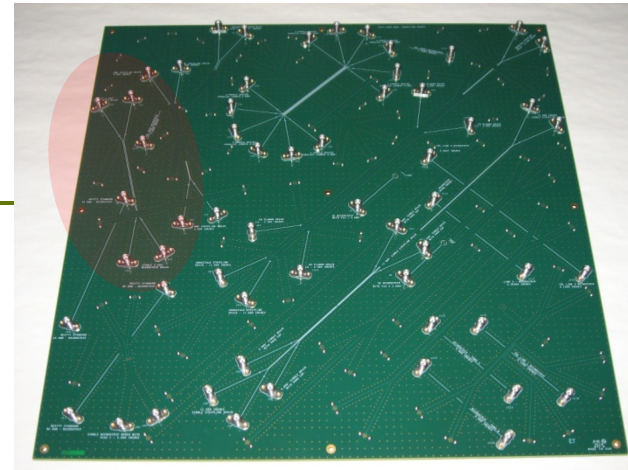


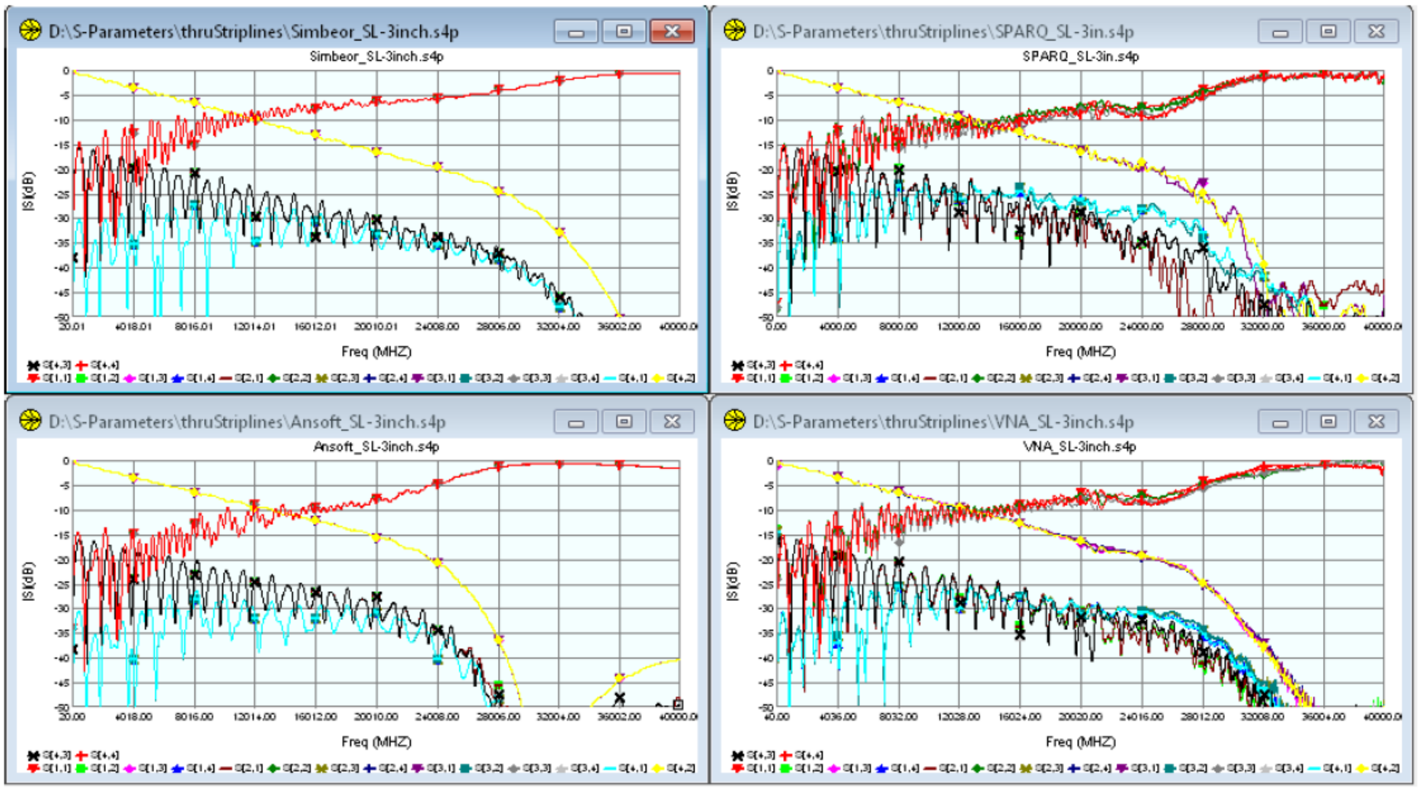
Analysis to measurement correlation investigation on 38 structures up to 30 GHz!

3”, 6”, and 11” Differential THRU structures are used to benchmark simulations-measurements, and jitter tools

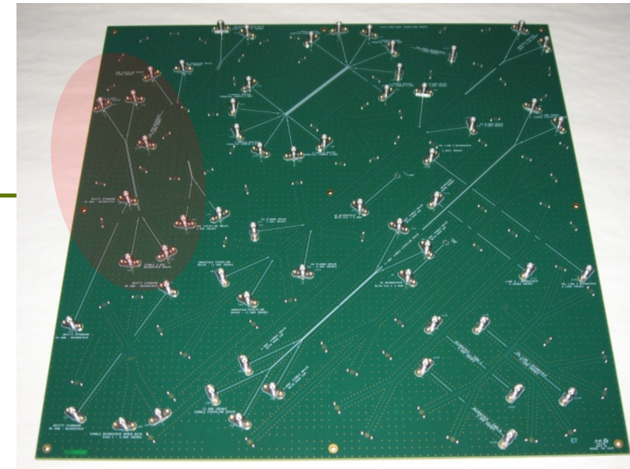
CMP-08 examples

- Three-inch stripline differential traces
- Results of S-parameter comparisons from models and from VNA and TDNA for the 3 inch differential stripline

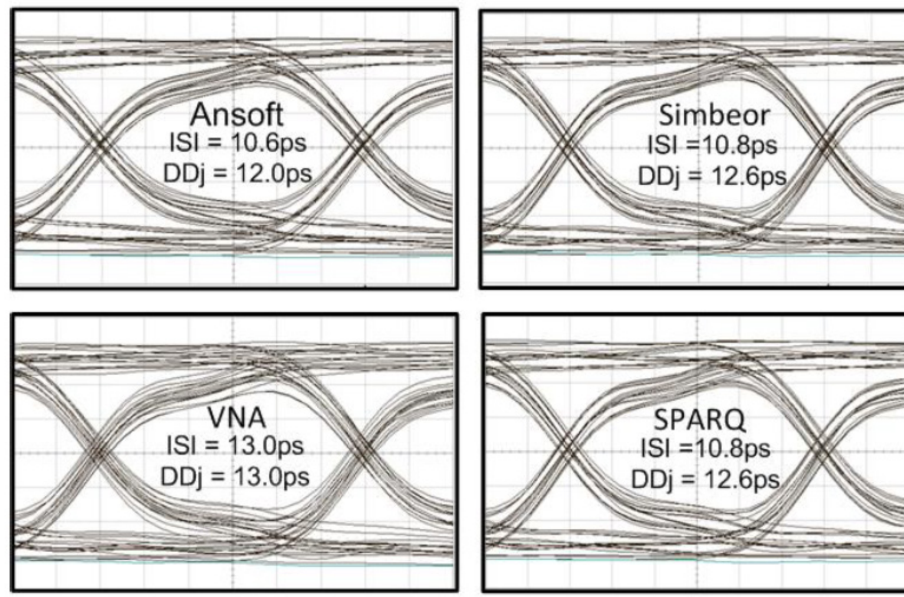


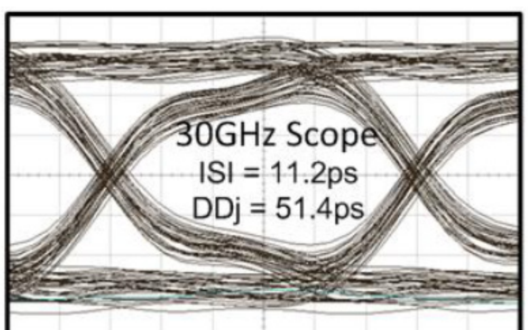


CMP-08 examples



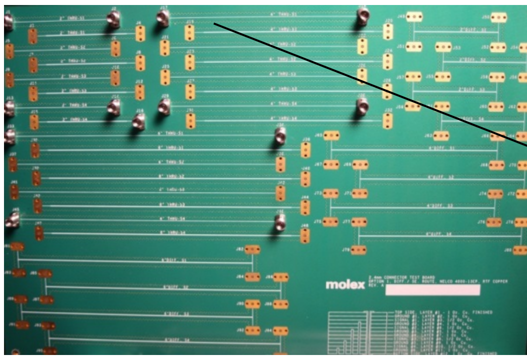
- Three-inch stripline differential traces
- Using recorded differential stimulus
- Two co-simulations with “modeled” S-parameters
- Two co-simulations with “measured” S-parameters
- One direct measurement
- Illustrating “good” agreement

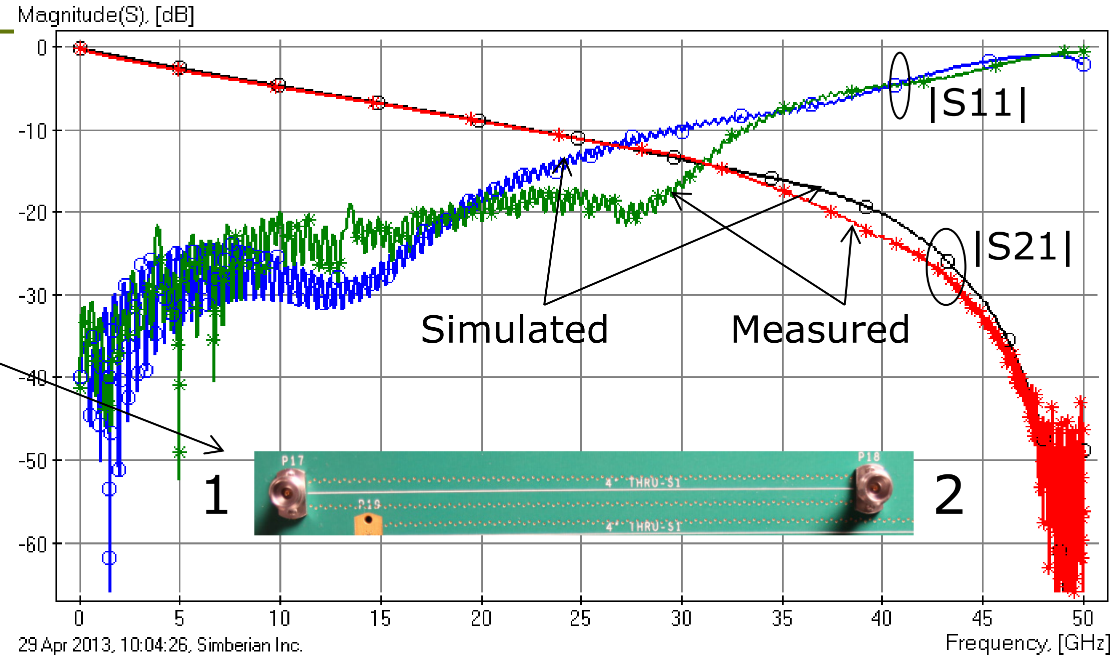




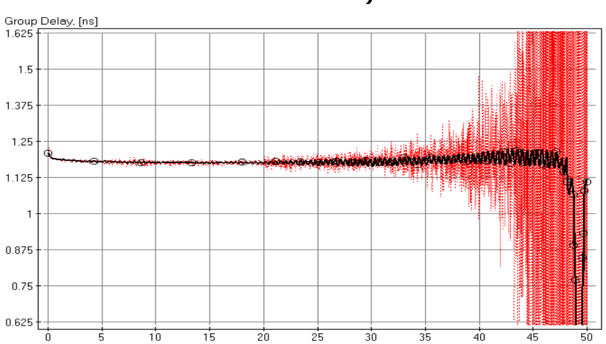
Molex board example – S1 Opt1

Material parameters are identified earlier

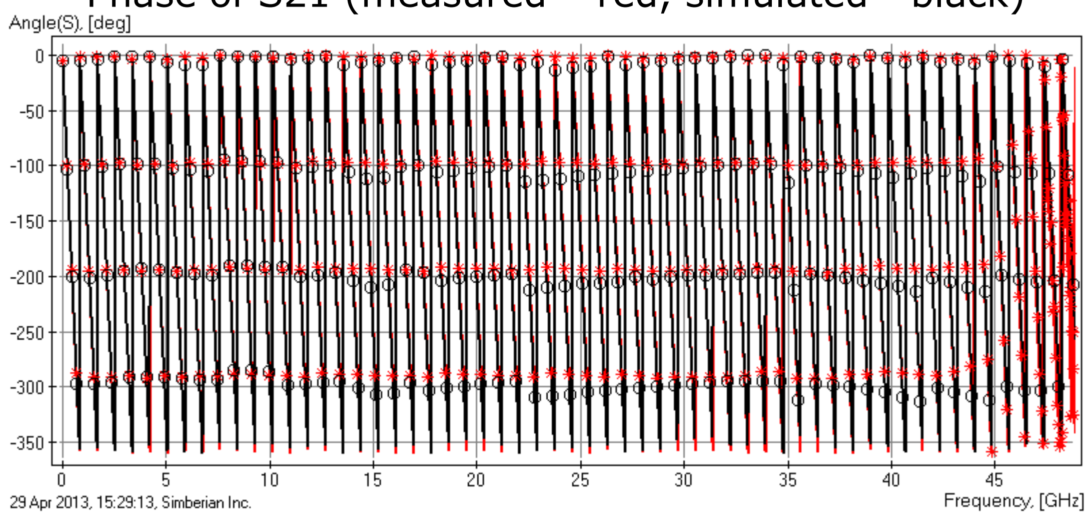




S21 Group Delay (measured – red, simulated - black)



Phase of S21 (measured – red, simulated - black)



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Conclusion

Decompositional electromagnetic analysis is the fastest and the most accurate technique for signal integrity analysis ONLY IF…

1) **S-parameter model quality is ensured**
   Valid for models both built and from vendors

2) **Material parameters are properly identified or confirmed**
   Accuracy of transmission line models depends on the dielectric and conductor roughness models

3) **All discontinuities in a channel are localized**
   Via-holes, breakouts and connector launches must be designed to allow analysis in isolation

4) **Analysis tools are validated with measurements**
   Magnitude and angles or GD of all S-parameters should be compared

Contact and resources

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  Tel: 206-409-2368
- **Webinars on decompositional analysis, S-parameters quality and material identification http://www.simberian.com/Webinars.php**
- Simberian web site and contacts www.simberian.com
- Demo-videos http://www.simberian.com/ScreenCasts.php
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