DesignCon® 2014

JANUARY 28-31, 2014
SANTA CLARA CONVENTION CENTER

Dielectric and Conductor Roughness Model Identification for Successful PCB and Packaging Interconnect Design up to 50 GHz

Dr. Yuriy Shlepnev
Simberian Inc.

Simberian Electromagnetic Solutions

UBM Electronics

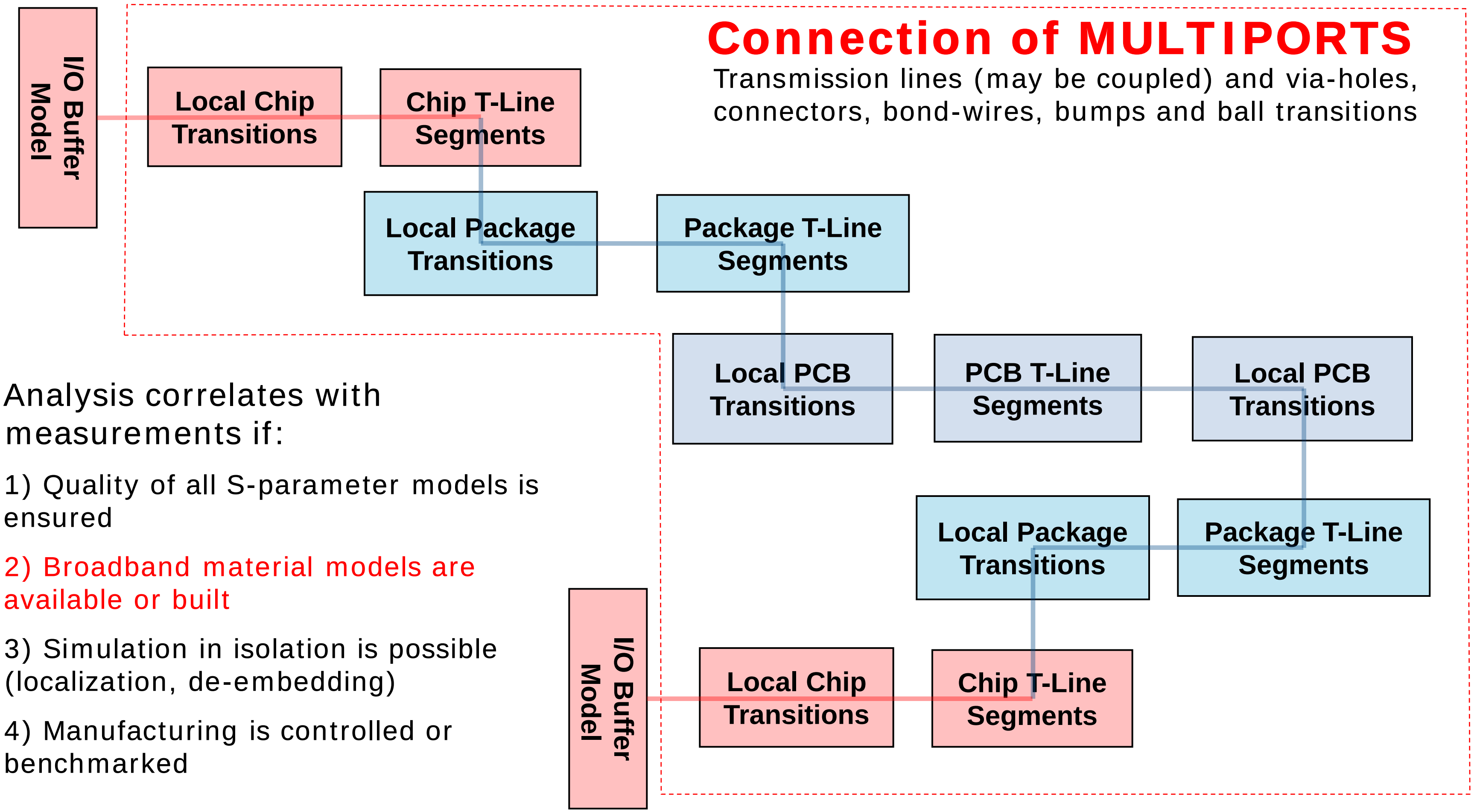
Outline

- Introduction
- Elements of de-compositional electromagnetic analysis
- Dielectric and conductor roughness model identification
  - Theory of identification with GMS-parameters
  - Demo and practical examples
- Pre- and post-layout analysis with broadband models
- Conclusion

Introduction

- Data links running at bitrates 10-50 Gbps and beyond are becoming the mainstream in the communication and other electronic systems
- Why is design of PCB and packaging interconnects for such systems is a challenging problem?
  - Extremely broad frequency bandwidth from DC to 20-50 GHz
  - No frequency-continuous dielectric models available from manufactures
  - No conductor roughness models available from manufacturers
  - Boards are routed in old-style based on rules and approximate models
  - Boards are not manufactured as designed – variations and manipulations by manufacturers
- Is it possible to design and build copper interconnects with analysis to measurement correlation from DC to 20-50 GHz systematically?
  - Only if some conditions are satisfied

Decompositional analysis of a link path



Analysis correlates with measurements if:

1) Quality of all S-parameter models is ensured

2) Broadband material models are available or built

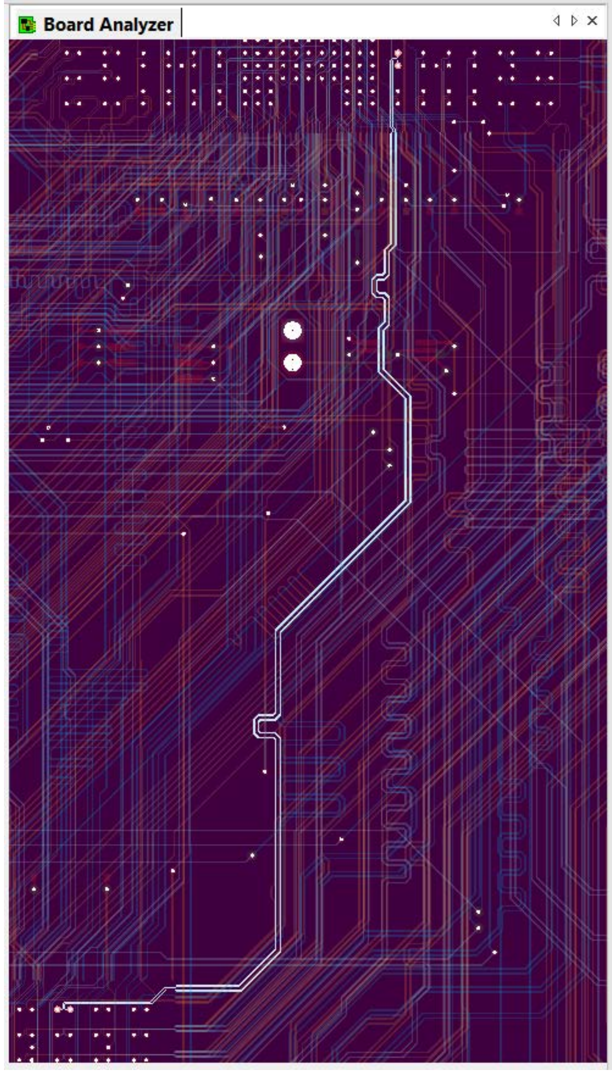
3) Simulation in isolation is possible (localization, de-embedding)

4) Manufacturing is controlled or benchmarked

See details in App. Notes #2013_02, 2013_03 and 2013_05 at www.simberian.com

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

- **Common PCB 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:

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

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

- **Common 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):

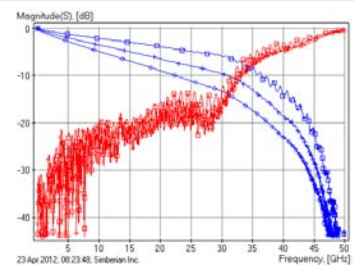
$$K_{rhu} = 1 + \left(\frac{N\cdot 4\pi \cdot r^2}{A_{hex}}\right) \bigg/ \left(1 + \frac{\delta}{r} + \frac{\delta^2}{2\cdot r^2}\right)$$

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

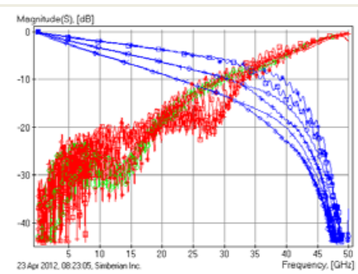
Material model identification techniques

- For test structures …
  - **Transmission line segments**
  - Patch or parallel-plate resonators
  - Resonators coupled or connected to a transmission line

- … take measurements …
  - **S-parameters** measured with VNA
  - TDR/TDT measurements
  - Combination of both

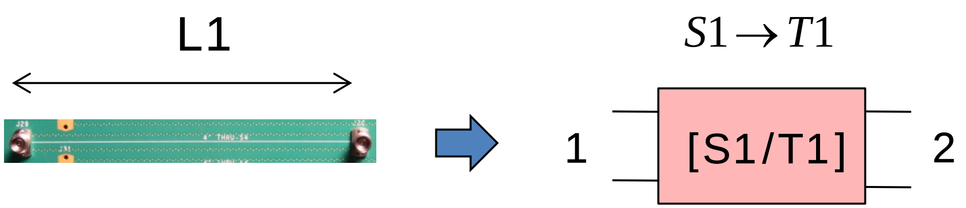


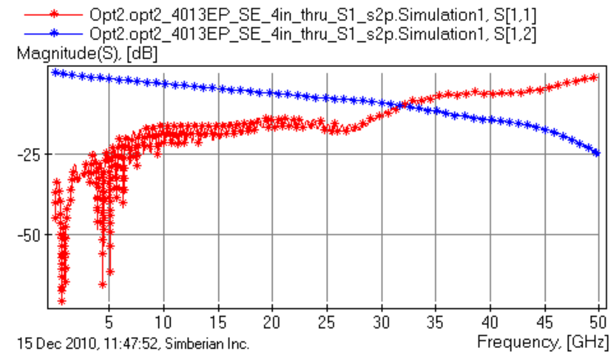
- … and correlate with a numerical model
  - Analytical or closed-form
  - Static or quasi-static field solvers
  - **3D full-wave solvers**



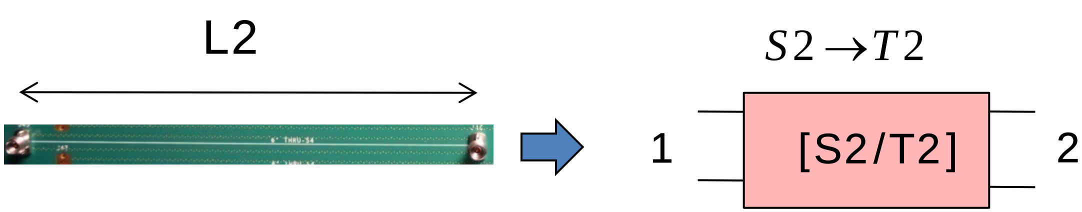
Measure S-parameters of two line segments

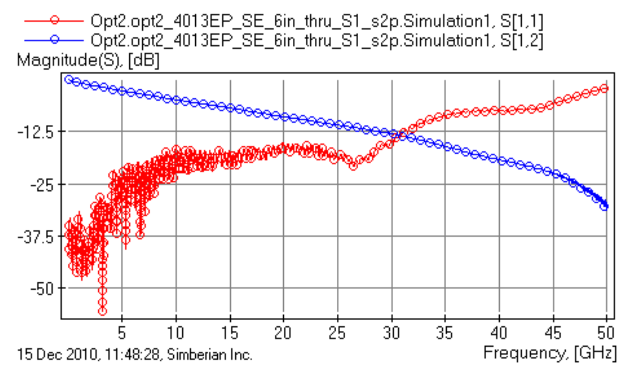
- S1 and T1 for line with length L1





- S2 and T2 for line with length L2

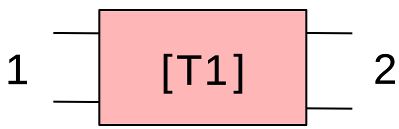




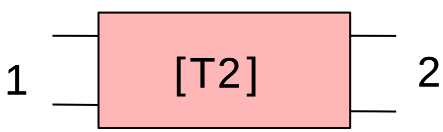
T1 and T2 matrices are scattering T-parameters (computed directly from S-parameters)

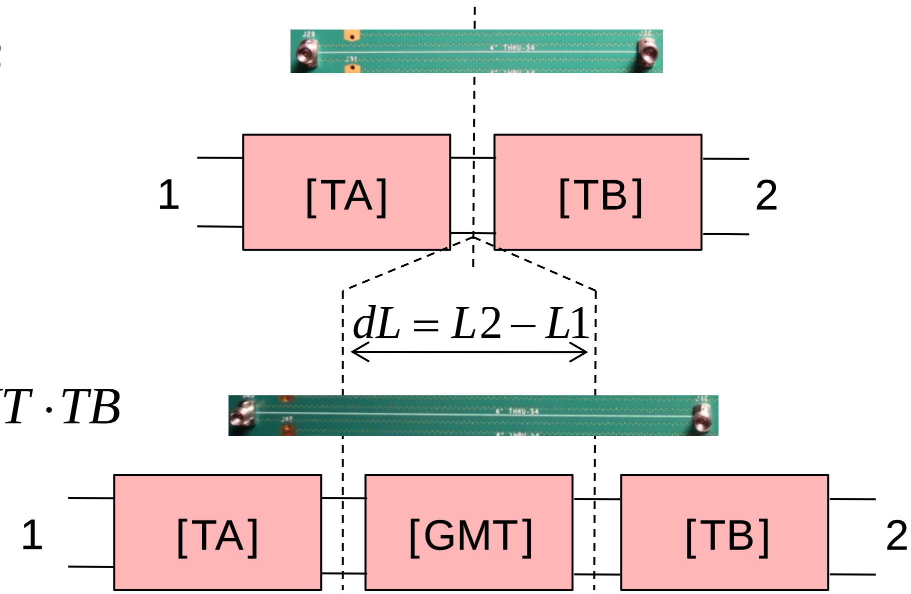
Extract Generalized Modal T-parameters (GMT) and then GMS-Parameters (1-conductor case)

Segment L1 $T1 = TA \cdot TB$



Segment L2 $T2 = TA \cdot GMT \cdot TB$





GMT is non-reflective modal T-matrix (normalized to the unknown characteristic impedances of the modes)

$$T2 \cdot T1^{-1} = TA \cdot GMT \cdot TA^{-1}$$

⇩

$$GMT = eigenvals\left(T2 \cdot T1^{-1}\right)$$

Easy to compute!

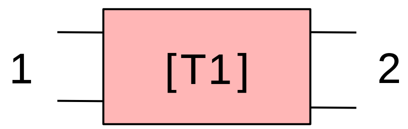
For 1-conductor line we get:

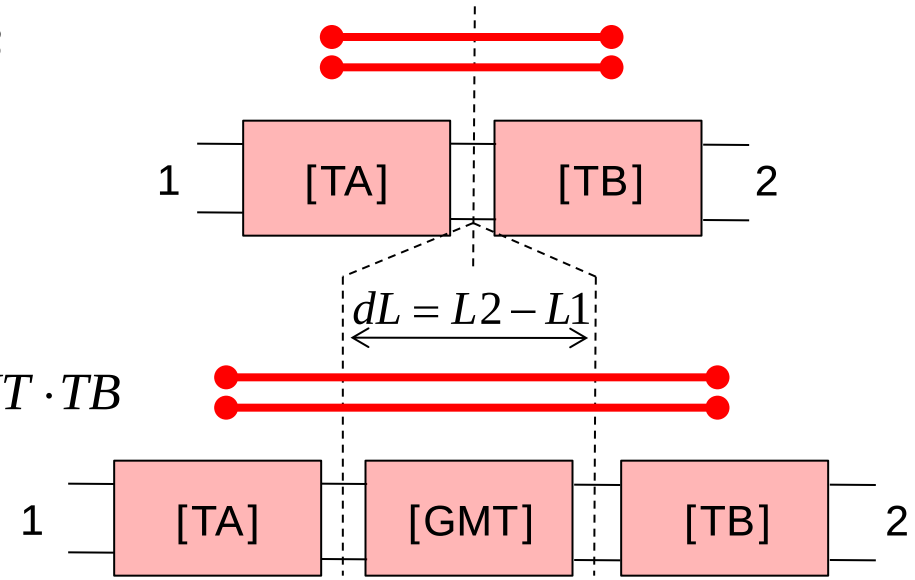
$$GMT = \begin{bmatrix} T_{11} & 0 \\ 0 & T_{11}^{-1} \end{bmatrix} \Rightarrow GMSm = \begin{bmatrix} 0 & T_{11} \\ T_{11} & 0 \end{bmatrix}$$

Just 1 complex function!

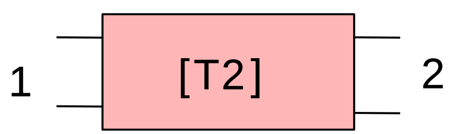
Extract Generalized Modal T-parameters (GMT) and then GMS-Parameters (2-conductor case)

Segment L1 $T1 = TA \cdot TB$





Segment L2 $T2 = TA \cdot GMT \cdot TB$



GMT is non-reflective modal T-matrix (normalized to the unknown characteristic impedances of the modes)

$$T2 \cdot T1^{-1} = TA \cdot GMT \cdot TA^{-1}$$

⇓

$$GMT = eigenvals\left(T2 \cdot T1^{-1}\right)$$

For 2-conductor line we get:

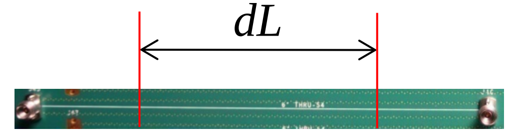
$$GMT = \begin{bmatrix} T_{11} & 0 & 0 & 0 \\ 0 & T_{22} & 0 & 0 \\ 0 & 0 & T_{11}^{-1} & 0 \\ 0 & 0 & 0 & T_{22}^{-1} \end{bmatrix} \Rightarrow GMSm = \begin{bmatrix} 0 & 0 & T_{11} & 0 \\ 0 & 0 & 0 & T_{22} \\ T_{11} & 0 & 0 & 0 \\ 0 & T_{22} & 0 & 0 \end{bmatrix}$$

Just 2 complex functions!

Identifying dielectrics by matching GMS-parameters (1-conductor case)

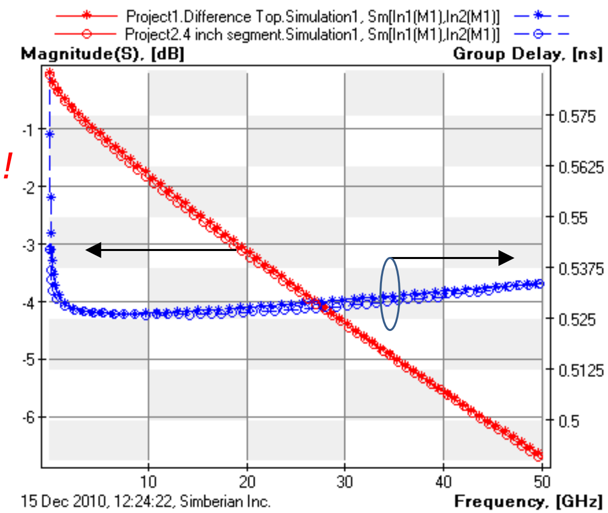
- Solve Maxwell's equations for 1-conductor line:

$$GMSc = \begin{bmatrix} 0 & \exp(-\Gamma \cdot dL) \\ \exp(-\Gamma \cdot dL) & 0 \end{bmatrix}$$



- Match to measured data: *Only 1 complex function!*

$$GMSm = \begin{bmatrix} 0 & T_{11} \\ T_{11} & 0 \end{bmatrix}$$

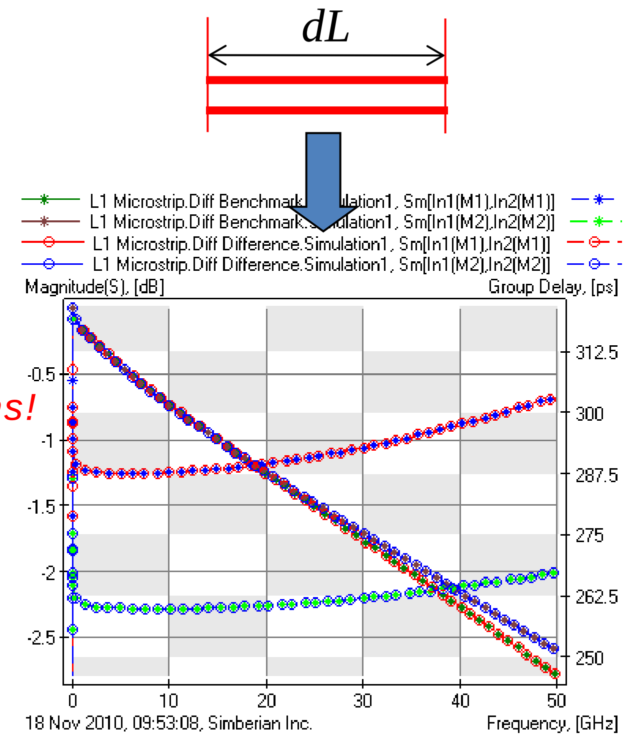


- Measured GMS-parameters of the segment can be matched with the calculated GMS-parameters for material parameters identification
- Phase or group delay can be used to identify DK and insertion loss to identify LT or conductor roughness!

Identifying dielectrics by matching GMS-parameters (2-conductor case)

- Solve Maxwell's equations for 2-conductor line:

$$GMSc = \begin{bmatrix} 0 & 0 & \exp(-\Gamma_1 \cdot dL) & 0 \\ 0 & 0 & 0 & \exp(-\Gamma_2 \cdot dL) \\ \exp(-\Gamma_1 \cdot dL) & 0 & 0 & 0 \\ 0 & \exp(-\Gamma_2 \cdot dL) & 0 & 0 \end{bmatrix}$$

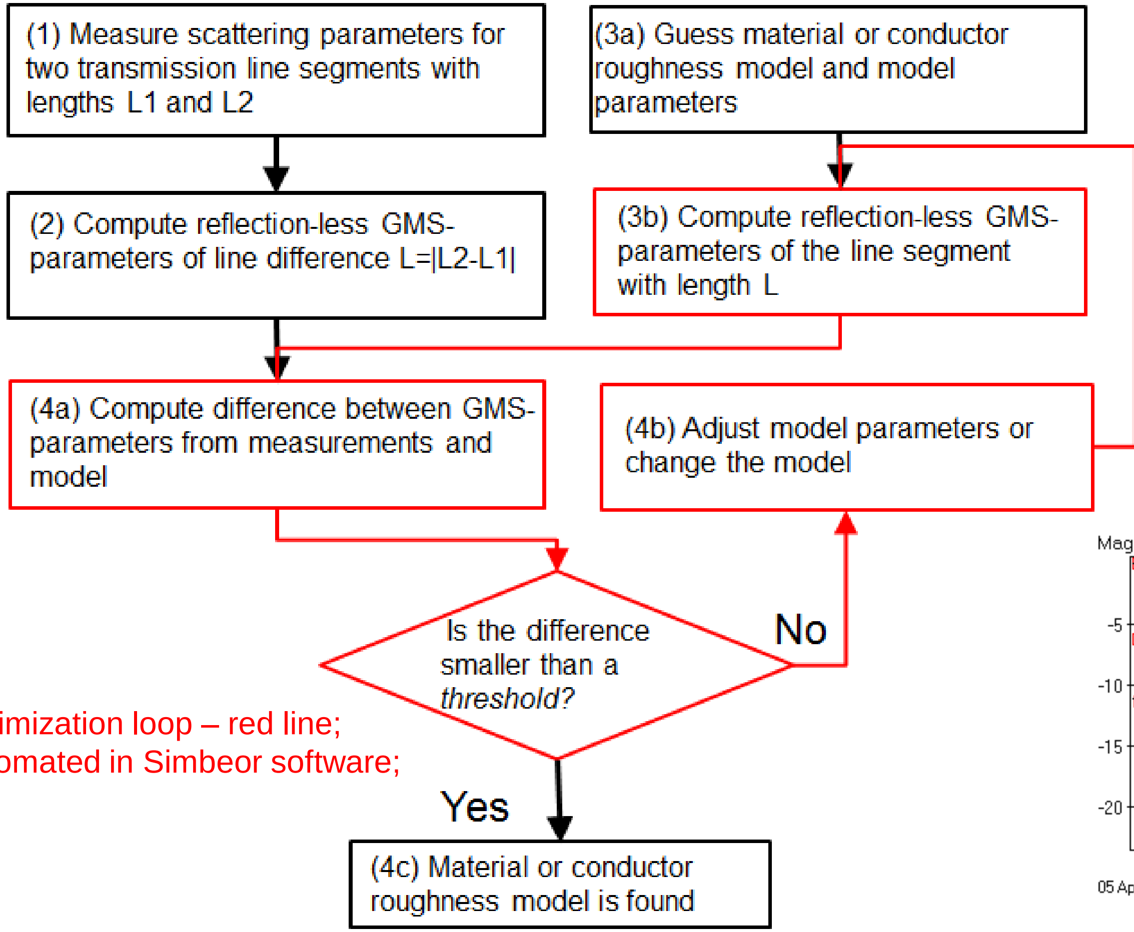


- Match to measured data: *Only 2 complex functions!*

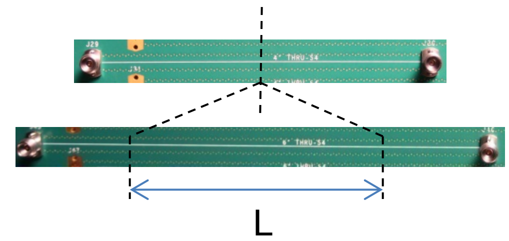
$$GMSm = \begin{bmatrix} 0 & 0 & T_{11} & 0 \\ 0 & 0 & 0 & T_{22} \\ T_{11} & 0 & 0 & 0 \\ 0 & T_{22} & 0 & 0 \end{bmatrix}$$

- Measured GMS-parameters of the segment can be directly fitted with the calculated GMS-parameters for material parameters identification
- Two functions can be used to identify 2 materials!

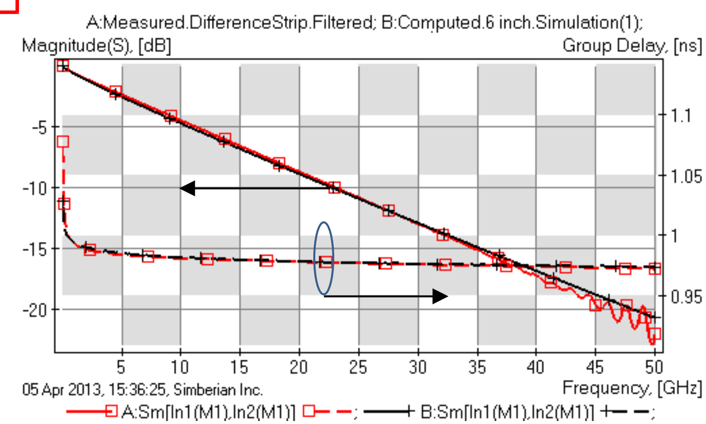
Material Model Identification with GMS-Parameters



Optimization loop – red line;
Automated in Simbeor software;

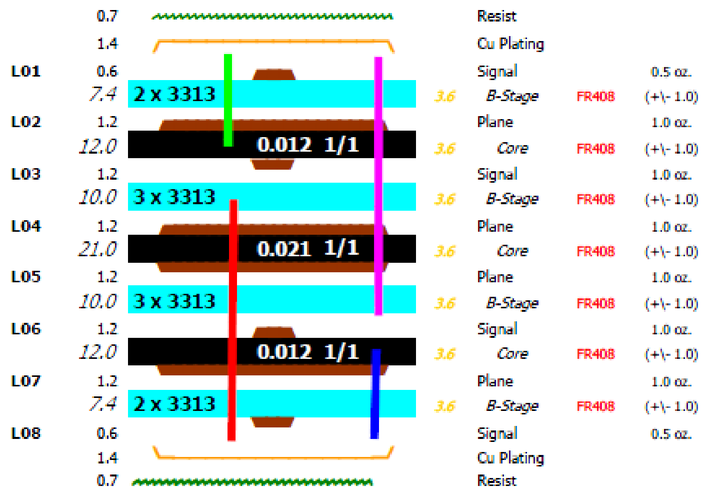


Applicable to dielectric and conductor roughness models;

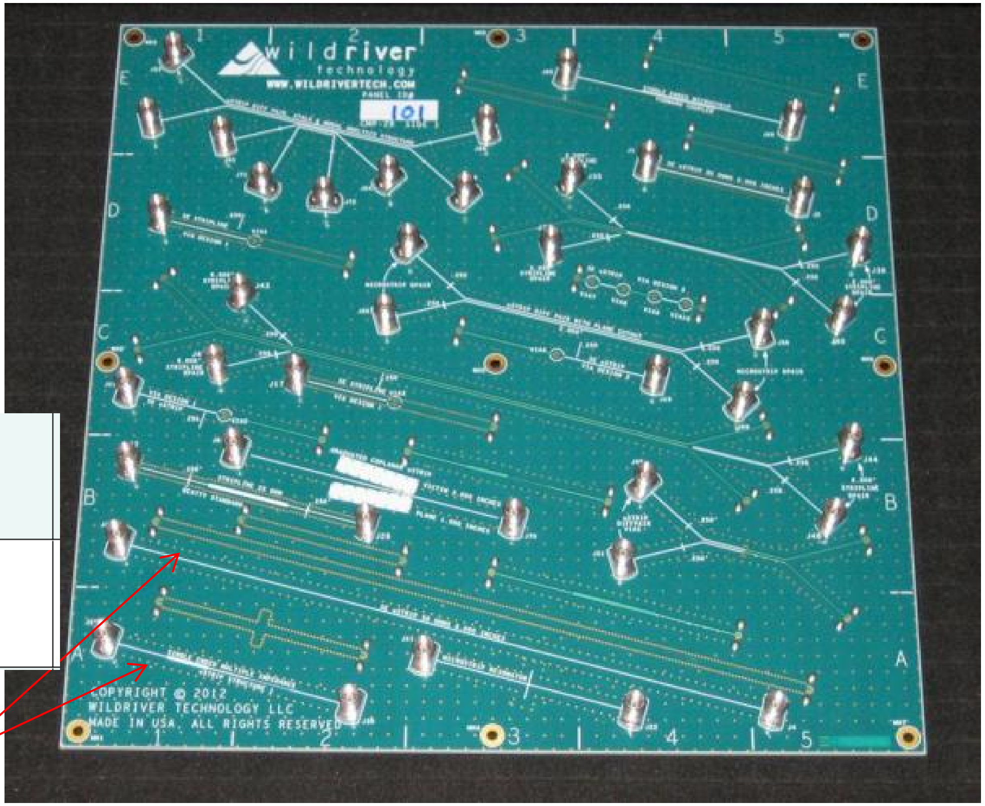


Simberian's USA patent #8577632 and patent pending #14/045,392

Demo of dielectric identification in Simbeor



CMP-28 validation board designed and investigated by Wild River Technology http://wildrivertech.com/

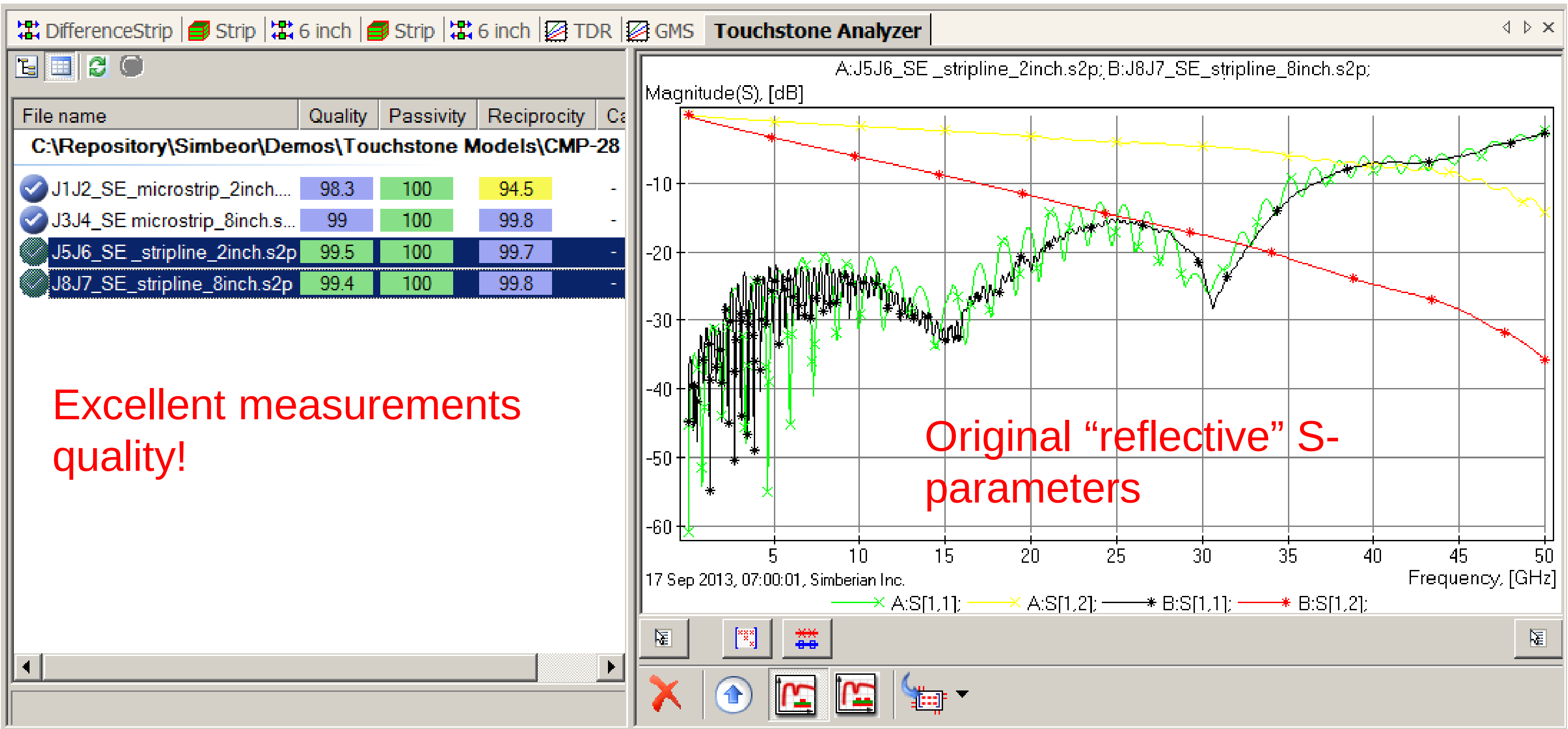


From Isola FR408 specifications

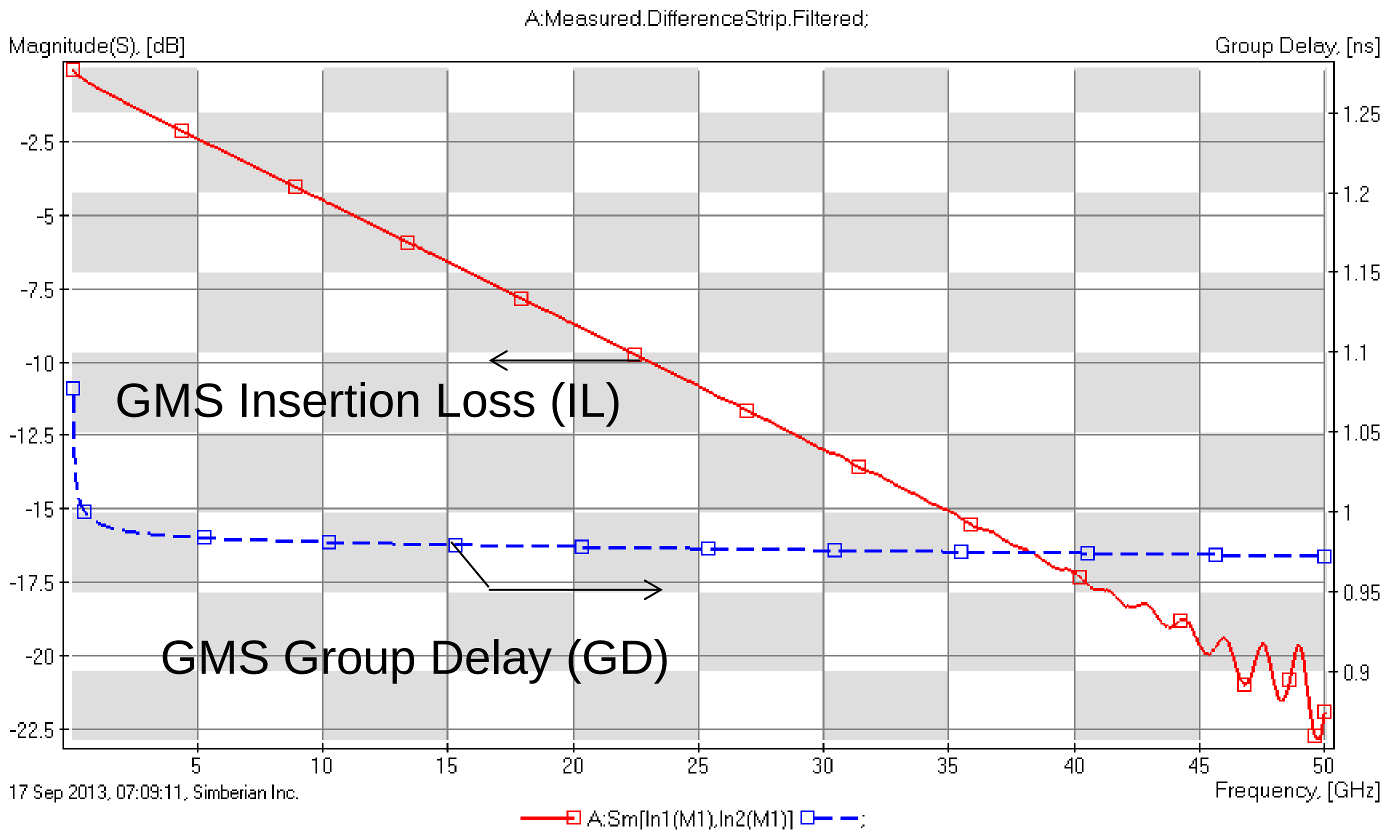
Dk, Permittivity (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A) B. @ 1 GHz (HP4291A) C. @ 2 GHz (Bereskin Stripline) D. @ 5 GHz (Bereskin Stripline) E. @ 10 GHz (Bereskin Stripline)	3.69 3.66 3.67 3.66 3.65
Df, Loss Tangent (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A) B. @ 1 GHz (HP4291A) C. @ 2 GHz (Bereskin Stripline) D. @ 5 GHz (Bereskin Stripline) E. @ 10 GHz (Bereskin Stripline)	0.0094 0.0117 0.0120 0.0127 0.0125

10.5-11 mil wide strip lines,
Use measured S-parameters for 2 segments (2 inch and 8 inch)

Measured S-parameters for 2 and 8 inch segments



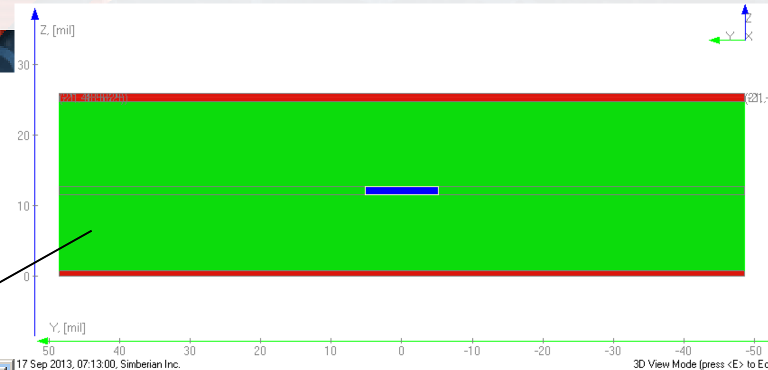
GMS-parameters computed from measured S-parameters

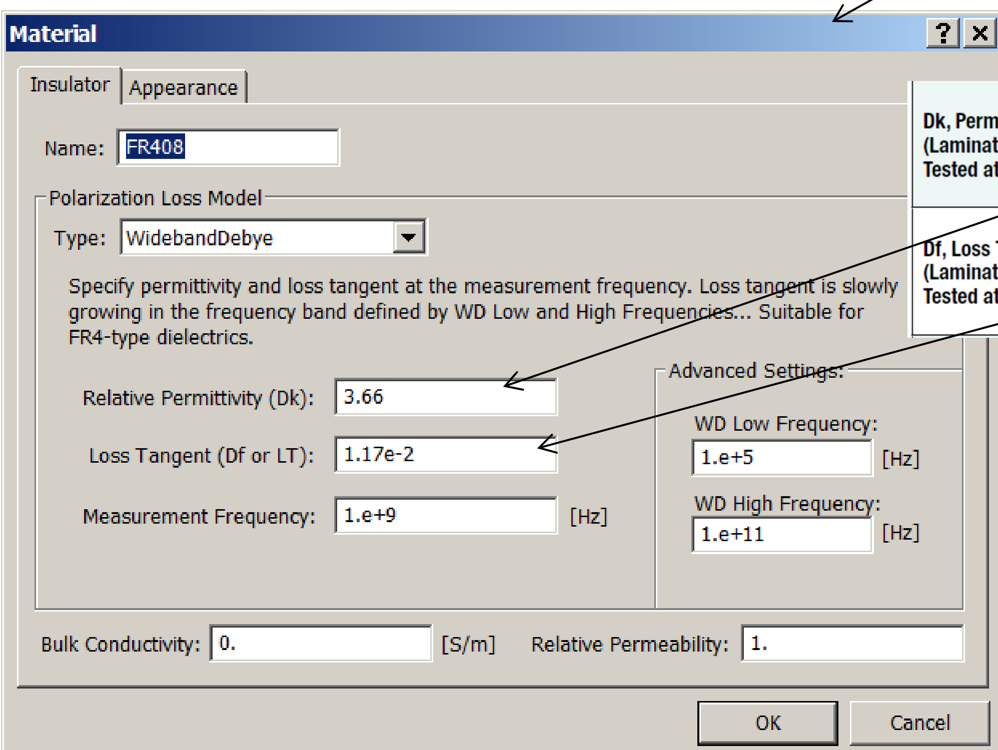


Reflection in generalized modal S-parameters is exactly zero – makes material model identification much easier!

Material models for strip line analysis - definition

First, try to use material parameters from specs





Dk, Permittivity (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A)	3.69
	B. @ 1 GHz (HP4291A)	3.66
	C. @ 2 GHz (Bereskin Stripline)	3.67
	D. @ 5 GHz (Bereskin Stripline)	3.66
	E. @ 10 GHz (Bereskin Stripline)	3.65
Df, Loss Tangent (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A)	0.0094
	B. @ 1 GHz (HP4291A)	0.0117
	C. @ 2 GHz (Bereskin Stripline)	0.0120
	D. @ 5 GHz (Bereskin Stripline)	0.0127
	E. @ 10 GHz (Bereskin Stripline)	0.0125

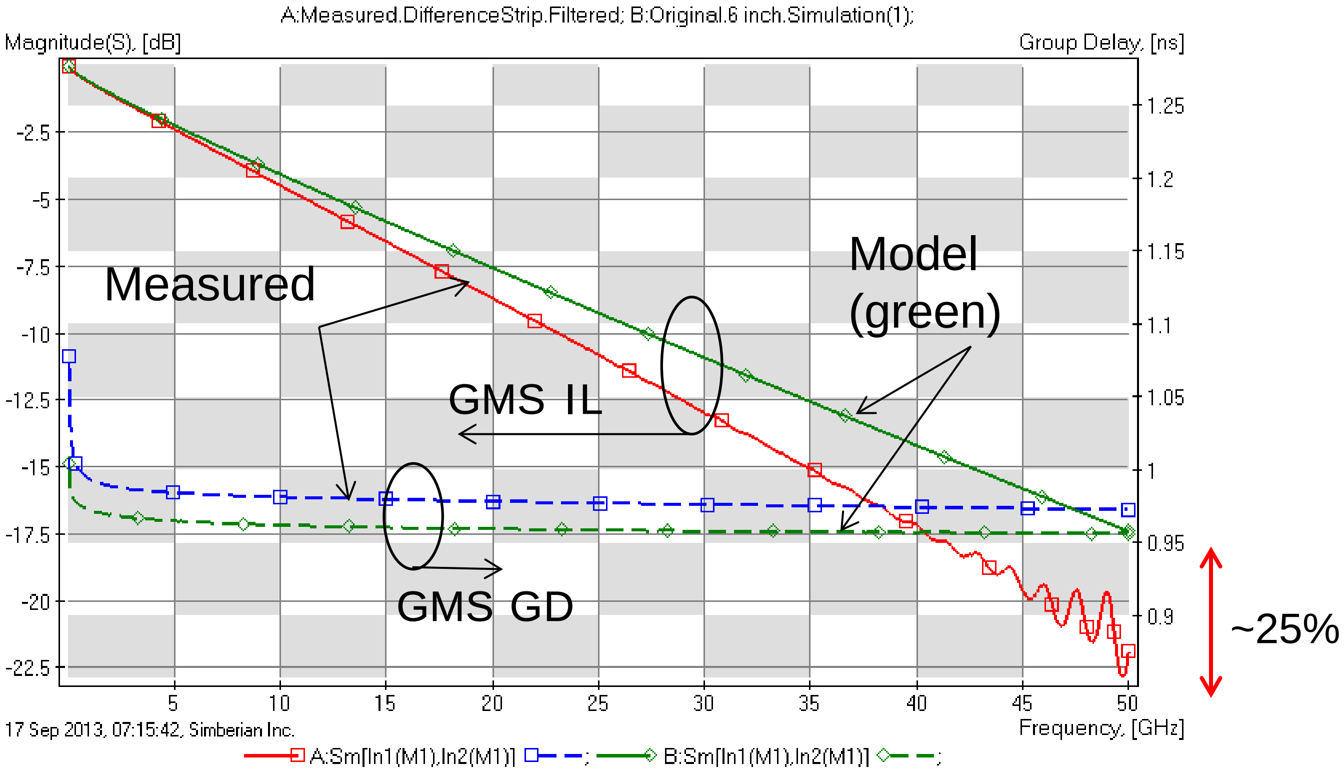
Wideband Debye model can be described with just one Dk and LT

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

Conductor is copper, no roughness in specs

Results with available material models

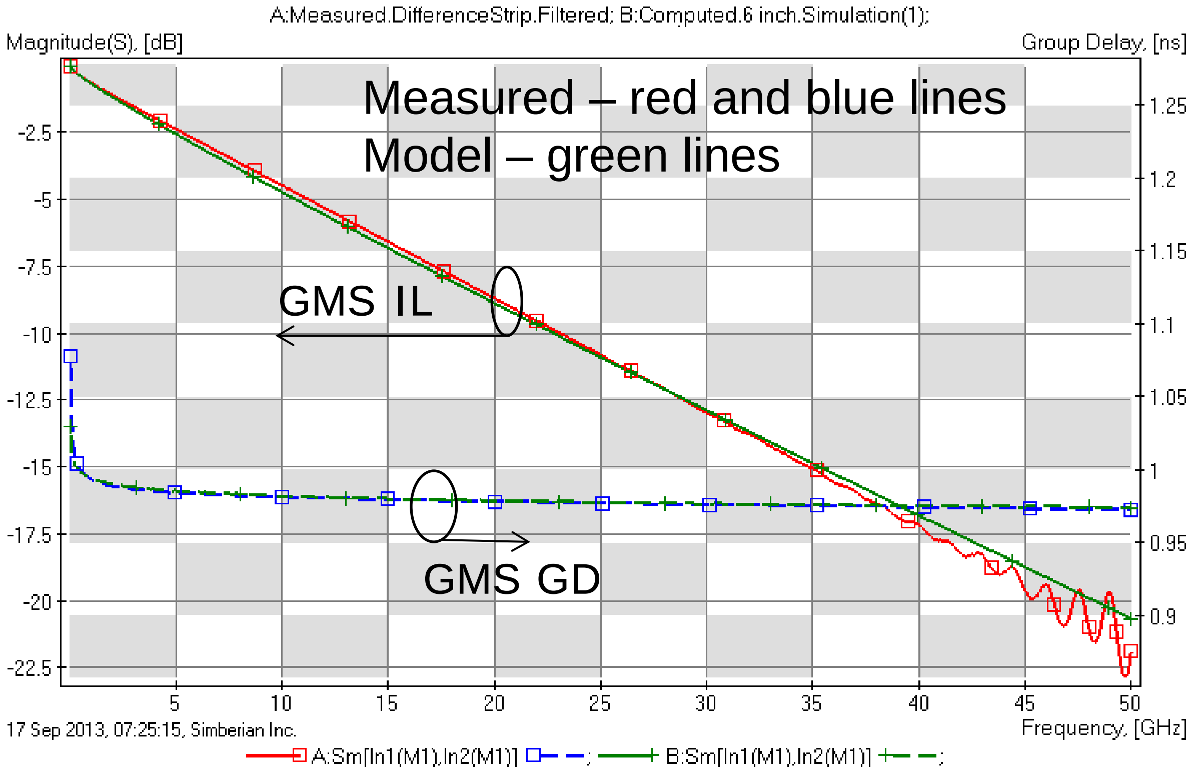
The original model produces considerably lower insertion losses (GMS IL) above 5 GHz and smaller group delay (GMS GD) at all frequencies:



Two options: 1) Increase Dk and LT in the dielectric model;
2) Increase Dk in dielectric model and model conductor roughness

Option 1: Increase Dk and LT in dielectric model (no conductor roughness)

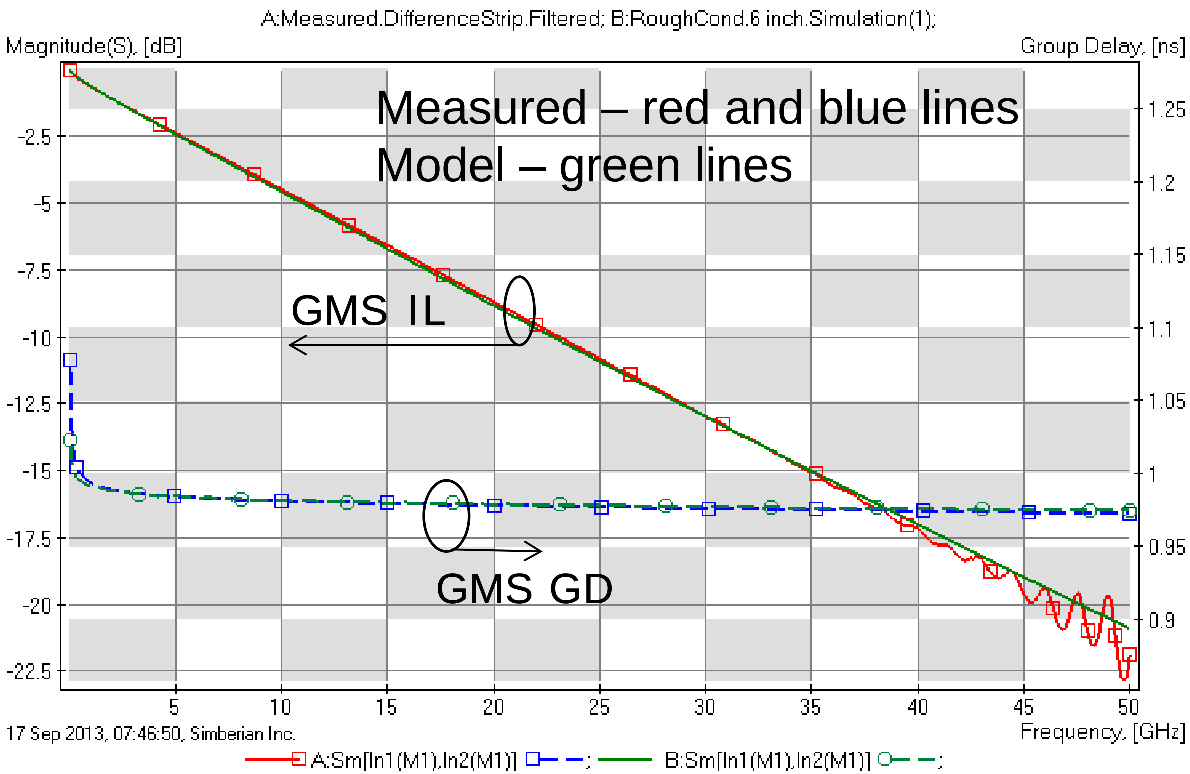
Good match with: Dk=3.83 (4.6% increase), LT=0.0138 (18% increase), Wideband Debye model



Good match, but what if conductors are actually rough?

Option 2: Increase Dk and model conductor roughness (proper modeling)

Dielectric: Dk=3.8 (3.8% increase), LT=0.0117 (no change), Wideband Debye model
Conductor: Modified Hammerstadt model with SR=0.32 um, RF=3.3

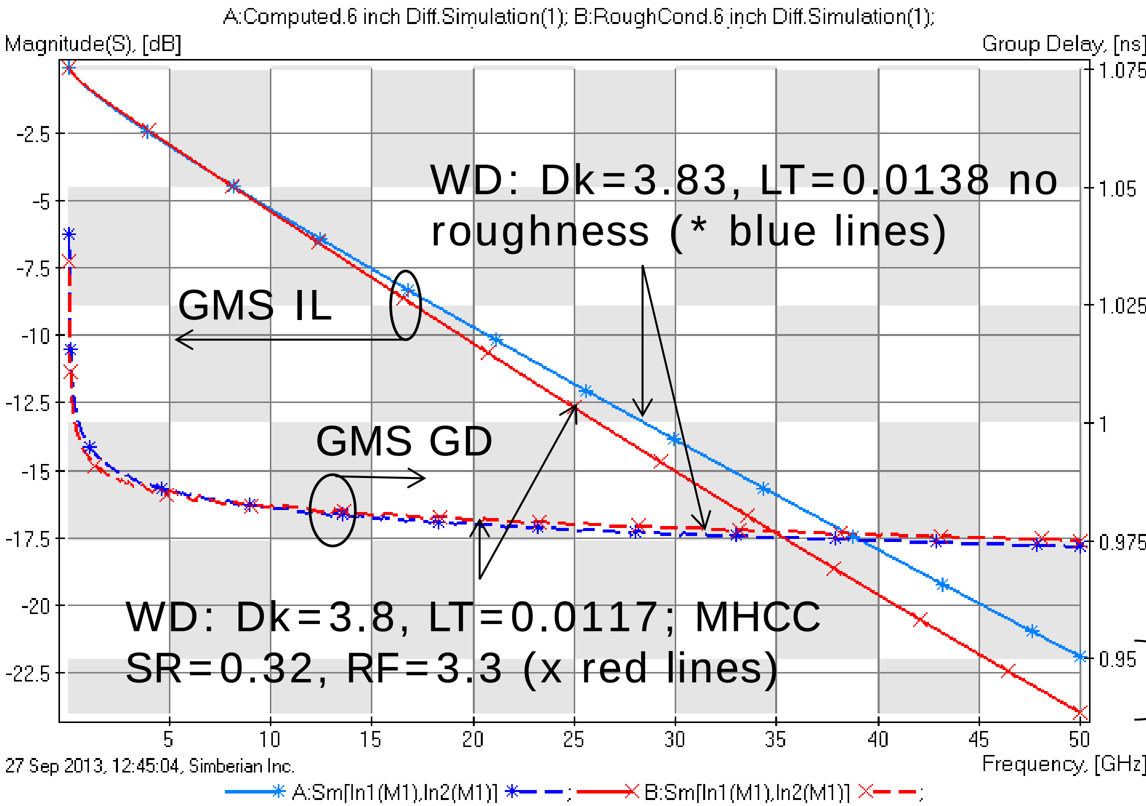


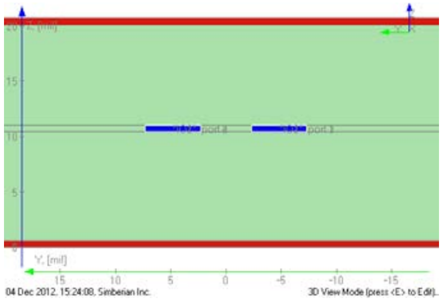
Excellent match and proper dispersion and loss separation!
This model is expected to work for strips with different widths

Can we use models for another cross-section?

- Differential 6 mil strips, 7.5 mil distance

GD is close, but the loss is different:





Which one is better?

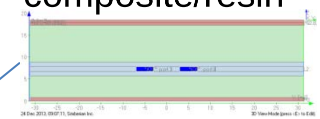
About 10% difference for medium-loss dielectric

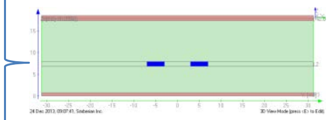
Examples of practical material models identification with coupled lines

- 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

See details at W. Beyene at all, Lessons learned: How to Make Predictable PCB Interconnects for Data Rates of 50 Gbps and Beyond, DesignCon2014

The GMS-parameters technique is the simplest possible

- Needs measurements for 2 t-lines with any geometry of cross-section and transitions
  - No extraction of propagation constants (Gamma) from measured data (difficult, error-prone)
  - No de-embedding of connectors and launches (difficult, error-prone)
- Needs the simplest numerical model
  - Requires computation of only propagation constants
  - No 3D electromagnetic models of the transitions
- Minimal number of smooth complex functions to match
  - One parameter for single and two parameters for differential
  - All reflection and modal transformation parameters are exactly zeroes

Summary on material models

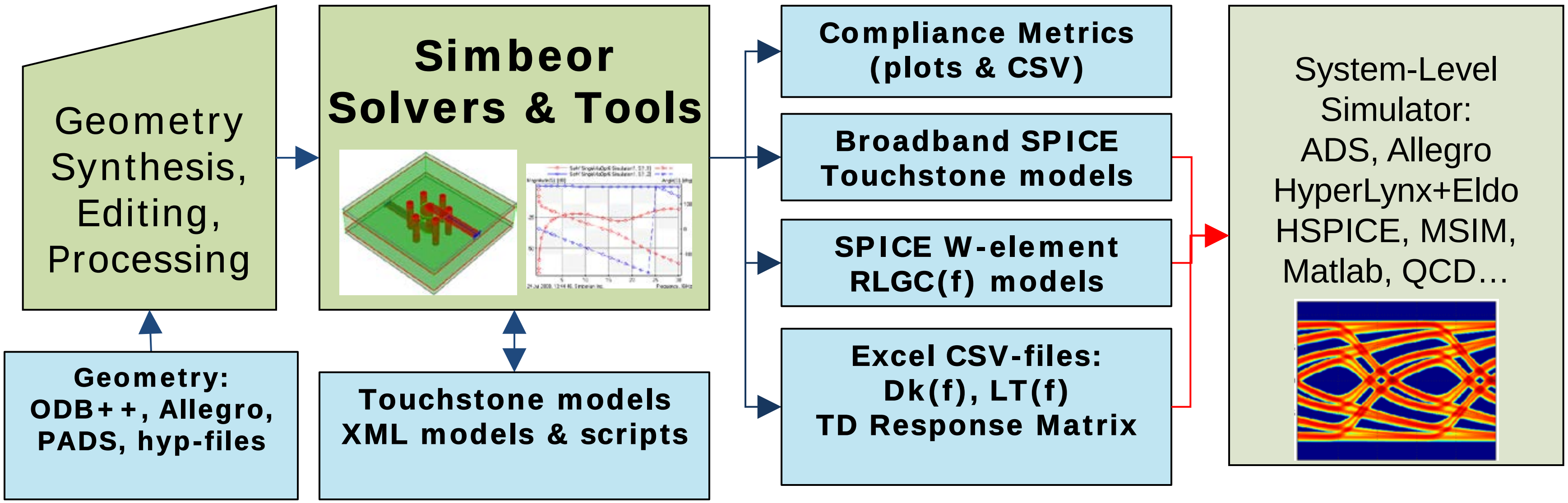
- Broadband dielectric and conductor roughness models must be identified or verified
- Proper separation of loss and dispersion effects between dielectric and conductor models is very important, but not easy task
- Without proper roughness model, dielectric models is dependent on strip width
  - If strip width is changed, difference in insertion loss predicted by different models may have up to 20-30% for low-loss dielectrics
  - See examples for Panasonic Megtron 6 and Nelco 4000 EP at “Which one is better?...” presentation and “Elements of decompositional analysis…” tutorial from DesignCon 2013 (available at www.simberian.com)
- In addition, PCB materials are composed of glass fiber and resin and have layered structure
  - Different dielectric models for composite and resin layers may be required
  - Vertical and horizontal components of dielectric constant may be different (anisotropy)
  - Periodic inhomogeneity may cause skew and resonances (fiber-weave effect)
  - All that can be modelled in Simbeor software

Interconnect analysis tasks

- Pre-layout tasks
  - Synthesize geometry for t-lines with target impedance
  - Synthesize geometry for transitions with minimal reflection and localization over the target frequency range
  - Evaluate transitions impact on compliance metrics
  - Evaluate impact of manufacturing tolerances
- Post-layout tasks
  - Modify board design to fit manufactured
  - Identify geometry of discontinuities and t-lines
  - Build models and simulate

Simbeor is synthesis, full-wave analysis and macro-modeling tool for interconnects

*Simbeor enables **geometry synthesis** for controlled impedance transmission lines and via-holes, has **geometry import** and selection capabilities, and **3D geometry editor***

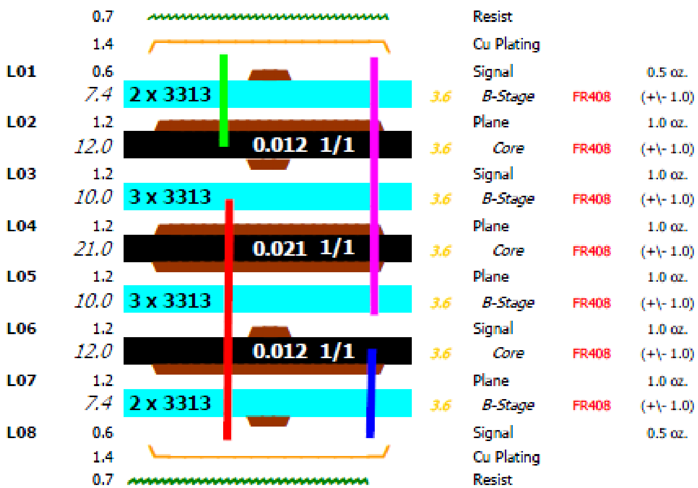


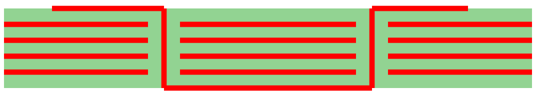
Simbeor is one-stop solution for passive interconnect pre and post-layout analyses with advanced electromagnetic models, for macro-modeling and material parameters identification tasks

Demo of pre-layout analysis in Simbeor

1) Synthesize transmission line line model with the target impedance
2) Synthesize geometry of via transition through the board
3) Simulate simple link path with one or two via transitions
4) Plot S-parameters, TDR response or eye diagram
5) Output BB SPICE or Touchstone model

Stackup and materials from CMP-28 Wild River Technology
http://wildrivertech.com/

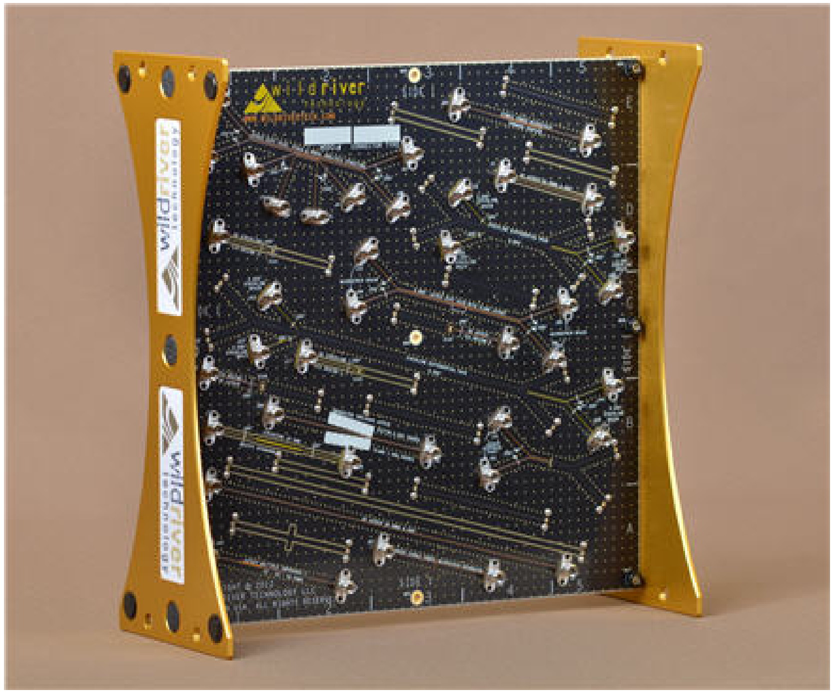




Demo of post-layout analysis in Simbeor

1) Import or convert board design into Board Analyzer
2) Select nets and create Network Selector (NS) for analysis
3) Optionally adjust geometry extraction, signal, solvers and accuracy options
4) Break selected nets into discontinuities and t-line segments
5) Generate Linear Network (LN) and 3D Circuits and run analysis
6) Plot S-parameters, TDR or eye diagram
7) Output BB SPICE or Touchstone models

CMP-28/32 validation board from Wild River Technology
http://wildrivertech.com/



Simbeor use case scenarios

- **Stand-alone**
  - Material parameters identification
  - S-parameters model quality assurance and macro-modeling
  - S-parameter and compliance analyses of links without Tx & Rx
- With a system-level tool (HSPICE, ADS, …)
  - Building advanced full-wave models of interconnects
  - S-parameters model quality assurance and macro-modeling
- With HFSS or CST – Simbeor compliments with
  - Analysis of t-lines with advanced dielectric and conductor roughness models
  - Analysis of planar discontinuities
  - S-parameters model quality assurance and macro-modeling
  - S-parameter and compliance analyses of links without Tx & Rx

Why use Simbeor?

1. **Algorithms are validated with measurements up to 50 GHz!**
2. **Unique algorithm for material models identification**
3. Advanced models of transmission lines
4. Fast via-hole and transmission line geometry synthesis
5. Fast and accurate pre- and post-layout de-compositional EM analysis
6. Quick compliance analysis in frequency domain
7. Unique quality assurance for Touchstone models
8. Unique macro-modeling capabilities for consistent FD and TD analyses
9. **Easy-to-learn and easy-to-use**
10. **Simbeor is #1 in price-performance (accuracy and productivity)**

References

(available at http://www.simberian.com/)

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Contacts and resources

- Yuriy Shlepnev, Simberian Inc., Booth #525
  shlepnev@simberian.com
  Tel: 206-409-2368
- Simberian web site and contacts www.simberian.com
- Webinars on material identification de-compositional analysis, S-parameters quality and http://www.simberian.com/Webinars.php
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