Broadband material model identification with GMS-parameters

Yuriy Olegovich Shlepnev

Simberian Inc.

shlepnev@simberian.com

2015 EPEPS Conference, October 27, 2015

Outline

- Introduction
- Dielectric and conductor roughness models for PCB/Packaging applications
- Model identification with GMS parameters
- Comparison of GMS-parameters with SPP techniques
- Separation of dielectric and conductor roughness models
- Practical examples
- Conclusion

Introduction

- Analysis of PCB and packaging interconnects for 10-30 Gbps 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 (with violations of localization)
  - Boards are not manufactured as designed – variations and manipulations by manufacturers
- There is only one IPC industry standard for identification of broadband models for PCB/packaging dielectric
  - IPC-TM-650 #2.5.5.12 – Short Pulse Propagation (SPP) technique
  - Originally promoted and supported by IBM

Broadband material models

- **Common PCB dielectric models:**

Empirical macroscopic temporal dispersion models for LTI PCB/packaging dielectrics

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)

- **Common conductor surface roughness models:**

Modified Hammerstad (2 parameters):

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

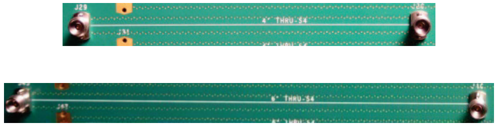
Huray snowball (1-ball, 2 parameters):

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

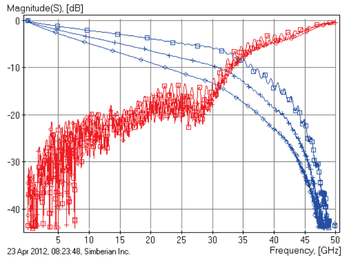
- Parameters for the models are not available and must be identified

Material model identification techniques

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

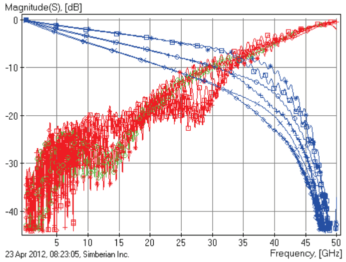


- … take measurements …
  - **S-parameters** measured with VNA
  - TDR/TDT measurements
  - Combination of both



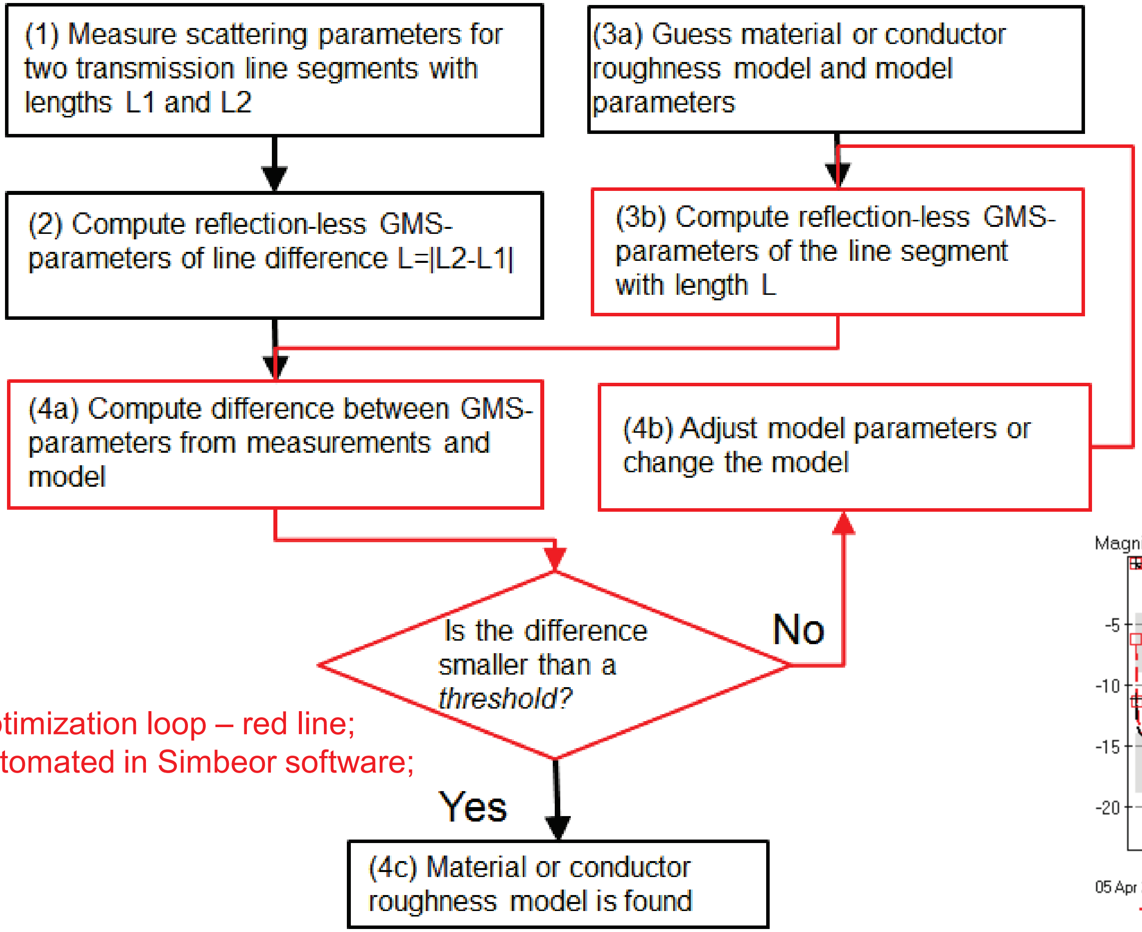
23 Apr 2012, 08:23:48, Simberian Inc.

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



23 Apr 2012, 08:23:05, Simberian Inc.

Material Model Identification with GMS-Parameters



(1) Measure scattering parameters for two transmission line segments with lengths L1 and L2

(2) Compute reflection-less GMS-parameters of line difference L=|L2-L1|

(3a) Guess material or conductor roughness model and model parameters

(3b) Compute reflection-less GMS-parameters of the line segment with length L

(4a) Compute difference between GMS-parameters from measurements and model

(4b) Adjust model parameters or change the model

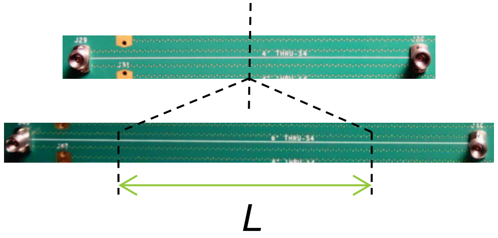
Is the difference smaller than a *threshold?*

No

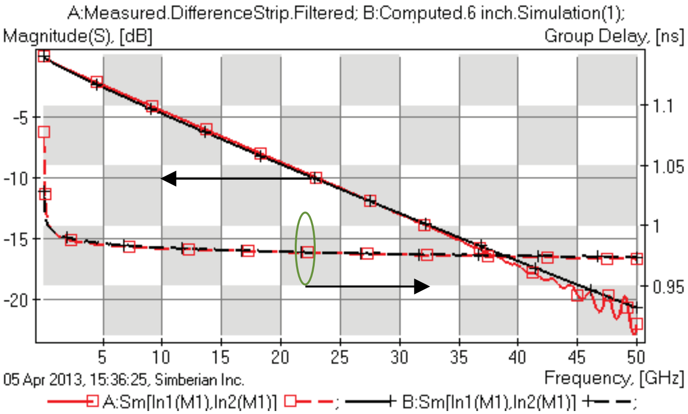
Yes

(4c) Material or conductor roughness model is found

Optimization loop – red line;
Automated in Simbeor software;



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



See details at: Y. Shlepnev, PCB and package design up to 50 GHz: Identifying dielectric and conductor roughness models, The PCB Design Magazine, February 2014, p. 12-28.

The GMS-parameters technique is the simplest possible for interconnects

- 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)
  - Works with single-ended and differential lines
- Needs the simplest numerical model
  - Requires computation of only propagation constants from cross-section (accuracy of the model is very important!)
  - 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

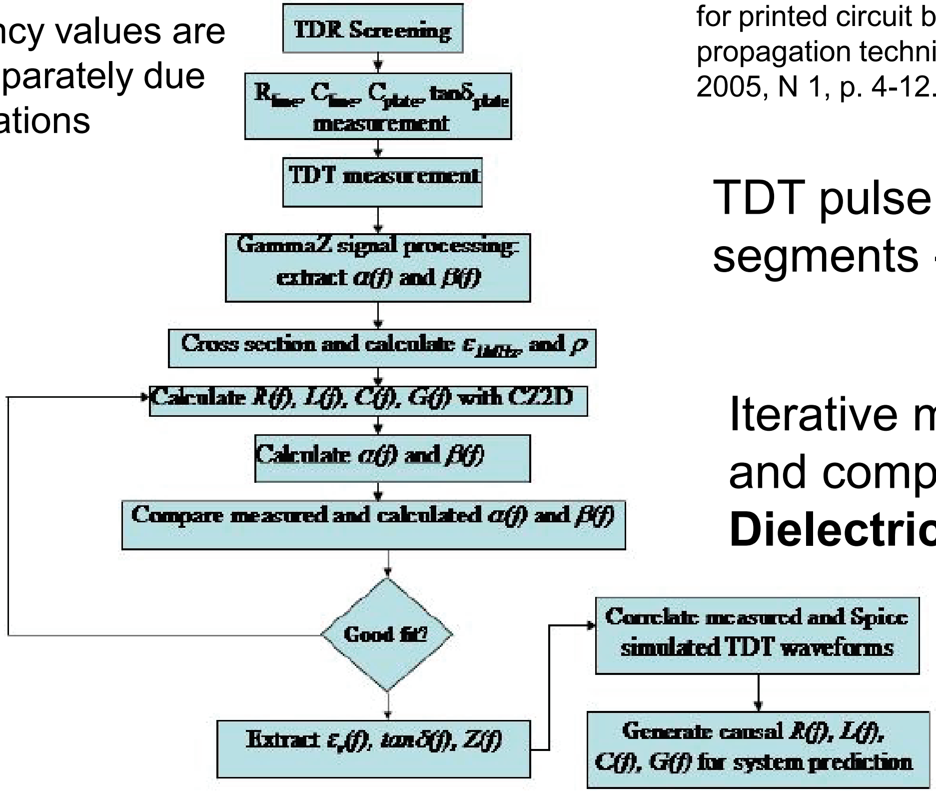
Material Model Identification with Short Pulse Propagation (SPP)

Step-by-Step Procedure for Short-Pulse-Propagation-Based Complex Permittivity Extraction

The following flowchart summarizes the extraction process:

A. Deutsch, T.-M. Winkel, G. V. Kopcsay, C. W. Surovic, B. J. Rubin, G. A. Katopis, B. J. Chamberlin, R. S. Krabbenhoft, Extraction of   and for printed circuit board insulators up to 30 GHz using the short-pulse propagation technique, IEEE Trans. on Adv. Packaging, vol. 28, 2005, N 1, p. 4-12.

Low frequency values are identified separately due to TDT limitations



TDT pulse responses of 2 line segments -> **Gamma**

Iterative matching of measured and computed Gamma -> **Dielectric Model**

Comparison of SPP and GMS techniques

- Measure S-parameters for 2 line segments
- Extract reflection-less S-parameters (GMS-parameters) of difference

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

Gamma can be extracted

- Build model of t-line cross-section and compute GMS-parameters of segment
- Change material model until measured and modeled GMS-parameters are matched

---

- Measure pulse response (TDT) for 2 line segments
- Extract complex propagation constant (Gamma)

- Build model of t-line cross-section
- Change material model until measured and modeled Gamma are matched

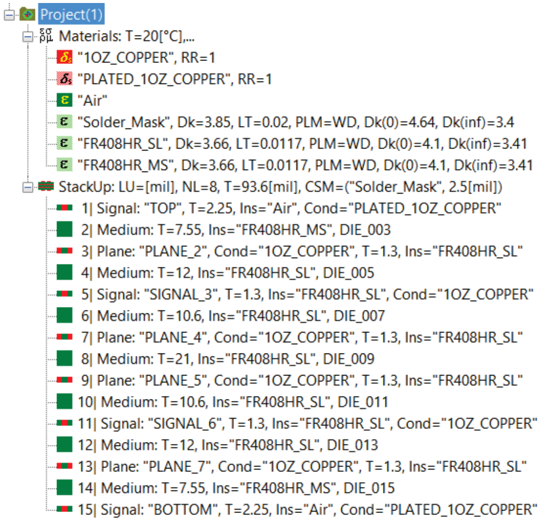
Commonalities and differences of GMS and SPP

- Commonalities:
  - Same test fixture can be used (2 segments)
  - Numerical transmission line model is used in both techniques
  - Resistance measurement at DC can be used to identify bulk resistivity in both techniques
- Differences:
  - Measured S-parameters are used to extract GMS-parameters (VNA), but short pulse TDT measurements are used in SPP technique to extract complex propagation constants
  - SPP uses measurements at 1 MHz to have low frequency asymptotes of dielectric constant - not needed with the GMS-parameters if S-parameters are measured starting from sufficiently low frequency
- If S-parameters are used to extract Gamma through GMS-parameters, such technique may be considered as a variation of SPP methodology – “SPP Light”

Separation of dispersion from dielectric and roughness

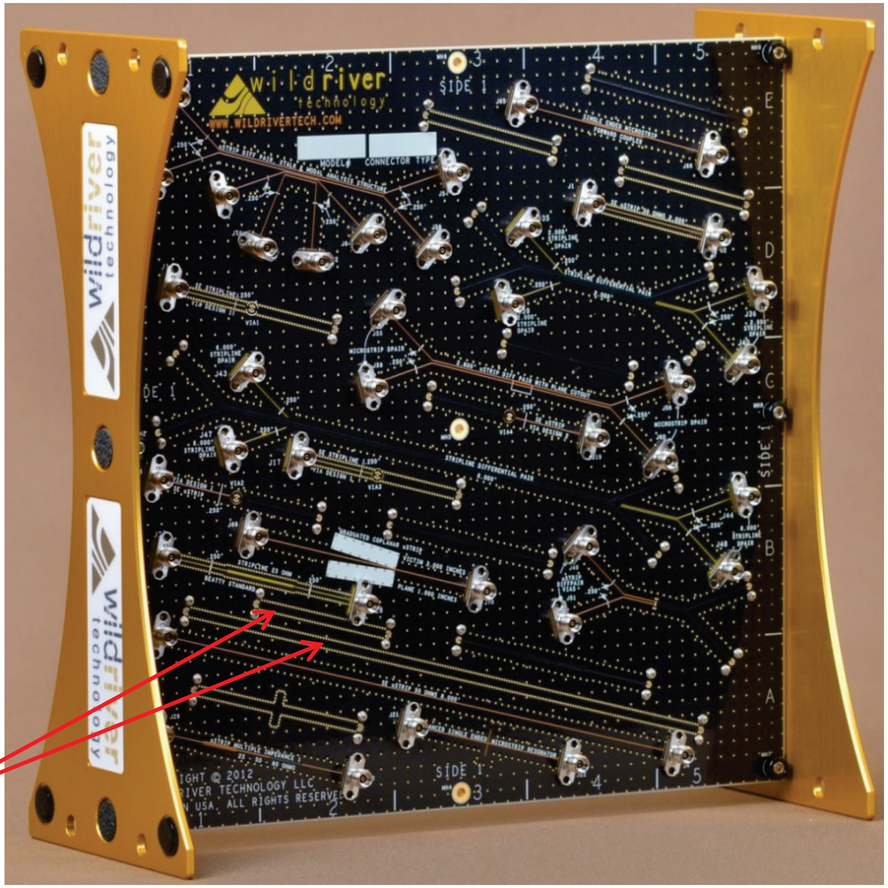
- Conductor roughness effect causes signal degradation (dispersion and loss) that are similar to the signal degradation caused by dielectrics
- Conductor roughness and dielectric models can be constructed as follows
  - Identify dielectric model and do not use any additional conductor roughness model (suitable for high-loss dielectrics and if cross-section is not changed);
  - **Define dielectric model with the data available from the dielectric manufacturer and then identify only the roughness model (simplest, works well with reliable data from manufacturers);**
  - Use segments with flat copper to identify parameters in dielectric model and then use segments made with rough copper to identify the conductor roughness model;
  - Identify dielectric and conductor roughness models simultaneously using multiple segment pairs with multiple trace width (most complicated and ambiguous);

Example of material model identification

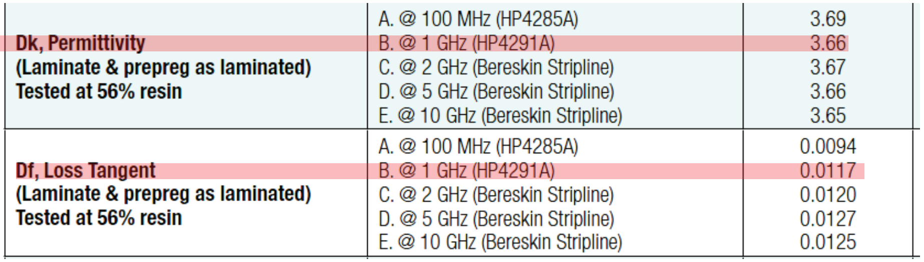


- Project(1)
  - Materials: T=20[°C],...
    - "1OZ_COPPER", RR=1
    - "PLATED_1OZ_COPPER", RR=1
    - "Air"
    - "Solder_Mask", Dk=3.85, LT=0.02, PLM=WD, Dk(0)=4.64, Dk(inf)=3.4
    - "FR408HR_SL", Dk=3.66, LT=0.0117, PLM=WD, Dk(0)=4.1, Dk(inf)=3.41
    - "FR408HR_MS", Dk=3.66, LT=0.0117, PLM=WD, Dk(0)=4.1, Dk(inf)=3.41
  - StackUp: LU=[mil], NL=8, T=93.6[mil], CSM=("Solder_Mask", 2.5[mil])
    - 1| Signal: "TOP", T=2.25, Ins="Air", Cond="PLATED_1OZ_COPPER"
    - 2| Medium: T=7.55, Ins="FR408HR_MS", DIE_003
    - 3| Plane: "PLANE_2", Cond="1OZ_COPPER", T=1.3, Ins="FR408HR_SL"
    - 4| Medium: T=12, Ins="FR408HR_SL", DIE_005
    - 5| Signal: "SIGNAL_3", T=1.3, Ins="FR408HR_SL", Cond="1OZ_COPPER"
    - 6| Medium: T=10.6, Ins="FR408HR_SL", DIE_007
    - 7| Plane: "PLANE_4", Cond="1OZ_COPPER", T=1.3, Ins="FR408HR_SL"
    - 8| Medium: T=21, Ins="FR408HR_SL", DIE_009
    - 9| Plane: "PLANE_5", Cond="1OZ_COPPER", T=1.3, Ins="FR408HR_SL"
    - 10| Medium: T=10.6, Ins="FR408HR_SL", DIE_011
    - 11| Signal: "SIGNAL_6", T=1.3, Ins="FR408HR_SL", Cond="1OZ_COPPER"
    - 12| Medium: T=12, Ins="FR408HR_SL", DIE_013
    - 13| Plane: "PLANE_7", Cond="1OZ_COPPER", T=1.3, Ins="FR408HR_SL"
    - 14| Medium: T=7.55, Ins="FR408HR_MS", DIE_015
    - 15| Signal: "BOTTOM", T=2.25, Ins="Air", Cond="PLATED_1OZ_COPPER"

CMP-28 channel modelling platform from Wild River Technology http://www.wildrivertech.com/



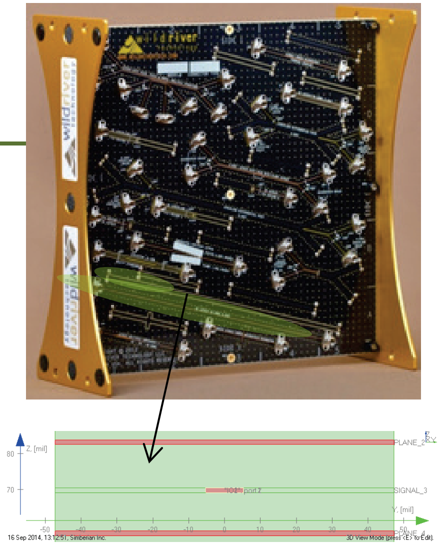
From Isola FR408 specifications



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

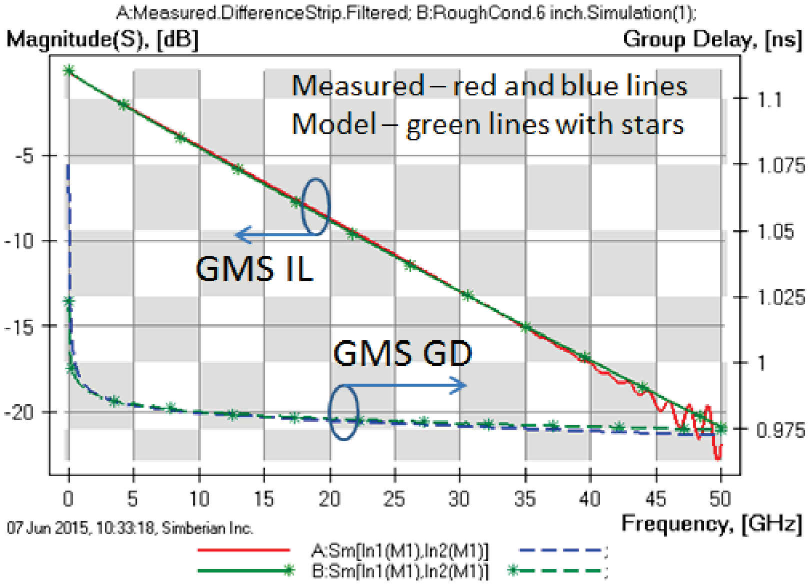
10.5 (11) mil strip lines; microstrips 13.5 (14.5) mil; Use measured S-parameters for 2 segments (2 inch and 8 inch); No data for conductor roughness model;

Example from CMP-28 platform

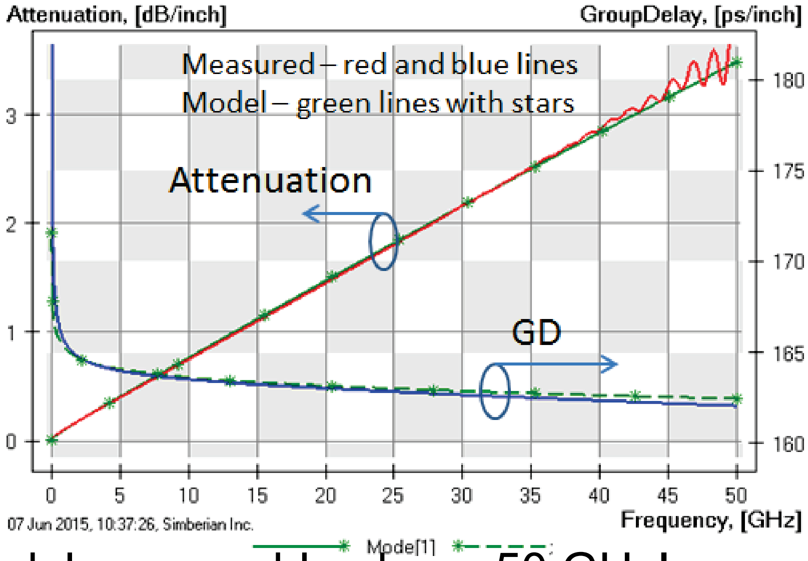


- Identification results:
  - Dielectric: Wideband Debye dielectric model with Dk=3.8 (3.66), LT=0.0117 @ 1 GHz;
  - Conductor roughness: modified Hammerstad model with SR=0.32 um, RF=3.3

GMS-parameters



Gamma (SPP Light)

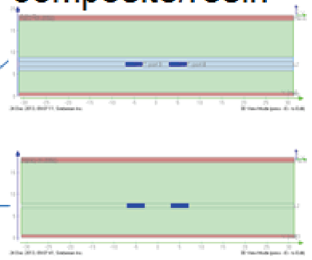


Models are usable above 50 GHz!

Examples of practical material models identification with differential 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

Conclusion

- Broadband dielectric and conductor roughness models must be identified or verified to have meaningful analysis in EDA tools
- Technique with GMS-parameters is accurate and simplest possible and may be considered as variant of SPP technique
- GMS or SPP light techniques can be also used to identify parameters of
  - Models of dielectric mixtures or mixture components
  - Permittivity of anisotropic dielectric models (in or off plane)
  - Macroscopic fiber weave effect models
- Sensitivity of GSM-parameters to geometry variations is investigated at app. note #2010_03 at http://www.simberian.com/AppNotes.php
- See more references on the next slide

References

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

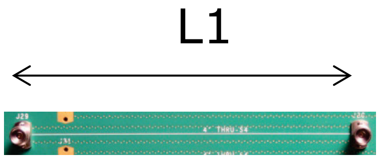
- Y. Shlepnev, A. Neves, T. Dagostino, S. McMorrow, Practical identification of dispersive dielectric models with generalized modal S-parameters for analysis of interconnects in 6-100 Gb/s applications, DesignCon 2010 (App Note #2010_01)
- Sensitivity of PCB Material Identification with GMS-Parameters to Variations in Test Fixtures, Simberian App Note #2010_03
- Material Identification With GMS-Parameters of Coupled Lines, Simberian App Note #2010_04
- J. Bell, S. McMorrow, M. Miller, A. P. Neves, Y. Shlepnev, Unified Methodology of 3D-EM/Channel Simulation/Robust Jitter Decomposition, DesignCon2011, (App Note #2011_02)
- D. Dunham, J. Lee, S. McMorrow, Y. Shlepnev, 2.4mm Design/Optimization with 50 GHz Material Characterization, DesignCon2011 (App Note #2011_03)
- Y. Shlepnev, S. McMorrow, Nickel characterization for interconnect analysis. - Proc. of the 2011 IEEE International Symposium on Electromagnetic Compatibility, Long Beach, CA, USA, August, 2011, p. 524-529.
- Y. Shlepnev, C. Nwachukwu, Roughness characterization for interconnect analysis. - Proc. of the 2011 IEEE International Symposium on Electromagnetic Compatibility, Long Beach, CA, USA, August, 2011, p. 518-523
- Y. Shlepnev, C. Nwachukwu, Practical methodology for analyzing the effect of conductor roughness on signal losses and dispersion in interconnects, DesignCon2012, Feb. 1st, 2012, Santa Clara, CA.

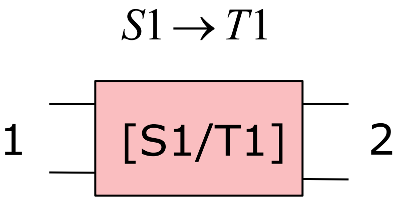
Backup slides

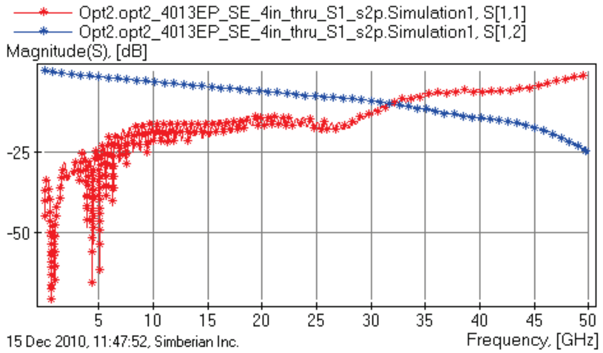
- Details of GMS-parameters algorithm

Measure S-parameters of two line segments

- S1 and T1 for line with length L1

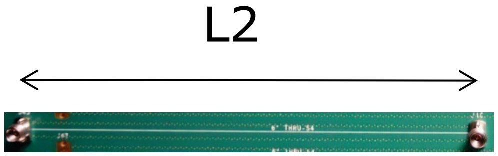


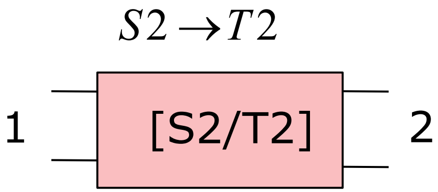


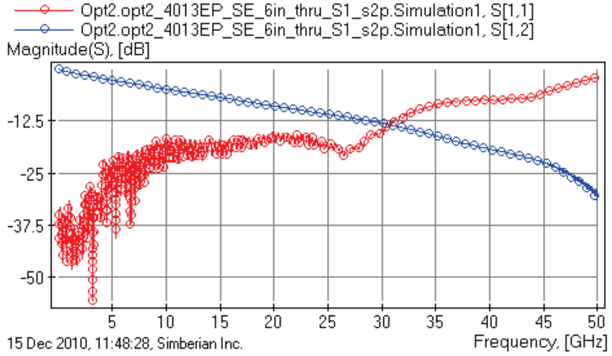


15 Dec 2010, 11:47:52, Simberian Inc.

- S2 and T2 for line with length L2



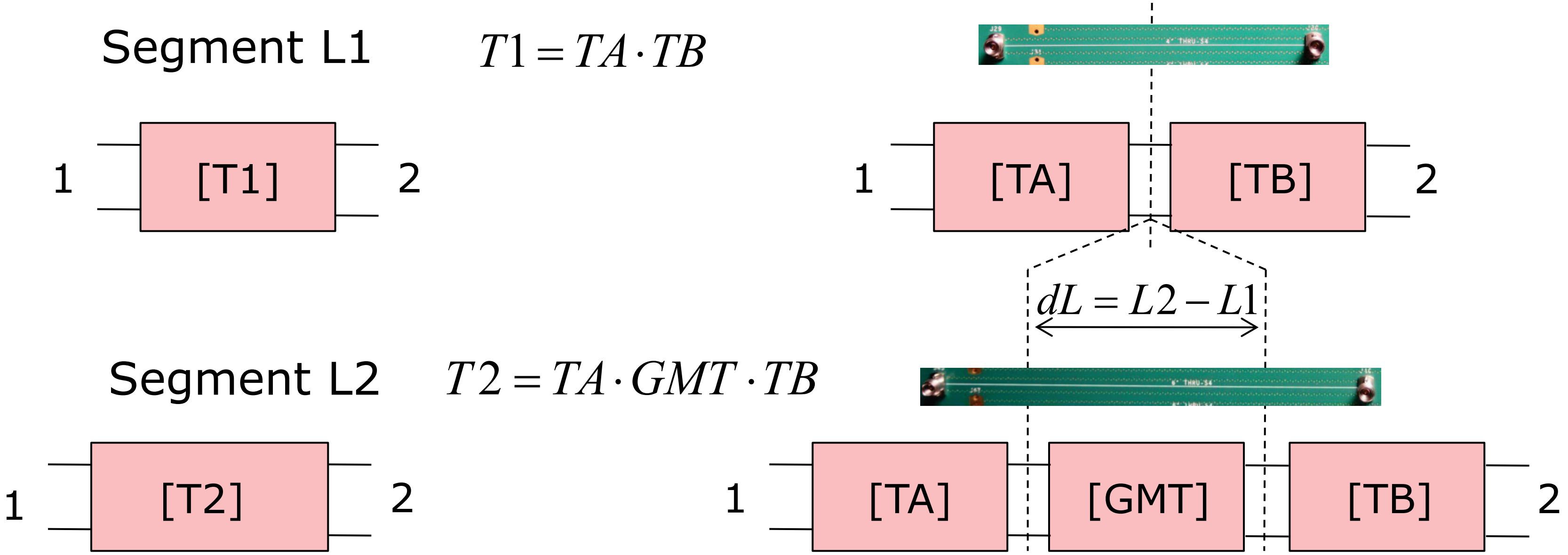




15 Dec 2010, 11:48:28, Simberian Inc.

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 $T1 = TA \cdot TB$

$dL = L2 - L1$

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

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

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

$$\Downarrow$$

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

Easy to compute!

For 1-conductor line we get:

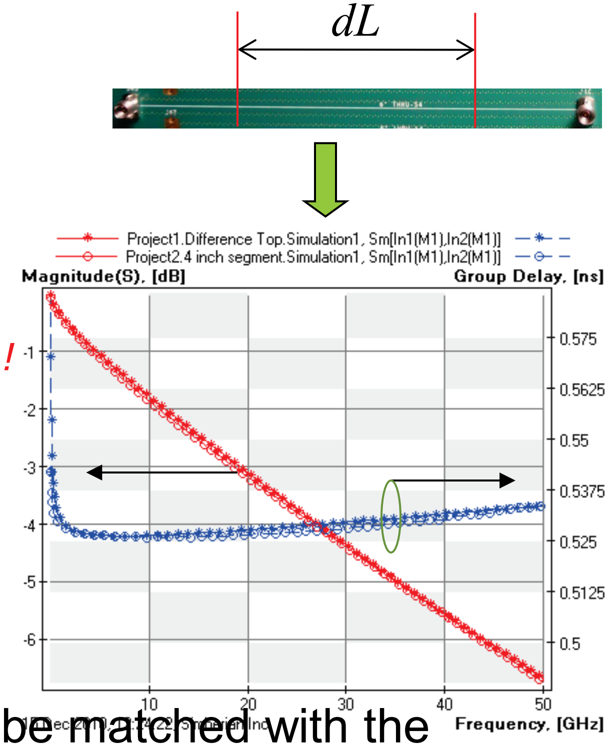
$$GMT = \begin{bmatrix} T_{11} & 0 \\ 0 & T_{11}^{-1} \end{bmatrix} \Rightarrow GMSm = \begin{bmatrix} 0 & T_{11} \\ T_{11} & 0 \end{bmatrix}$$

Just 1 complex function!

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

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

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



- 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!
- Technique is extended for N-conductor case – see the paper

Simberian
Electromagnetic Solutions