Drawbacks and Possible Improvements of Short Pulse Propagation Technique

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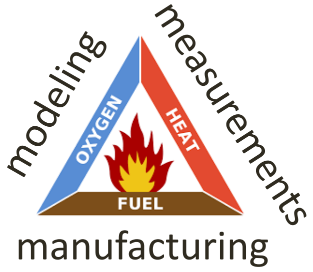
Outline

- Introduction
- Drawbacks of the original SPP technique
- Possible modifications: SPP Light with TDT and S-parameters
- Sensitivity to test fixture - numerical experiment
- Examples of low-cost practical model identification
- Example of model identification up to 50 GHz
- Conclusion

Introduction

- Design of PCB and packaging interconnects for data links running at bitrates 30 Gbps and beyond is challenging
  - Boards are not manufactured as designed
  - Making accurate measurements from DC to 50 GHz is very difficult
  - Accurate modeling over frequency bandwidth from DC to 50 GHz is difficult and even not possible in most of the EDA tools

Design success "fire triangle"



- To have consistency in modeling and manufacturing, the same technique must be used at the material model identification and production model validation stages

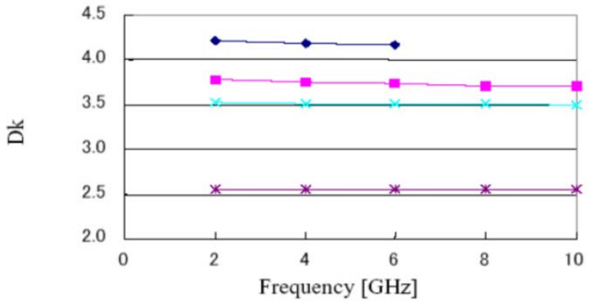
Material models - specs

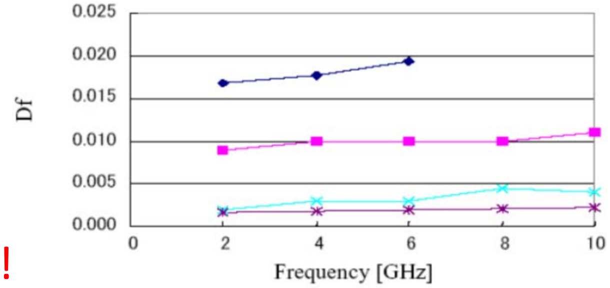
1GHz ; IPC TM650-2.5.5.9
6-50GHz ; The method by H. Kawabata, Proceedings of the 36th European Microwave Conference, 388-391 (2006)

Core Type	Actual Thickness mil	Actual Thickness mm	Cloth Style	ply	Typical Resin Content (%)	Typical Dk 1GHz	6GHz	12GHz	18GHz	23GHz	29GHz	34GHz	40GHz	45GHz	50GHz
2	2.0	0.050	1035	1	67	3.25	3.23	3.22	3.21	3.21	3.21	3.21	3.21	3.21	3.21
2.6	2.6	0.065	1078	1	59	3.37	3.33	3.31	3.31	3.30	3.30	3.30	3.30	3.30	3.30
3	3.0	0.075	1078	1	65	3.28	3.25	3.24	3.23	3.23	3.23	3.23	3.23	3.23	3.23

Core Type	Actual Thickness mil	Actual Thickness mm	Cloth Style	ply	Typical Resin Content (%)	Typical Df 1GHz	6GHz	12GHz	18GHz	23GHz	29GHz	34GHz	40GHz	45GHz	50GHz
2	2.0	0.050	1035	1	67	0.002	0.003	0.004	0.004	0.004	0.004	0.005	0.005	0.005	0.005
2.6	2.6	0.065	1078	1	59	0.002	0.003	0.004	0.004	0.004	0.004	0.004	0.005	0.005	0.005
3	3.0	0.075	1078	1	65	0.002	0.003	0.004	0.004	0.004	0.004	0.005	0.005	0.005	0.005

*The data above show actual values and are not guaranteed.





Not suitable directly for broadband modeling!
Nothing for conductor roughness!!!

Material models - needed

- **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:

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

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

- **PCB 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

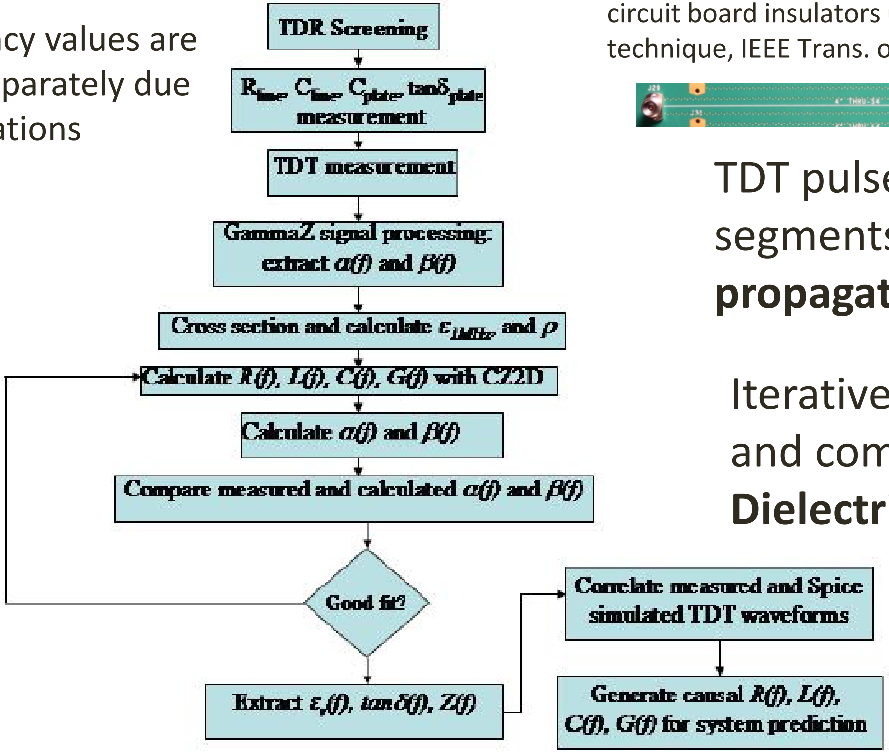
Possible low-cost identification options

- Delta-L – uncertainty due to dependency on all reflections, uses S-parameters (requires VNA + measurement skills)
- Complete de-embedding (TRL, AFR, ISD,…) – unnecessary complicated – VNA, test fixture S-parameters are not needed,…
- Identification with GMS-parameters – similar to SPP with the improvements suggested here and at EPEPS'2015 (Shlepnev…)
- Short Pulse Propagation – allows both model building and validation – standardized by IPC (IPC-TM-650 #2.5.5.12), simple, but may be confusing…

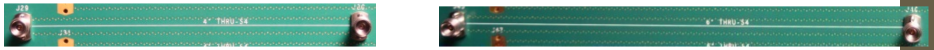
Step-by-Step Procedure for Short-Pulse-Propagation-Based Complex Permittivity Extraction

The following flowchart summarizes the extraction process:

Low frequency values are identified separately due to TDT limitations



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.



TDT pulse responses of 2 line segments -> **Gamma (complex propagation constant)**

Iterative matching of measured and computed Gamma -> **Dielectric and Roughness Models**

SPP Original: Steps 1-5

- **Step 1:** Select samples for the identification with TDR screening
  - Important step, sensitivity to the impedance variation should be investigated
- **Step 2:** Measure resistance of a t-line segment and capacitance of large disk at DC
  - Not needed - disk test can be eliminated by use of Wideband Debye model, resistance measurement can be replaced by matching attenuation at lower frequencies
- **Step 3:** Measure TDT step response, identify delay and construct preliminary transmission line model. – Not needed – eliminated by use of broadband models
- **Step 4:** Measure short pulse TDT for two line segments with about three to one ratio of the lengths.
  - TDT step should be allowed at this step to simplify the process, can be combined with step 1.
- **Step 5:** Convert short pulse TDT responses into complex propagation constant (Gamma) with windowing, Fourier transform and simple formula.
  - Can be improved by Gamma extraction from S-parameters

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SPP Original: Steps 6-9

- **Step 6:** Cross-section test board and take measurements of the test structures
  - Most important step if the accuracy is a concern, sensitivity of Gamma to the incorrect values of the cross section should be investigated
- **Step 7:** With the measured dimensions, compute dielectric constant from the disk capacitance and resistivity of conductor from resistance, both measured at DC in step 2. – Not needed with the broadband Debye model.
- **Step 8:** Create transmission line model with multipole Debye dielectric model and tune parameters in dielectric model to match the measured attenuation and phase constant (real and imaginary parts of Gamma). –
  - Main material model extraction step - requires an accurate field solver and use of Wideband Debye dielectric model and Huray or modified Hammerstad roughness
- **Step 9:** Compute dielectric constant and loss tangent (includes roughness)
  - Needed only in case if the roughness model in the field solver is not reusable and has to be converted into the effective loss tangent for other EDA tools

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SPP Light with TDT

- **Step a:** Measure TDR and TDT step responses of line segments – select TDT responses of two segments with the close TDR impedances (strict guidance is needed)
- **Step b:** Convert TDT into short pulse response, window it and extract Gamma following the original technique
- **Step c:** Optionally, cross-section the board traces and measure the dimensions, to improve accuracy
  - Additional test fixtures can be considered as the alternative to the cross-sectioning
- **Step d:** Use field solver to build cross-section model matching Gamma extracted in step b) following either the original procedure or as in GMS technique (to separate conductor and dielectric losses)

SPP Light with S-parameters

- **Step a:** Measure S-parameters of line segments, estimate quality and compute TDR and select two segments with the close TDR impedances (similar to GSM-parameters)
- **Step b:** Convert S-parameters into the reflection-less GMS-parameters and extract Gamma – see details at [EPEPS'2015]
- **Step c:** Optionally, cross-section the board traces and measure the dimensions, to improve accuracy
  - Additional test fixtures can be considered as the alternative to the cross-sectioning
- **Step d:** Use field solver to build cross-section model matching Gamma extracted in step b) following either the original procedure or as in GMS technique (to separate conductor and dielectric losses)

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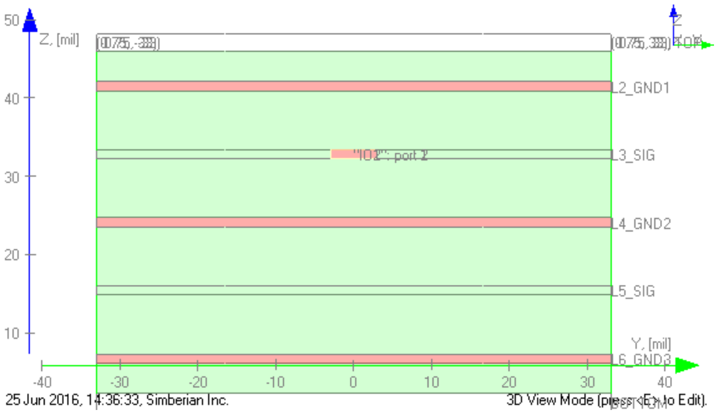
Numerical experiment

- Launches
  - Materials: T=20[°C],...
    - "COPPER", RR=1, SR=0.5, RF=2, RM=MHCC
    - "Air"
    - "FR4", Dk=4, LT=0.01, PLM=WD, Dk(0)=4.47, Dk(inf)=3.77
  - StackUp: LU=[mil], NL=7, T=49.2[mil]
    - 1| Medium: T=1, Ins="Air"
    - 2| Signal: "TOP", T=2.2, Ins="Air", Cond="COPPER"
    - 3| Medium: T=3.9, Ins="FR4", DIE_002
    - 4| Plane: "L2_GND1", Cond="COPPER", T=1.2, Ins="FR4"
    - 5| Medium: T=7.5, Ins="FR4", DIE_004
    - 6| Signal: "L3_SIG", T=1.2, Ins="FR4", Cond="COPPER"
    - 7| Medium: T=7.5, Ins="FR4", DIE_006
    - 8| Plane: "L4_GND2", Cond="COPPER", T=1.2, Ins="FR4"
    - 9| Medium: T=7.5, Ins="FR4", DIE_006
    - 10| Signal: "L5_SIG", T=1.2, Ins="FR4", Cond="COPPER"
    - 11| Medium: T=7.5, Ins="FR4", DIE_004
    - 12| Plane: "L6_GND3", Cond="COPPER", T=1.2, Ins="FR4"
    - 13| Medium: T=3.9, Ins="FR4", DIE_002
    - 14| Signal: "BOTTOM", T=2.2, Ins="Air", Cond="COPPER"

6 mil strip line, 2 and 6 inch segments

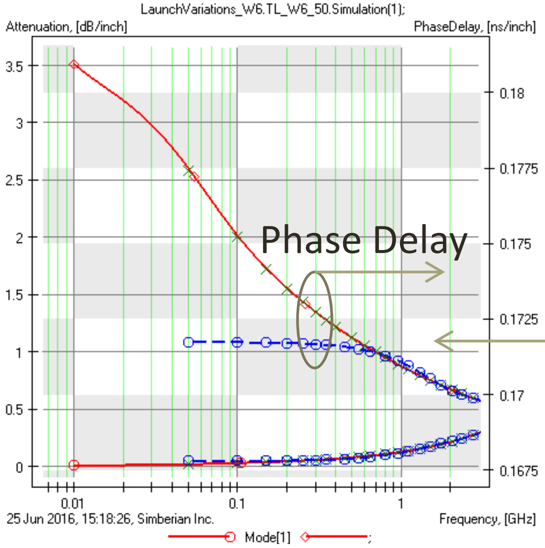


Dielectric: Wideband Debye, Dk=4, LT=0.01 @ 1 GHz;
Conductor roughness: MHCC, SR=0.5, RF=1

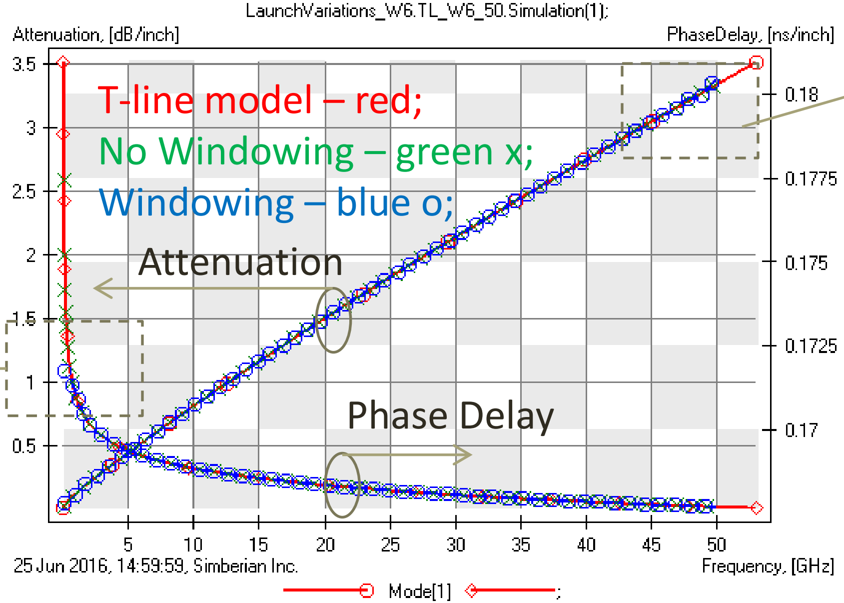
Modelled with Simbeor THz

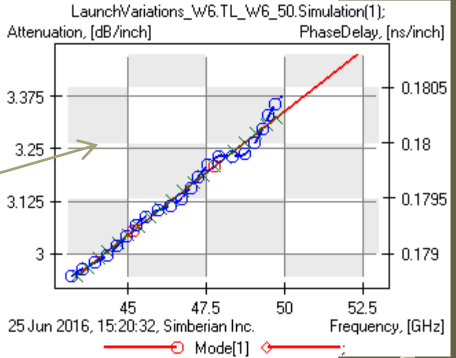
Gamma extraction from TDT – 2 and 6 inch segments, no launches

Windowing defect at low frequencies – wrong DC



Windowing defect at high frequencies - oscillations





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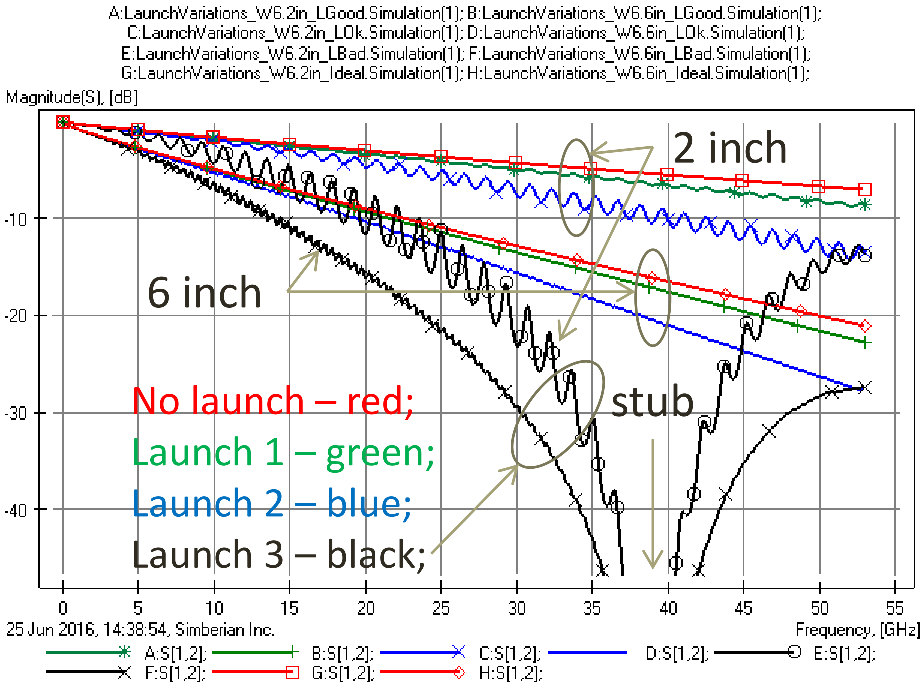
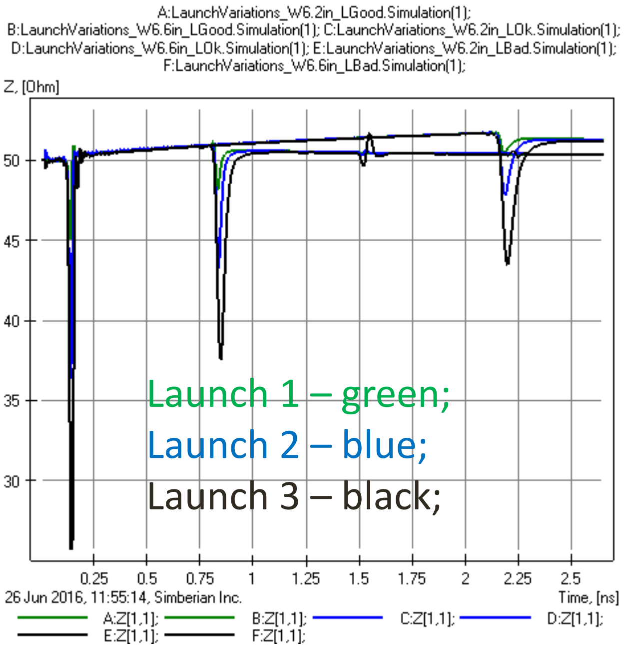
3 test pairs with different launches





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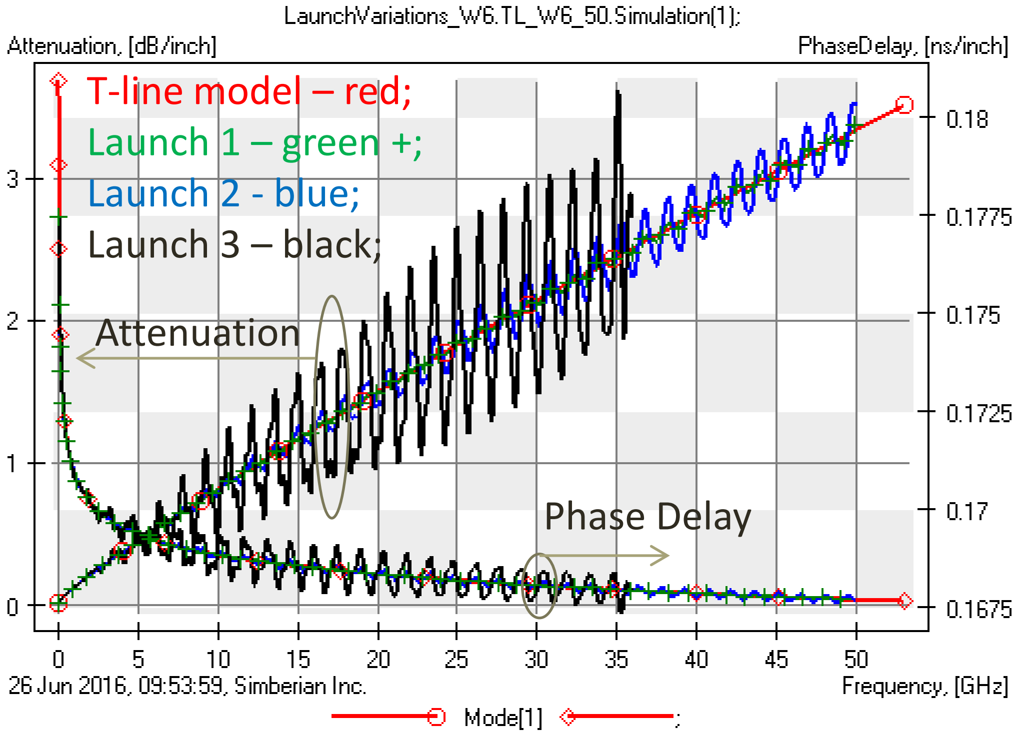
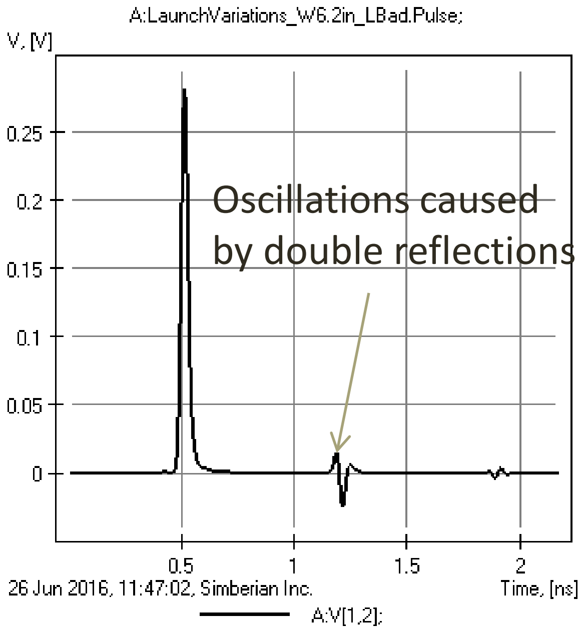
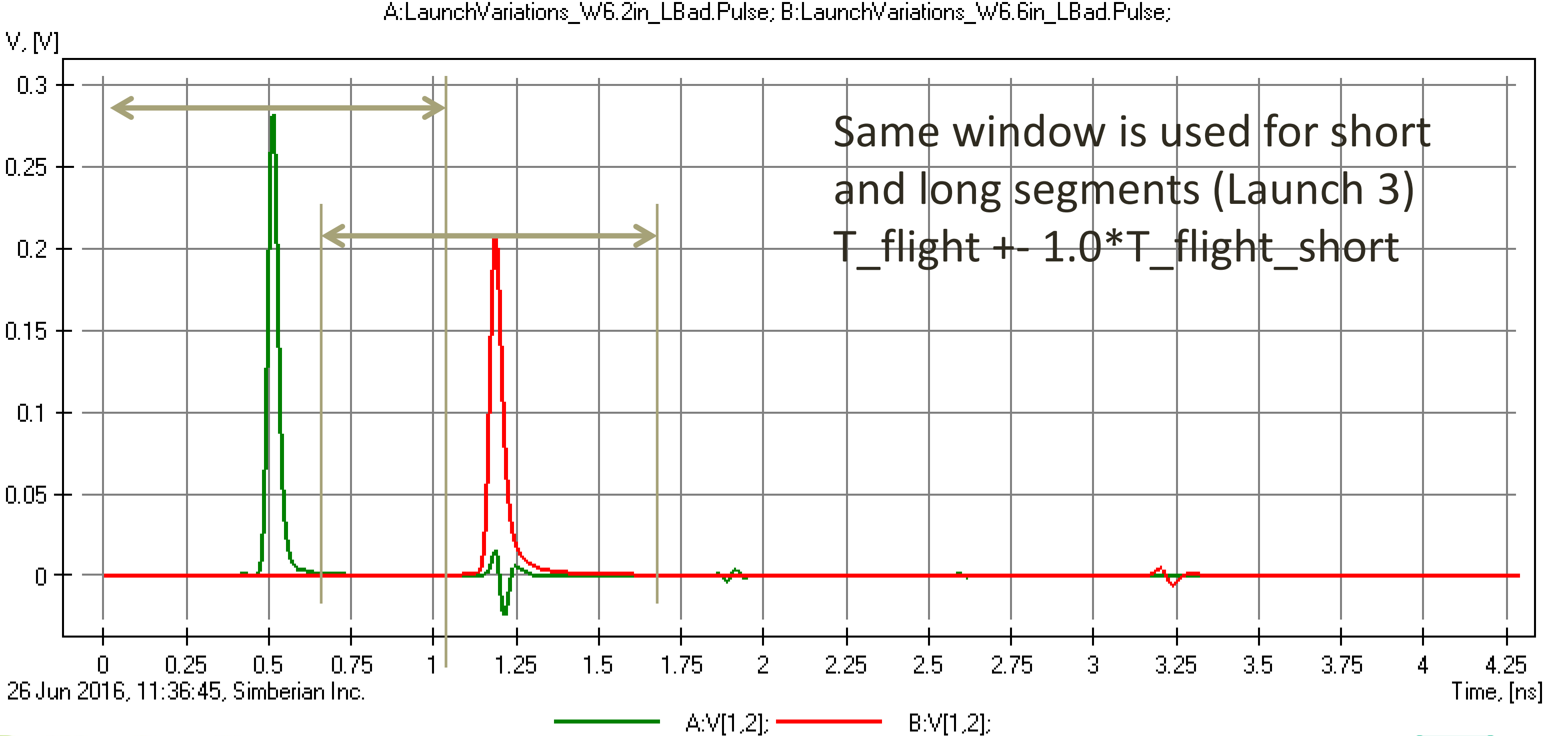
Gamma extraction from TDT without windowing





Windowing to eliminate double reflections (de-embedding)



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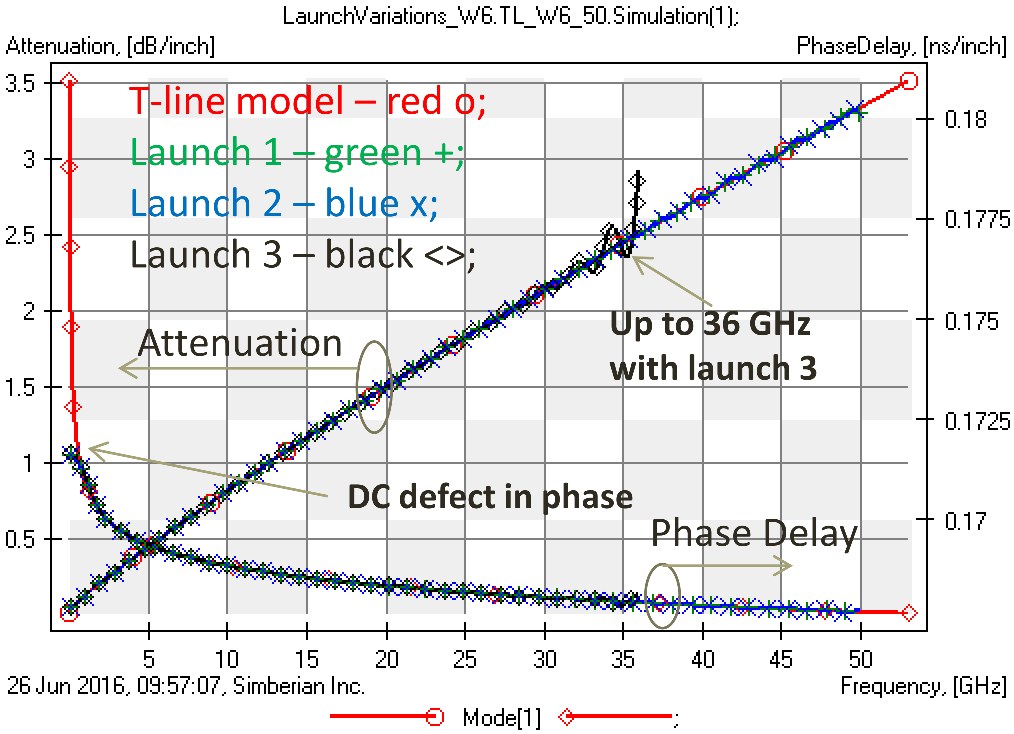
Gamma extraction from TDT with windowing



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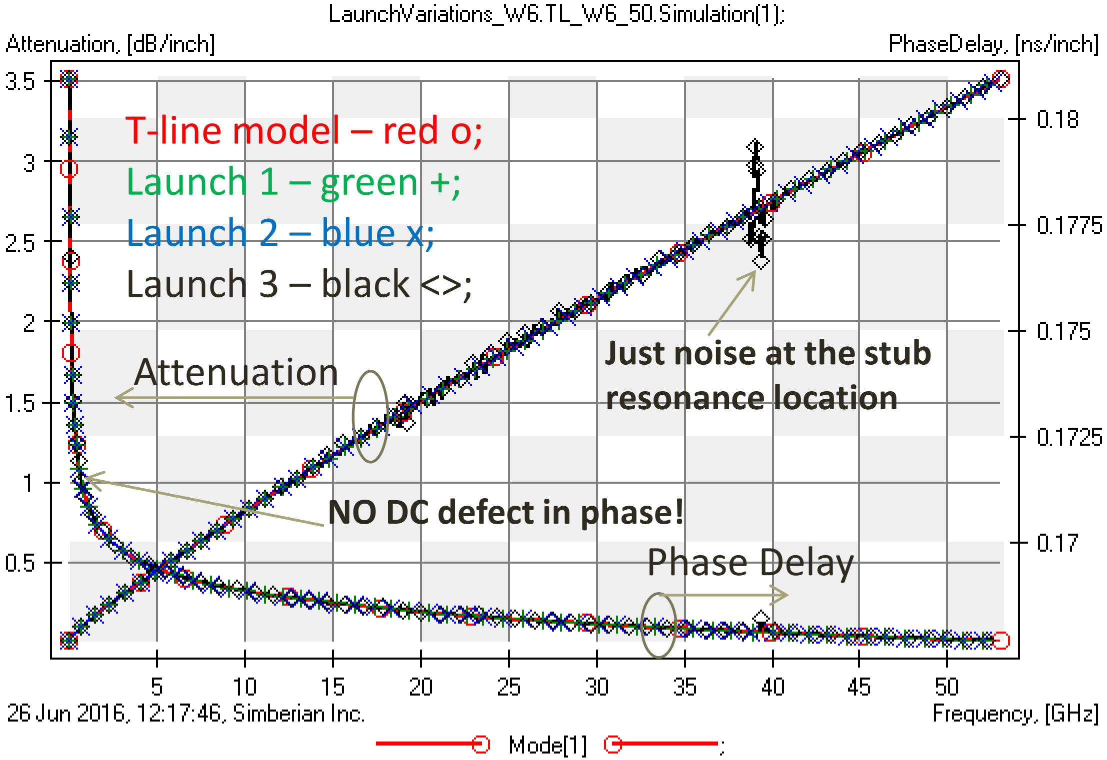
Gamma extraction from S-parameters



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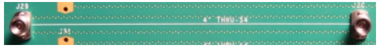
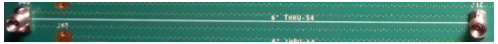
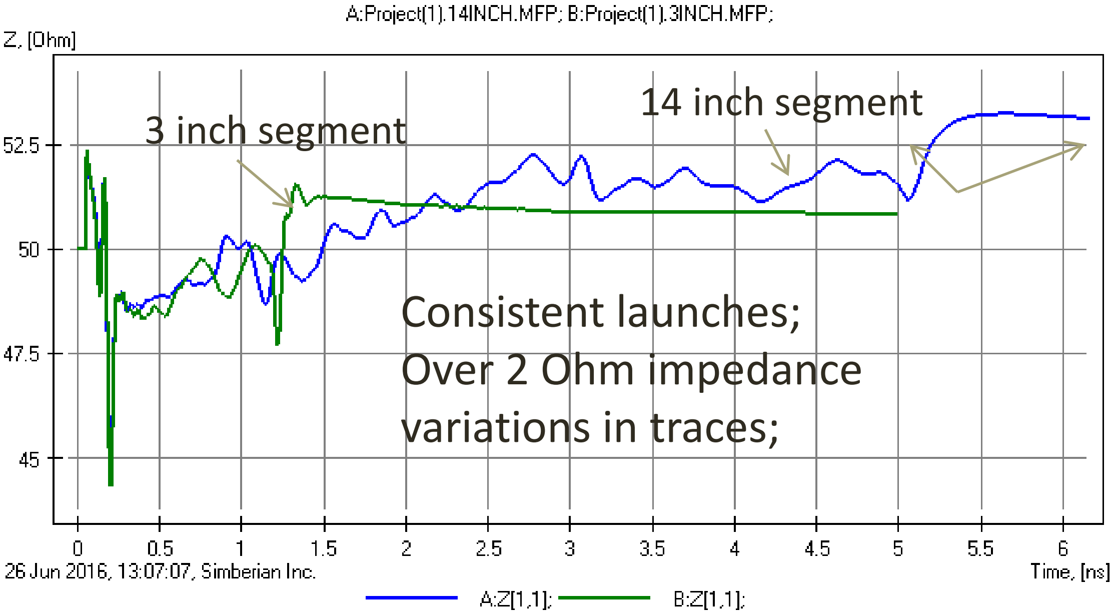
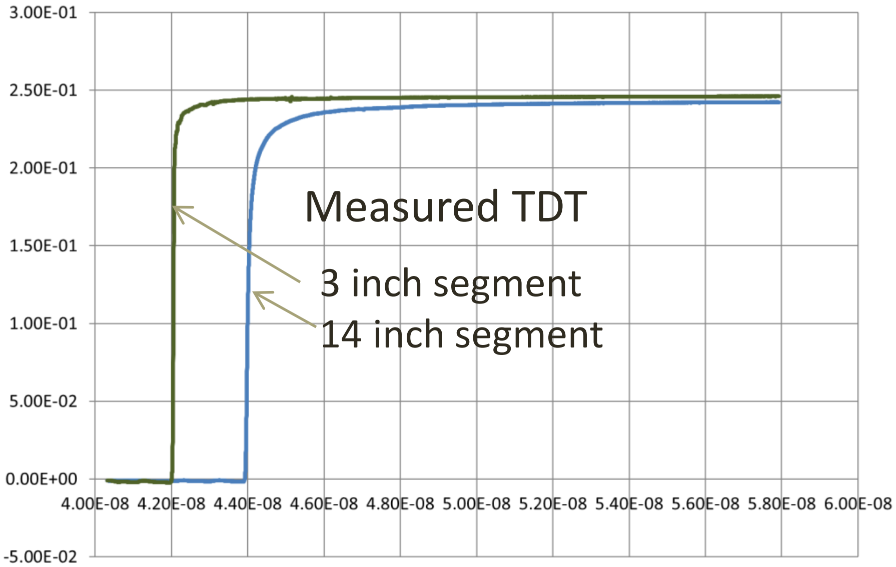
Test board with SMA connectors - TDR

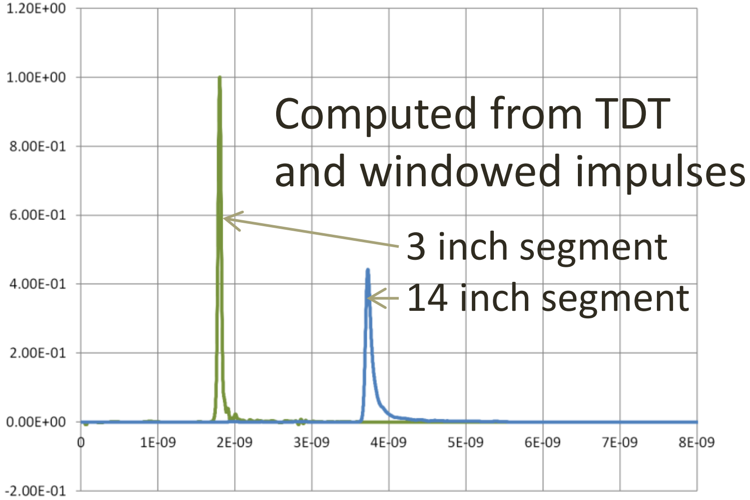






Test board with SMA connectors – TDT measurement





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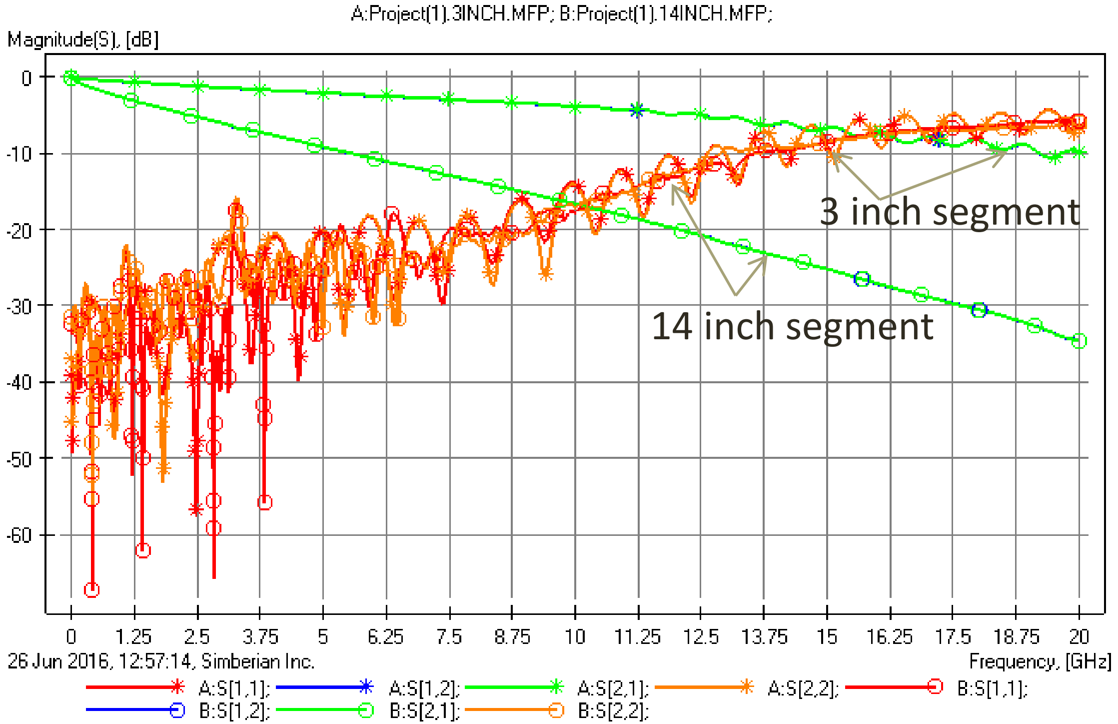
Test board with SMA connectors – S-parameters measurements



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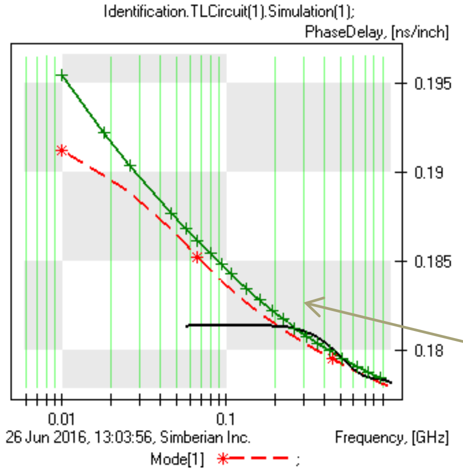
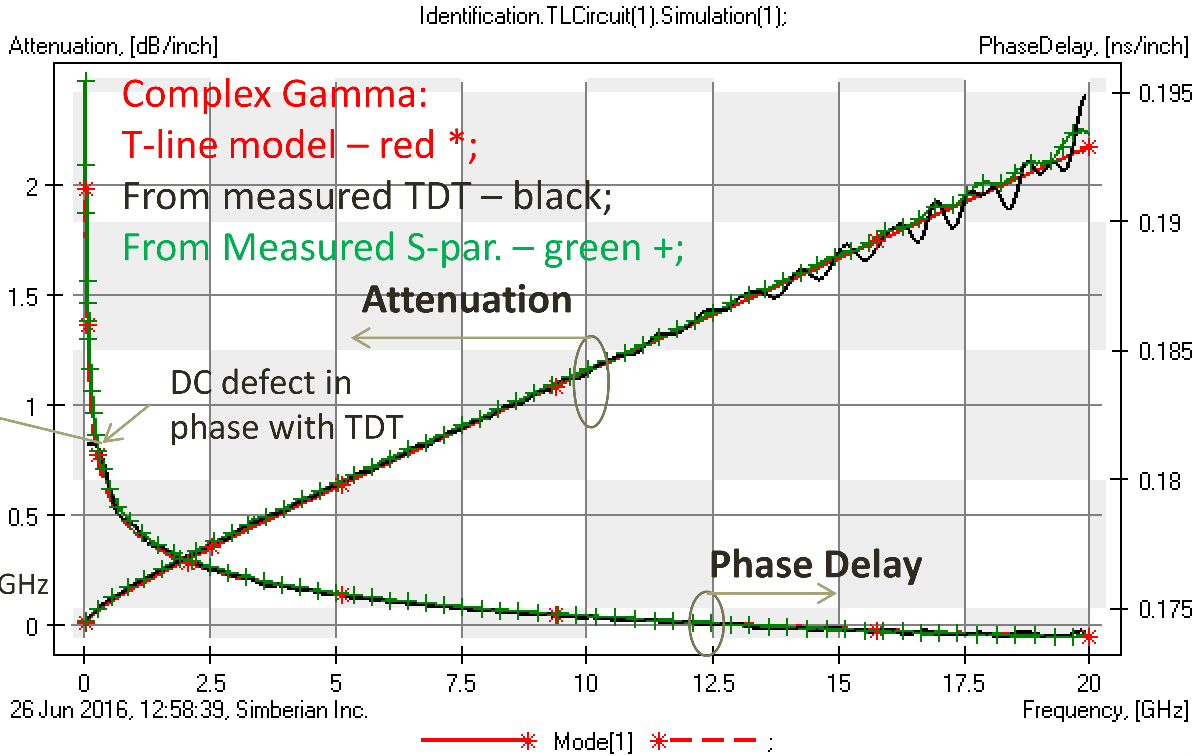
 10/24/2016

Identification on test board with SMAs

DC defect





Dielectric: WD, Dk=4.33, LT=0.017 @ 0.5 GHz
Roughness: MHCC, SR=0.3, RF=2

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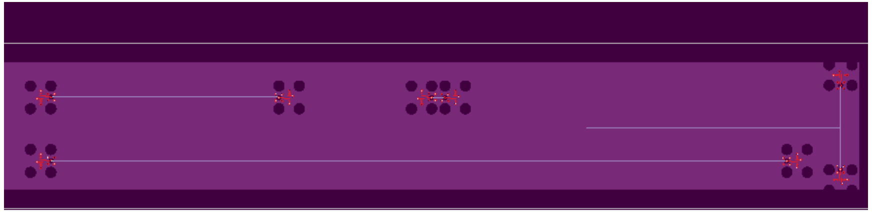
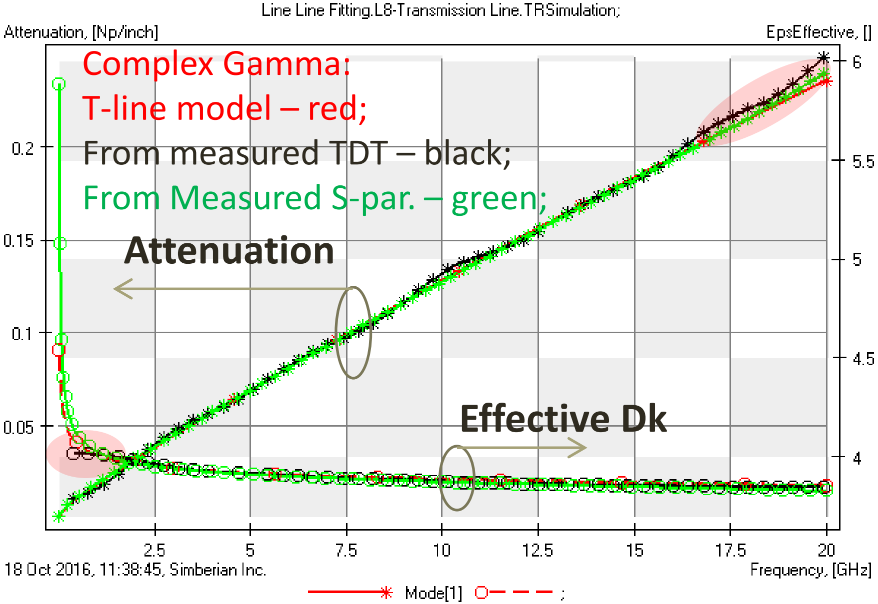
Identification on test board with **hand-held probes**

Roughness

Dielectric (WD)

- Materials: T=20[°C],...
  - "COPPER", RR=1, SR=0.575, RF=2.392, RM=MHCC
  - "Air"
  - "Insulator(1)", Dk=3.93326, LT=0.0133, PLM=WD, Dk(0)=4.46, Dk(inf)=3.69
  - "Insulator(2)", Dk=3.68, LT=0.013, PLM=WD, Dk(0)=4.17, Dk(inf)=3.47
- StackUp: LU=[mil], NL=10, T=61.28[mil]
  - 1| Signal: "TOP", T=2.1, Ins="Air", Cond="COPPER"
  - 2| Medium: T=4.18, Ins="Insulator(1)", DIE_002
  - 3| Plane: "L2_GND1", Cond="COPPER", T=1.25, Ins="Insulator(1)"
  - 4| Medium: T=6, Ins="Insulator(1)", DIE_004
  - 5| Signal: "L3_SIG1", T=1.25, Ins="Insulator(1)", Cond="COPPER"
  - 6| Medium: T=5.38, Ins="Insulator(1)", DIE_006
  - 7| Plane: "L4_GND2", Cond="COPPER", T=1.25, Ins="Insulator(1)"
  - 8| Medium: T=4, Ins="Insulator(1)", DIE_008
  - 9| Plane: "L5_PWR", Cond="COPPER", T=1.25, Ins="Insulator(1)"
  - 10| Medium: T=7.47, Ins="Insulator(1)", DIE_010
  - 11| Plane: "L6_PWR", Cond="COPPER", T=1.25, Ins="Insulator(1)"
  - 12| Medium: T=4, Ins="Insulator(1)", DIE_012
  - 13| Plane: "L7_GND3", Cond="COPPER", T=1.2, Ins="Insulator(1)"
  - 14| Medium: T=5.6, Ins="Insulator(1)", DIE_014
  - 15| Signal: "L8_SIG2", T=1.2, Ins="Insulator(1)", Cond="COPPER"
  - 16| Medium: T=6, Ins="Insulator(1)", DIE_016
  - 17| Plane: "L9_GND4", Cond="COPPER", T=1.2, Ins="Insulator(2)"
  - 18| Medium: T=4.5, Ins="Insulator(1)", DIE_018
  - 19| Signal: "BOTTOM", T=2.2, Ins="Air", Cond="COPPER"





Very inexpensive and quick!

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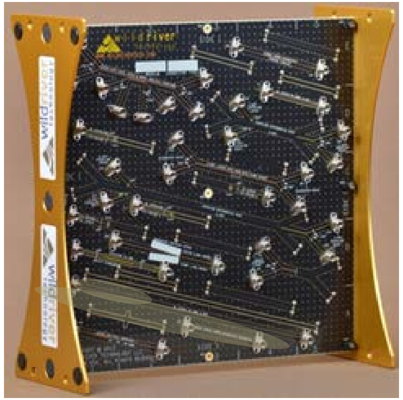
Identification on CMP-28

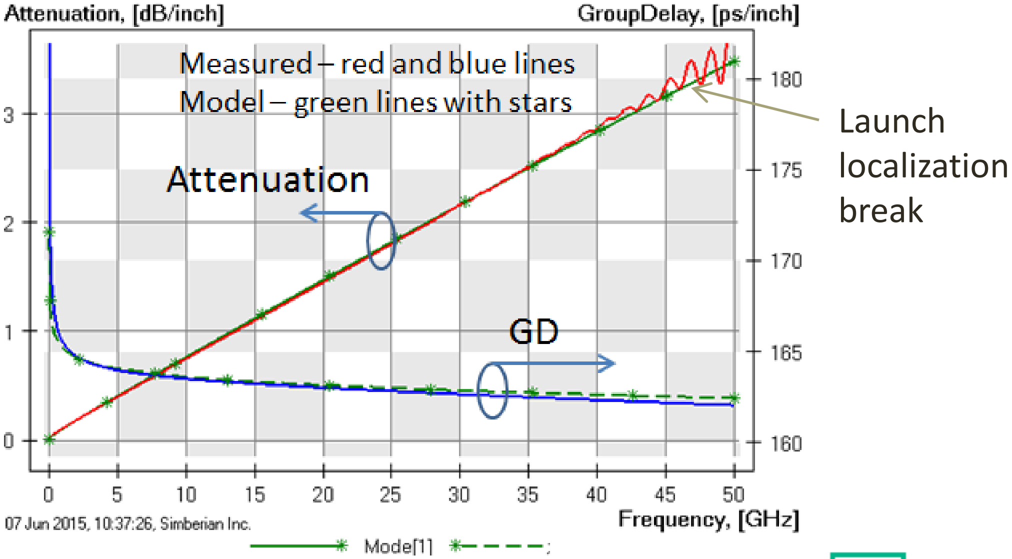
- Dielectric: Wideband Debye dielectric model with Dk=3.8 (3.66), LT=0.0117 @ 1 GHz;
- Conductor roughness: modified Hammerstad model with SR=0.32 um, RF=3.3

Models are usable even above 50 GHz!



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

Complex Gamma (SPP Light with S-parameters)



Simbeor EDA Kit (complete validation process):
http://www.simberian.com/Presentations/CMP-28_Simbeor_Kit_Guide.pdf

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Conclusion

- SPP technique has advantages over more complicated de-embedding techniques or simplistic like Delta-L – standardized, inexpensive, extendable, accurate, usable at design and manufacturing stages,…
  - SPP technique can be simplified from 9 to 4 steps (SPP Light)
  - SPP Light with S-parameters removes reflections and extends frequency range of SPP up to 50 GHz for PCB applications
- Further work – investigate sensitivity and improve dielectric and conductor roughness model separation with additional test structures

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