Cost-effective PCB Material Characterization for High-volume Production Monitoring

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Hewlett Packard Enterprise

Simberian
Electromagnetic Solutions

Issues for high-volume production

Want to know the statistics of the process variations

With

- Easy / Fast to measure
- Accurate enough
- Identifying the material model
- Readily deployable
- Guide the manufacturers to adjust the process

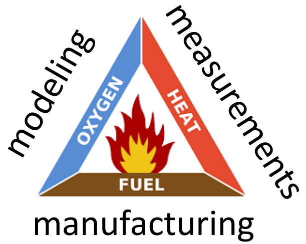
Outline

- Introduction
- Material models
- Broadband model identification with Gamma-T
  - T-resonator technique – Dk and LT extraction at low frequency
  - Gamma extraction from TDT or S-parameters
  - Model identification with field solver
- Sensitivity to strip width variations
- Sensitivity to test fixture
- Examples of low-cost practical model identification
- Conclusion

Introduction

- Design of PCB and packaging interconnects for data links running at data rates 10-30 Gbps and beyond is challenging
  - Boards are not manufactured as designed
  - Making accurate measurements from DC to 20-50 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 material characterization technique must be used at the material model identification and production validation stages

Objectives for the material characterization process

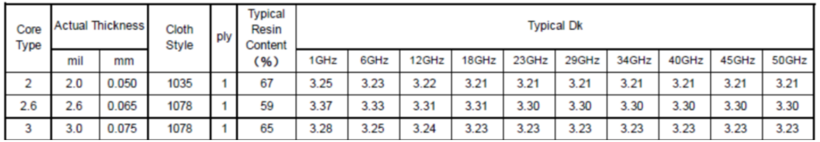
- Space efficient structure on PCB – t-line segments only;
- Time domain method using existing factory testing infrastructure (TDR/TDR equipment with hand-held probes);
- High throughput method using handheld probe with TDR scope, no time consuming SMA mounting or VNA calibration;
- Limited cross-sectioning needed, identification method should tolerate geometric variations – limited cross-sectioning;
- Separate dielectric and conductor roughness effects;
- Complement SET2DEL to help identify material properties once the loss exceed target spec;
- Utilize accurate low-cost EDA tools to design test fixture and do the material model identification;
- Version with higher accuracy and bandwidth for validation purpose;

Possible characterization options

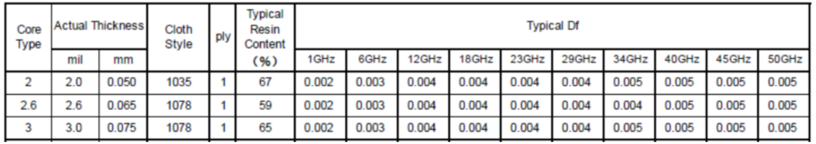
- SET2DIL – pass/fail at a set of frequency points, no material model
- Delta-L – uncertainty due to dependency on all reflections, uses S-parameters (requires VNA + measurement skills), no material model
- Complete de-embedding (TRL, AFR, ISD,…) – unnecessary complicated – VNA, test fixture S-parameters are not needed,…
- Short Pulse Propagation (SPP) – standardized by IPC (IPC-TM-650 #2.5.5.12), but too many steps, large structures, expensive equipment,
  - Possible improvements (SPP Light) suggested at EPEPS’2016 (Shlepnev, Choi, Cheng, Damgaci)
  - Has low-frequency defect preventing separation of conductor and dielectric losses
- Identification with GMS-parameters – similar to SPP Light with S-parameters (EPEPS’2015, Shlepnev…);
- T-resonator – simple, uses either TDT or S-parameters, Dk and LT at a few points
- Combine identification with Gamma (from SPP or GMS-parameters) extraction and T-resonator and build hybrid technique (Gamma-T)

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)

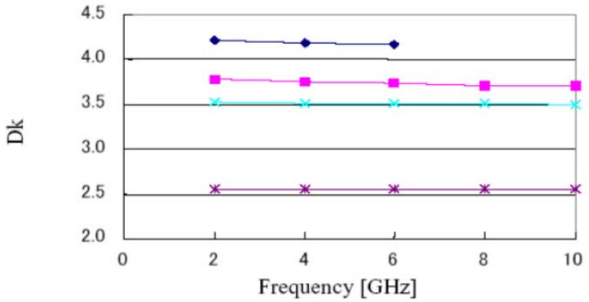


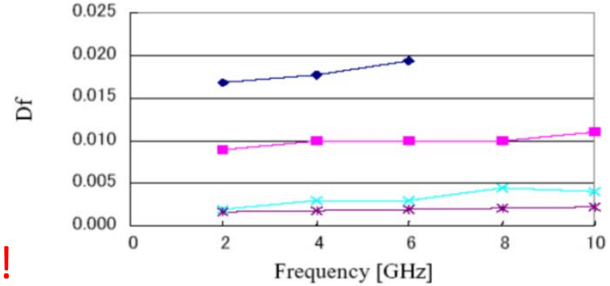
Core Type	Actual Thickness		Cloth Style	ply	Typical Resin Content (%)	Typical Dk									
	mil	mm				1GHz	6GHz	12GHz	18GHz	23GHz	29GHz	34GHz	40GHz	45GHz	50GHz
2	2.0	0.050	1035	1	67	3.25	3.23	3.22	3.21	3.21	3.21	3.21	3.21	3.21	3.21
2.6	2.6	0.065	1078	1	59	3.37	3.33	3.31	3.31	3.30	3.30	3.30	3.30	3.30	3.30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

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

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

- **PCB conductor surface roughness models:**

Modified Hammerstad (2 parameters):

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

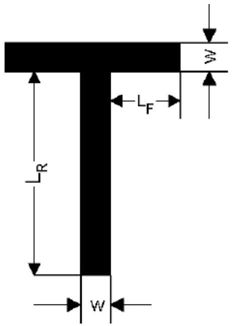
Huray snowball (1-ball, 2 parameters):

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

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

T-resonator technique

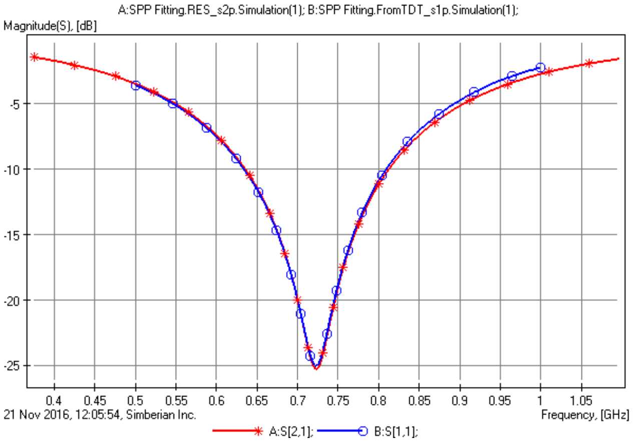
- Dk and LT identification at one frequency point



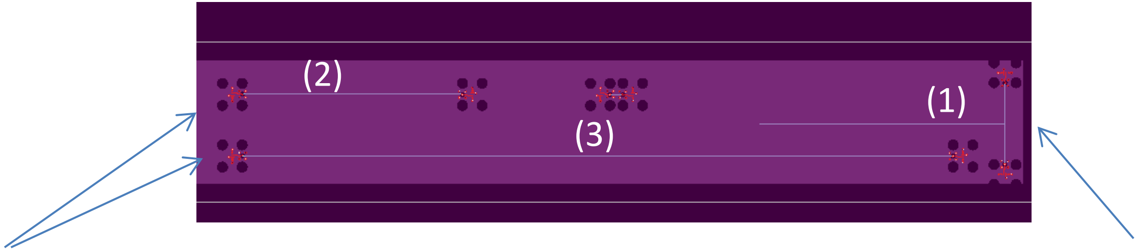
$$\alpha_T = \alpha_C + \alpha_d$$

$$\frac{1}{Q_T} = \frac{1}{Q_C} + \frac{1}{Q_d}$$

$$tan\delta = \frac{1}{Q_T} - \frac{1}{Q_C}$$



Gamma-T technique



- 2 transmission lines with identical launches and cross-sections and different lengths;
- About 1:3 line length difference, short line length defines lowest frequency;

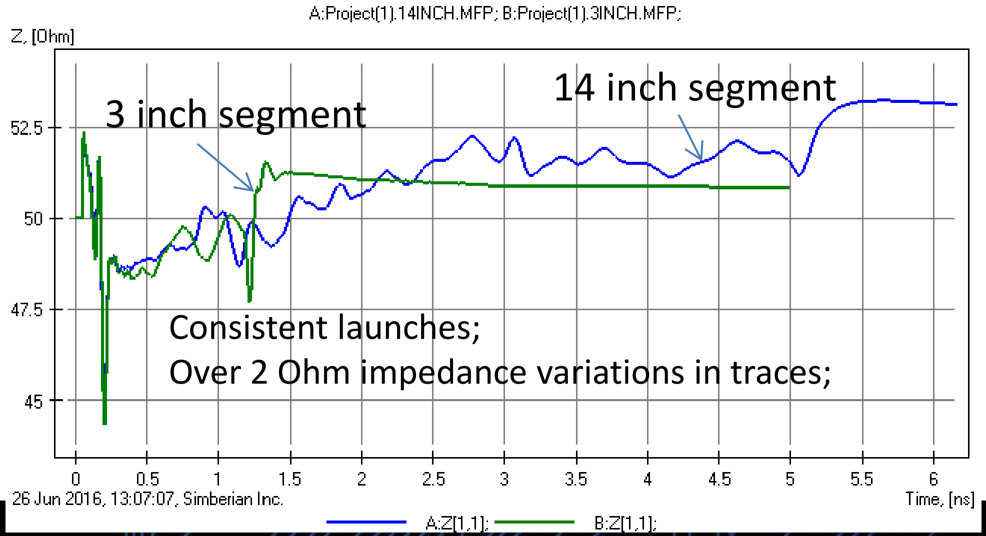
- T-resonator with resonance frequency about 500 MHz;

- Single-ended or differential, strip or microstrip;
- Launches for hand-held probes (production/cost-effective) or regular probes or SMA connectors (lab/precise);
- Use TDR/TDT (production/cost-effective) or S-parameter measurements (lab/precise) to extract complex propagation constant Gamma;
- Identify LT at 500 MHz with the T-resonator and use it to define Wideband Debye dielectric model;
- Identify Dk at 500 MHz for Wideband Debye model and conductor roughness model parameters by matching measured and simulated Gammas;

Identification with Gamma-T: Step 1

- **Cost-effective:** Measure TDR and TDT step responses of line segments
- **Precise:** Measure S-parameters of line segments and compute TDR
- Select responses of two segments with the close TDR impedances – < 5 Ohm for 20 GHz, < 3 Ohm for 50 GHz frequency bandwidth;

Example of pre-qualification on test board;



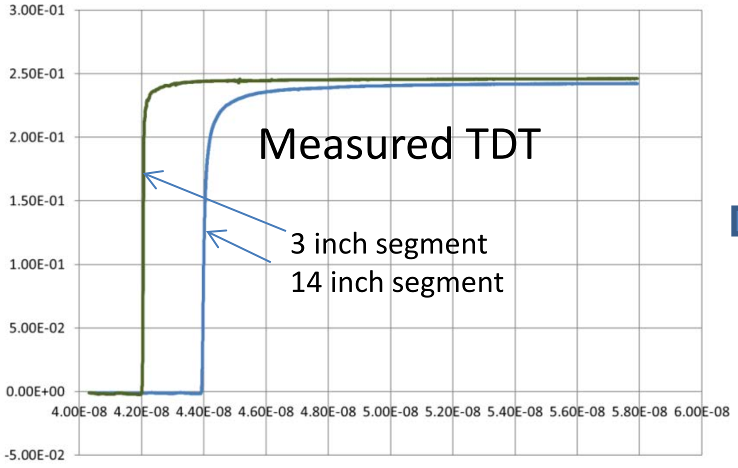
3 inch segment

14 inch segment

Consistent launches;
Over 2 Ohm impedance variations in traces;

Identification with Gamma-T: Step 2

- **Cost-effective:** Convert TDT into short pulse response, window it and extract Gamma following the SPP technique

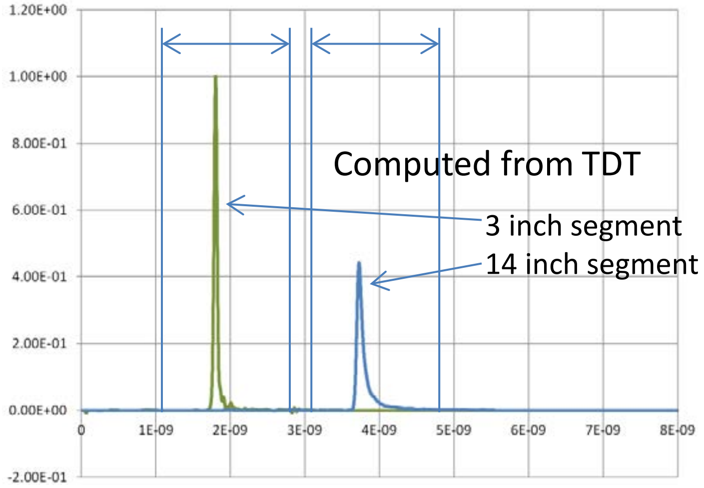


Measured TDT

3 inch segment

14 inch segment

Same window is used for short and long segments: T_flight +- 1.0*T_flight_short



Computed from TDT

3 inch segment

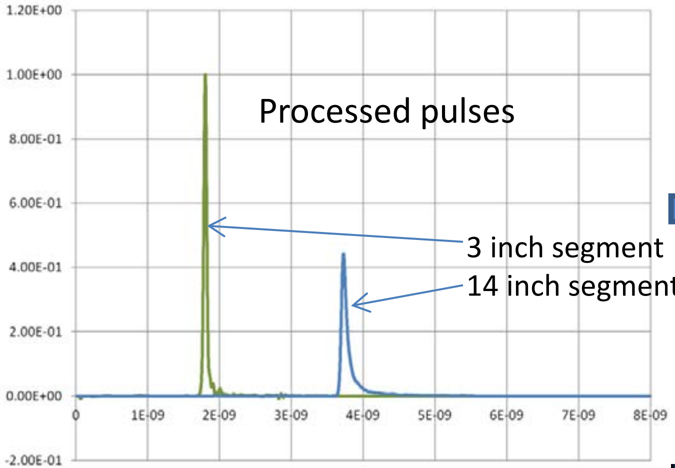
14 inch segment

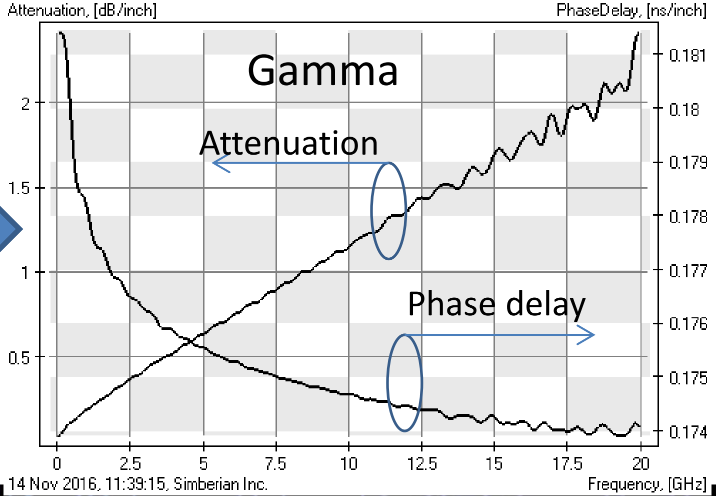
Identification with Gamma-T: Step 2

- **Cost-effective:** Convert TDT into short pulse response, window it and extract Gamma following the SPP technique

$$\Gamma(f)=\alpha(f)+i\beta(f)=\frac{1}{\Delta L}\ln\left(\left|\frac{V_{long}(f)}{V_{short}(f)}\right|\right)+i\cdot\frac{1}{\Delta L}\arg\left(\frac{V_{long}(f)}{V_{short}(f)}\right)$$

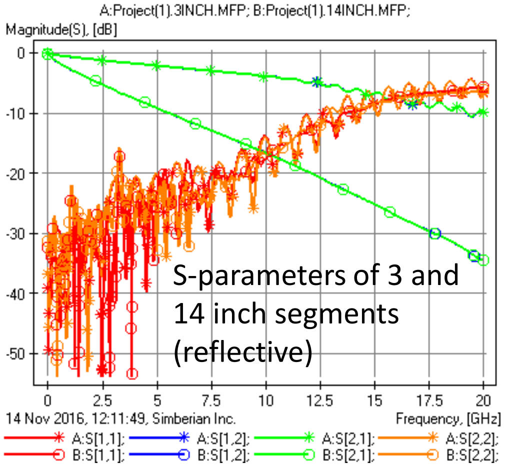
$$V(f)=fft\left(V(t)\right)$$



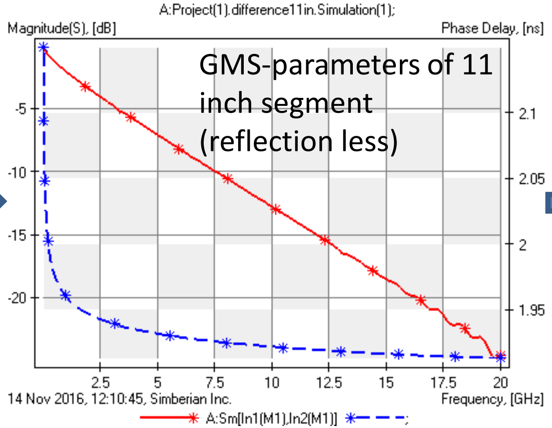


Identification with Gamma-T: Step 2

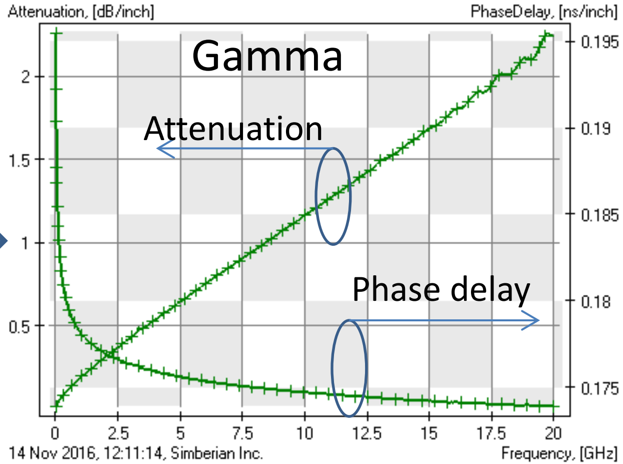
- **Precise:** Extract Gamma from GMS-parameters computed from S-parameters of two segments (EPEPS’2015, Shlepnev);



S-parameters of 3 and 14 inch segments (reflective)



GMS-parameters of 11 inch segment (reflection less)



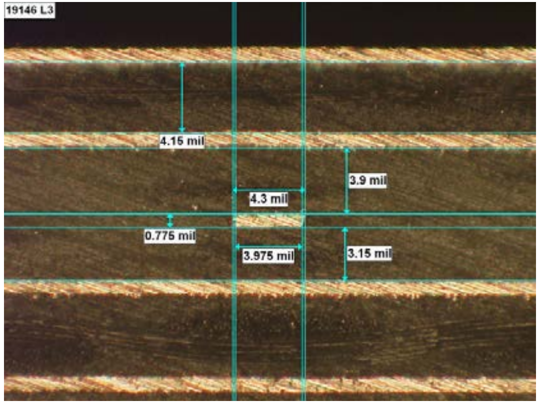
Gamma

Attenuation

Phase delay

Identification with Gamma-T: Step 3

- Optionally, cross-section the board traces and measure the dimensions, to improve accuracy

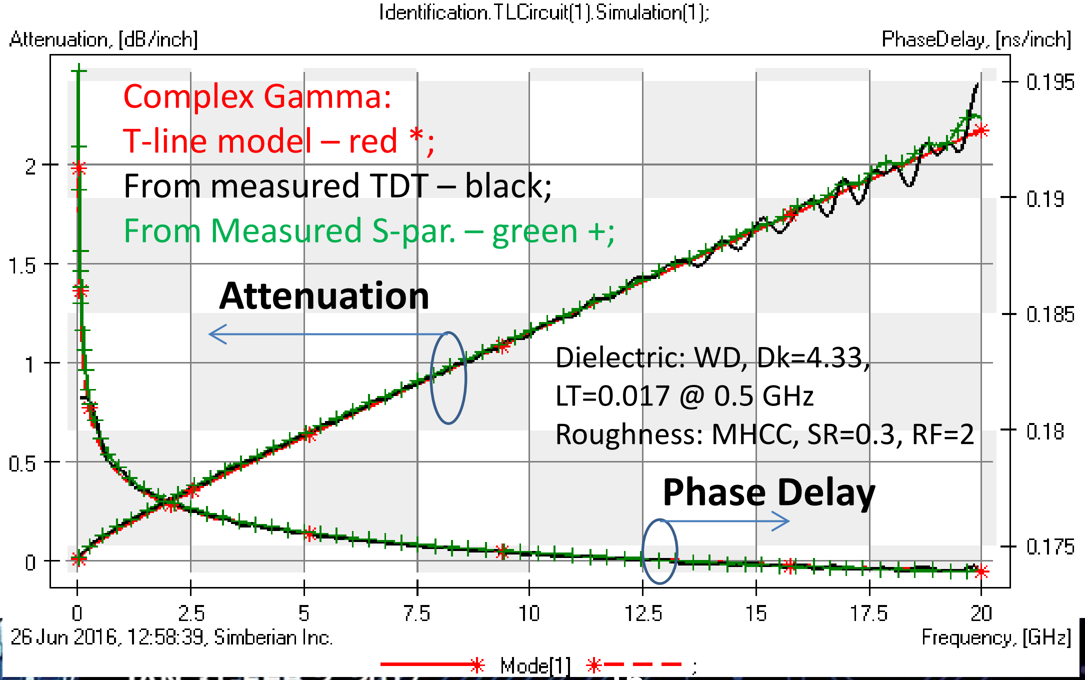


One cross-sectioning per batch

Identification with Gamma-T: Step 4

- Use field solver to build cross-section model matching Gamma extracted in step 2
  - Use LT from T-resonator to define Wideband Debye model
  - Adjust Dk to match phase delay, adjust roughness model parameters to match insertions loss

Example of identification with Gamma-T (cost-effective and precise)



Complex Gamma:
T-line model – red *;
From measured TDT – black;
From Measured S-par. – green +;

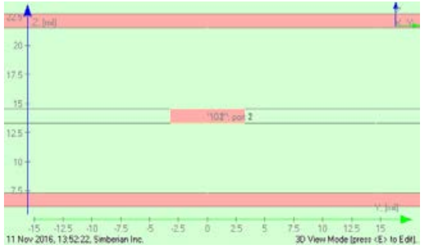
Attenuation

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

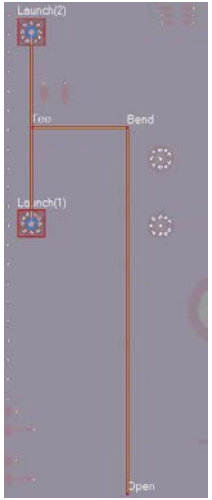
Phase Delay

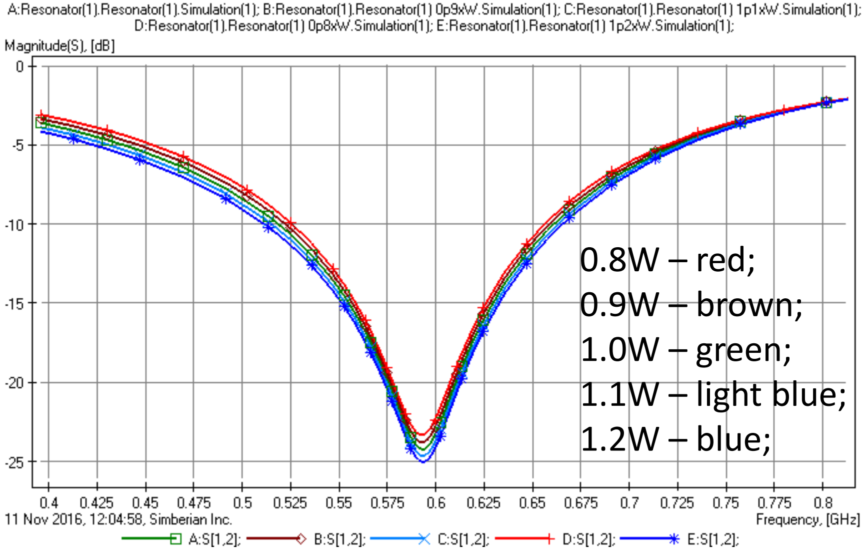
T-resonator sensitivity to strip width

Strip line in dielectric with Dk=4.1135, LT=0.02176 @ 1 GHz;
W=6.5 mil, t=1.2 mil; distance to top plane 7 mil, to bottom 6 mil;
Resonance at 593 MHz



Strip line in dielectric with Dk=4.1135, LT=0.02176 @ 1 GHz;
W=6.5 mil, t=1.2 mil; distance to top plane 7 mil, to bottom 6 mil;
Resonance at 593 MHz



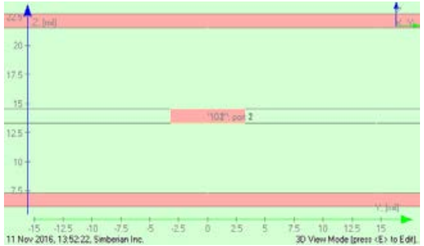


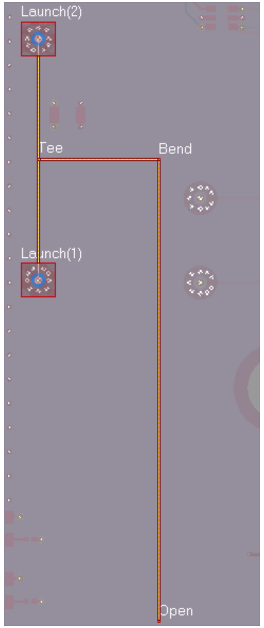
0.8W – red;
0.9W – brown;
1.0W – green;
1.1W – light blue;
1.2W – blue;

T-resonator sensitivity results

- Calculated loss tangent values @593Mhz (actual value is 0.021536)
- W=6.5 mil

strip width	LT	variation
0.8W	0.0196	2.60%
0.9W	0.0195	2.10%
1.0W	0.0191	0%
1.1W	0.0195	2.10%
1.2W	0.0195	2.10%

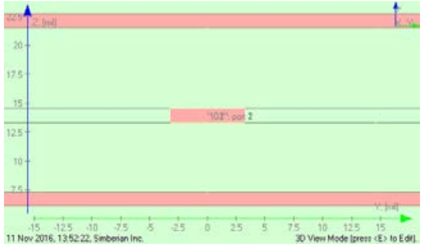




- When the width variation is 20%, the loss tangent at the resonant frequency is within 2.5% variation, or about 0.05 dB/inch at 20 GHz

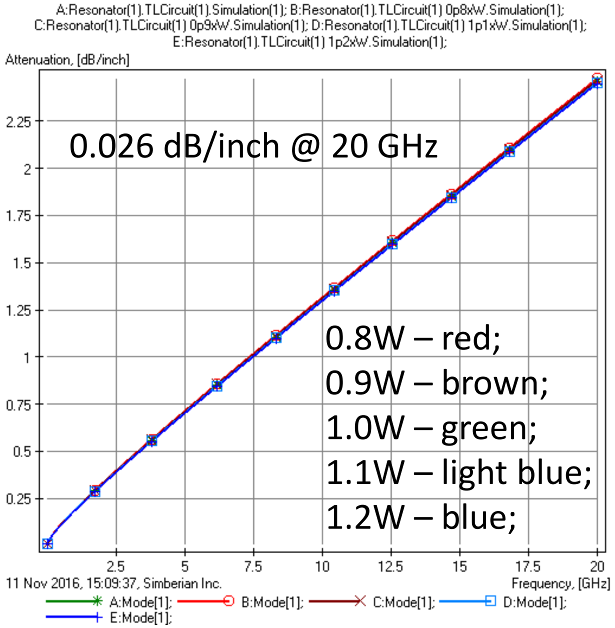
Sensitivity of identification with Gamma to strip width

Strip line in dielectric with Dk=4.1135, LT=0.02176 @ 1 GHz;
W=6.5 mil, t=1.2 mil; distance to top plane 7 mil, to bottom 6 mil;
Wideband Debye model defined @ 1 GHz;



strip width	LT	variation
0.8W	0.02197	+0.97%
0.9W	0.02185	+0.42%
1.0W	0.02176	0%
1.1W	0.02171	-0.24%
1.2W	0.02163	-0.58%

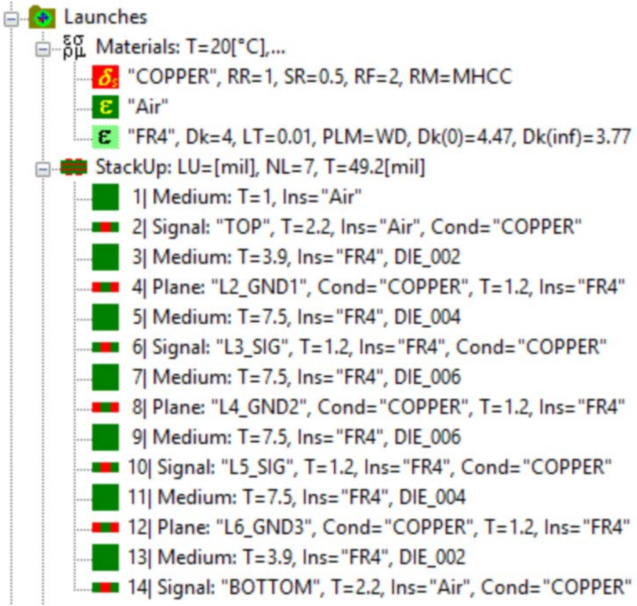
When the width variation is 20%, the loss tangent at 1 GHz is within 1% variation, or about 0.026 dB/inch at 20 GHz



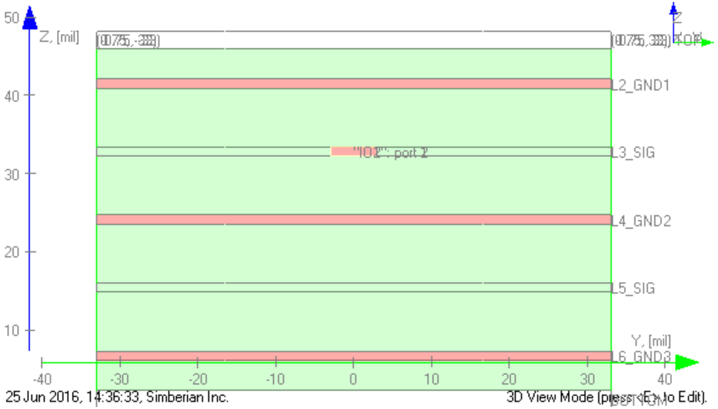
0.026 dB/inch @ 20 GHz

0.8W – red;
0.9W – brown;
1.0W – green;
1.1W – light blue;
1.2W – blue;

Sensitivity of identification with Gamma to launch design


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

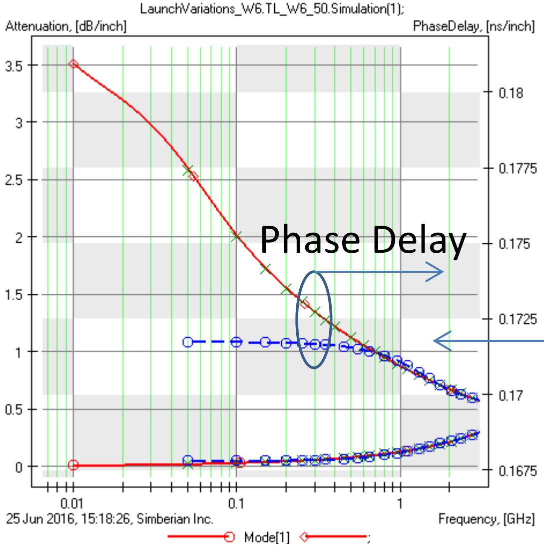


Dielectric: Wideband Debye, Dk=4, LT=0.01 @ 1 GHz;
Conductor roughness: MHCC, SR=0.5, RF=1

Modelled with Simbeor THz

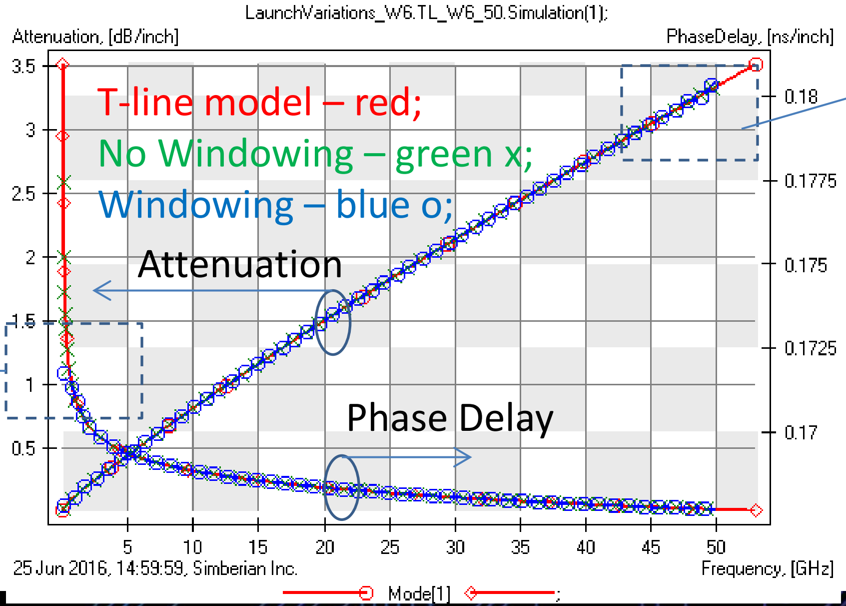
Gamma extraction from TDT – 2 and 6 inch segments, no launches

Windowing defect at low frequencies – wrong DC



Phase Delay

Windowing defect at high frequencies - oscillations



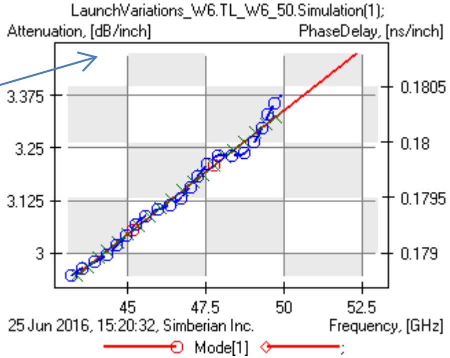
T-line model – red;

No Windowing – green x;

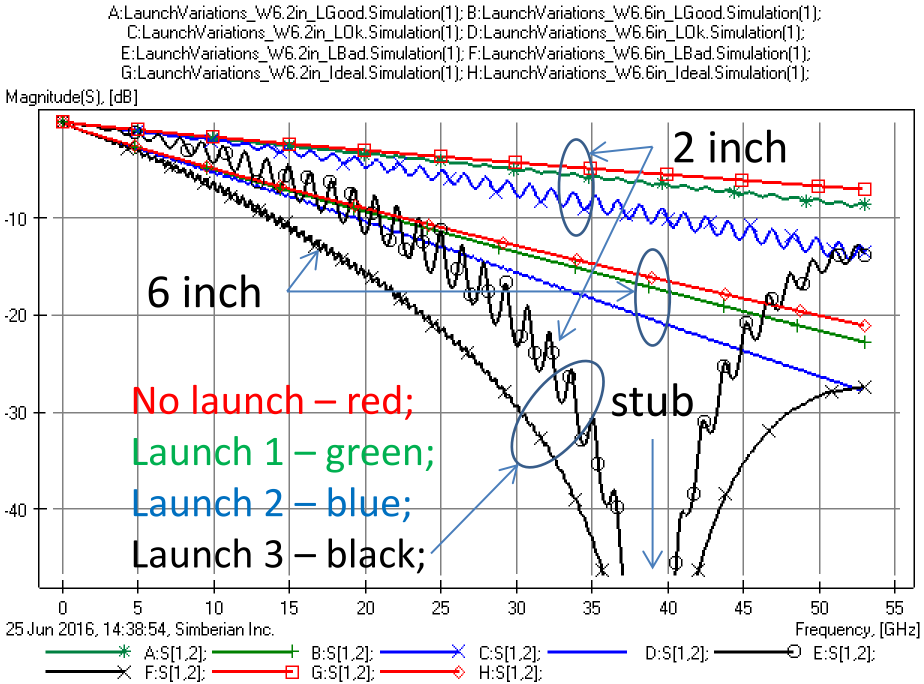
Windowing – blue o;

Attenuation

Phase Delay



3 test pairs with different launches



2 inch

6 inch

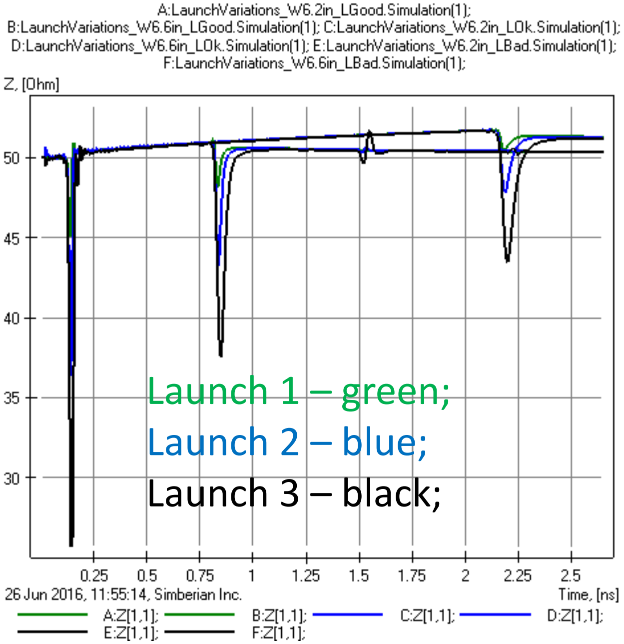
stub

No launch – red;

Launch 1 – green;

Launch 2 – blue;

Launch 3 – black;

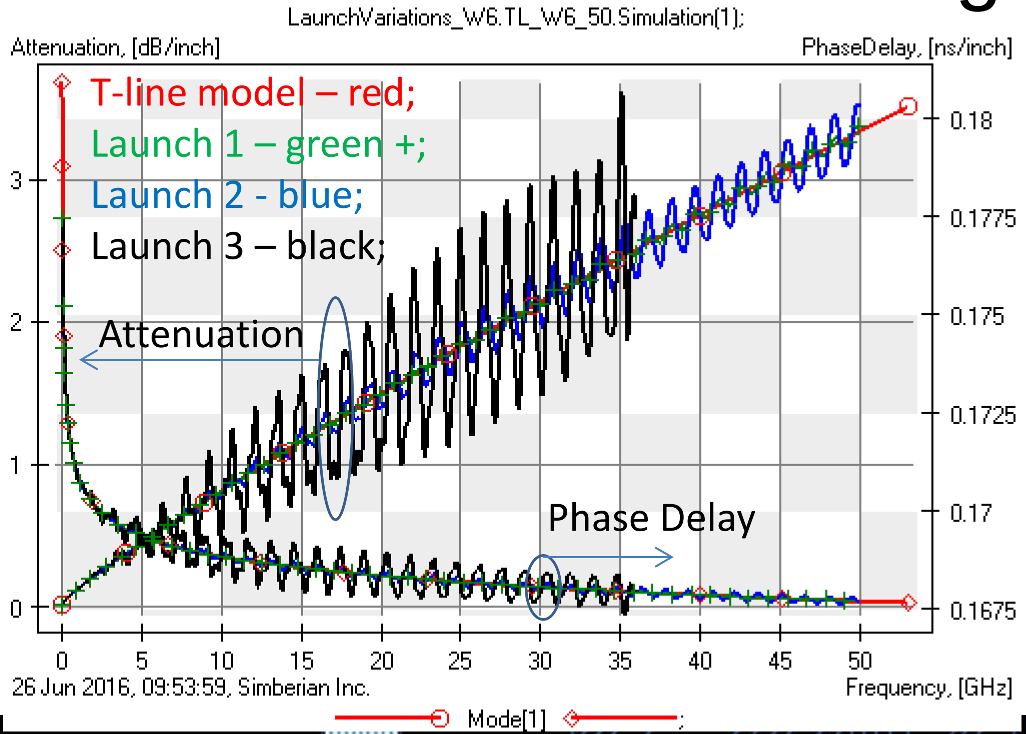


Launch 1 – green;

Launch 2 – blue;

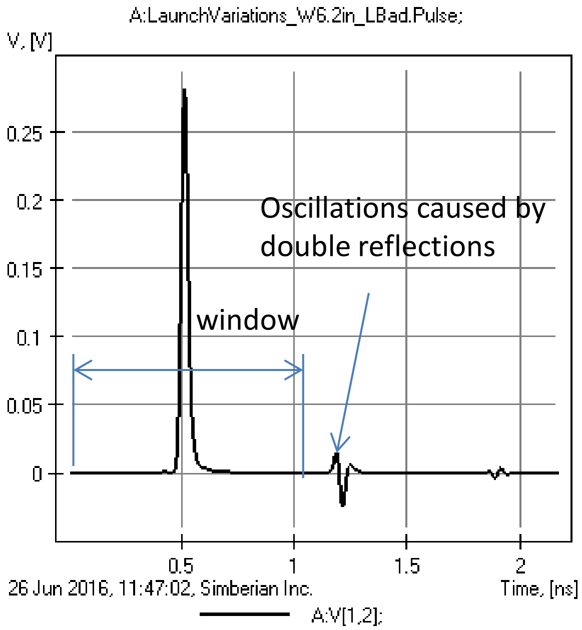
Launch 3 – black;

Gamma extraction from TDT without windowing


T-line model – red;
Launch 1 – green +;
Launch 2 - blue;
Launch 3 – black;

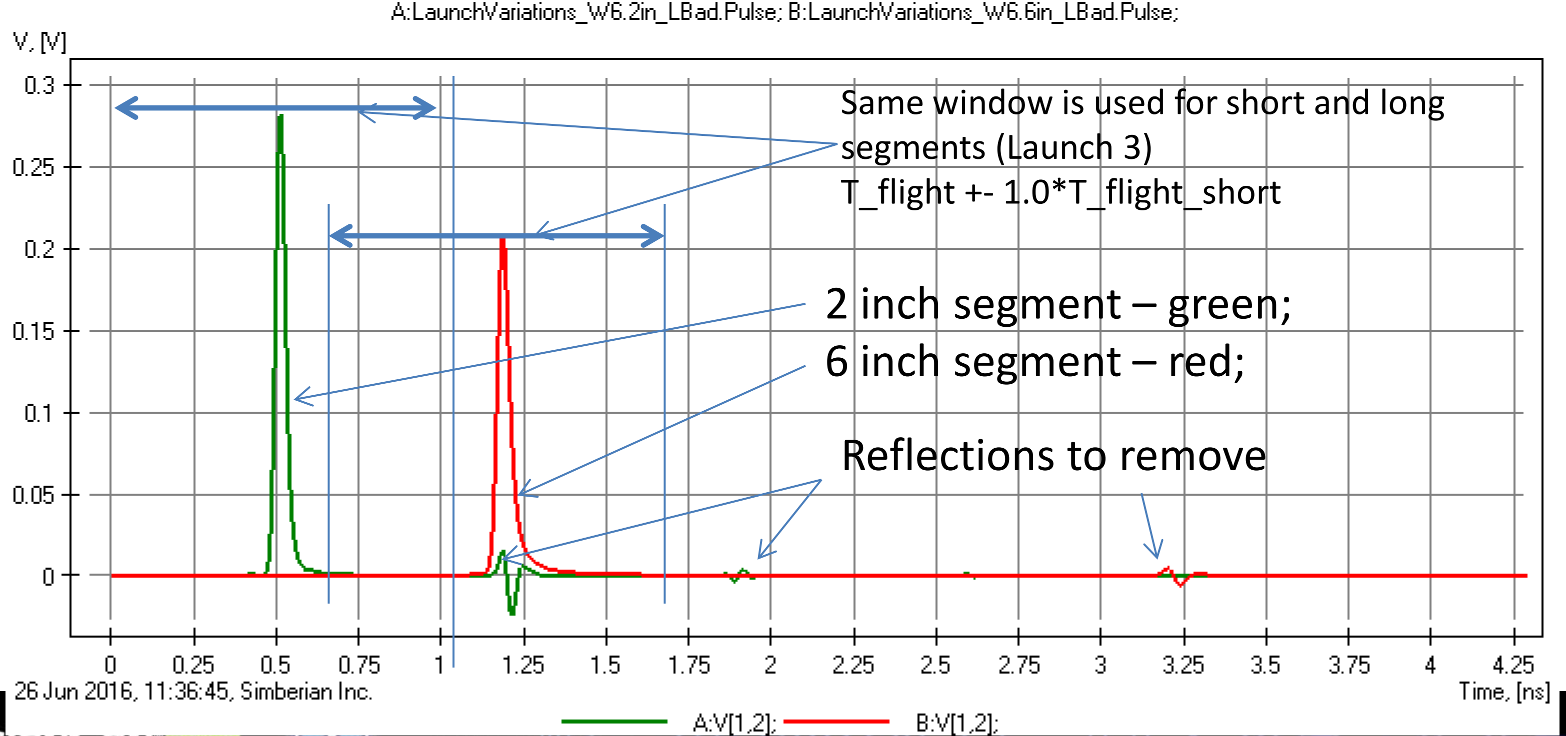
Attenuation

Phase Delay


Oscillations caused by double reflections

window

Windowing to eliminate double reflections (de-embedding)



Same window is used for short and long segments (Launch 3)

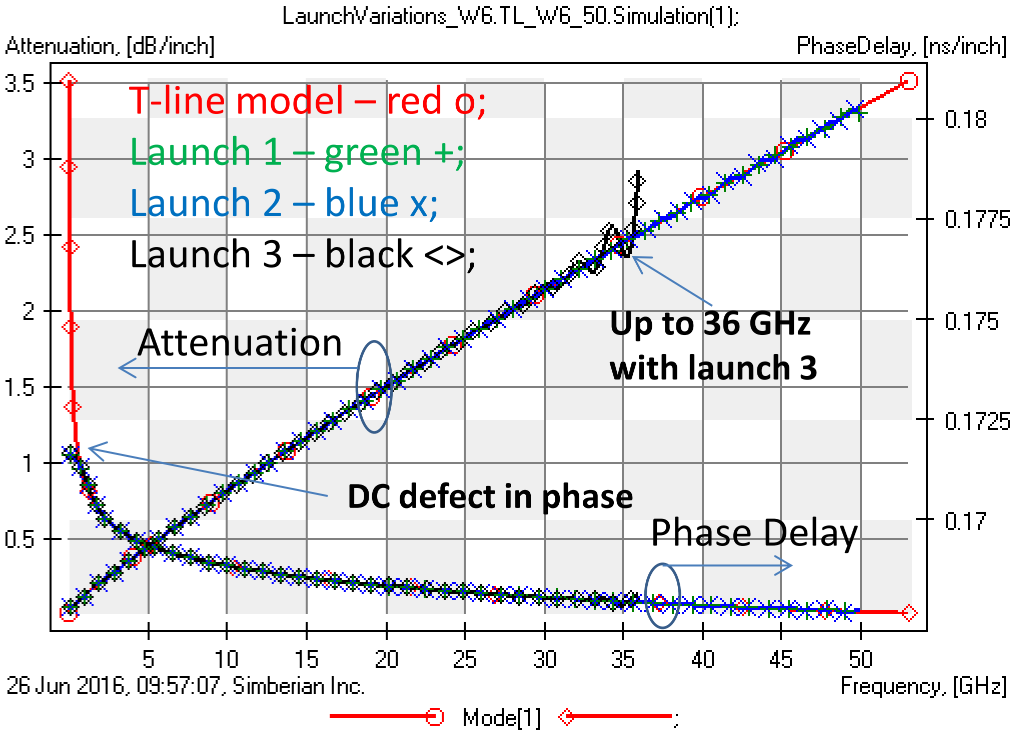
T_flight +- 1.0*T_flight_short

2 inch segment – green;

6 inch segment – red;

Reflections to remove

Gamma extraction from TDT with windowing



T-line model – red o;

Launch 1 – green +;

Launch 2 – blue x;

Launch 3 – black <>;

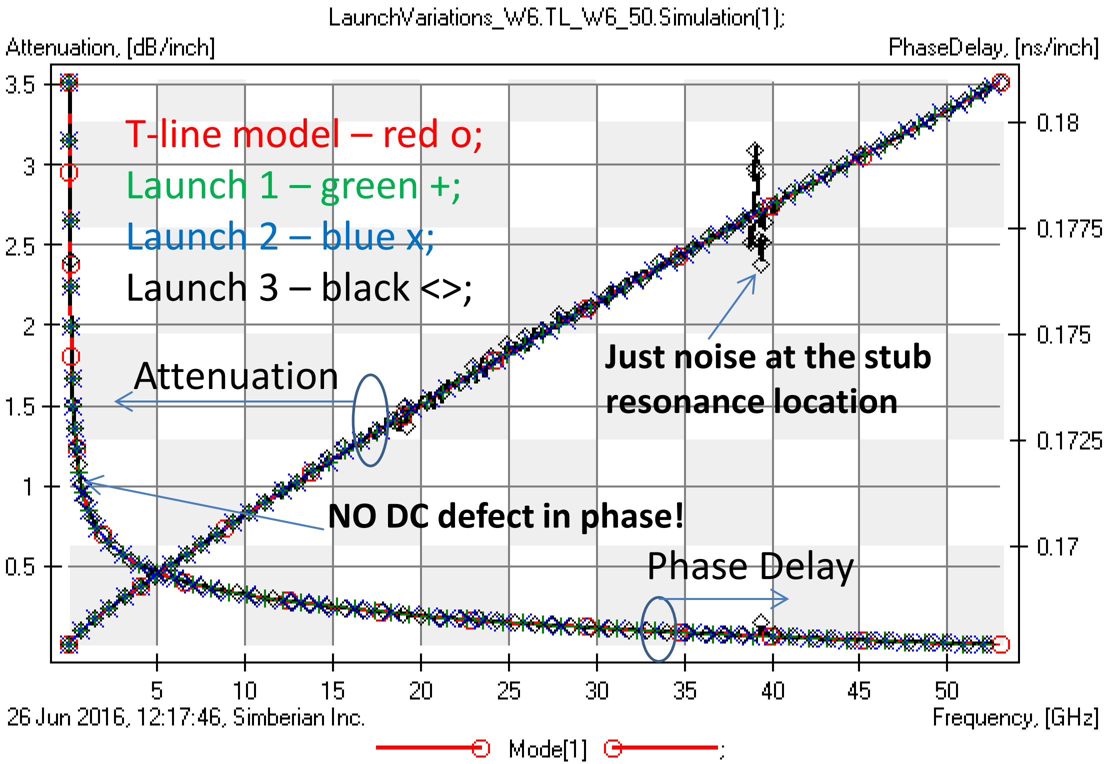
Attenuation

Up to 36 GHz with launch 3

DC defect in phase

Phase Delay

Gamma extraction from S-parameters



T-line model – red o;

Launch 1 – green +;

Launch 2 – blue x;

Launch 3 – black <>;

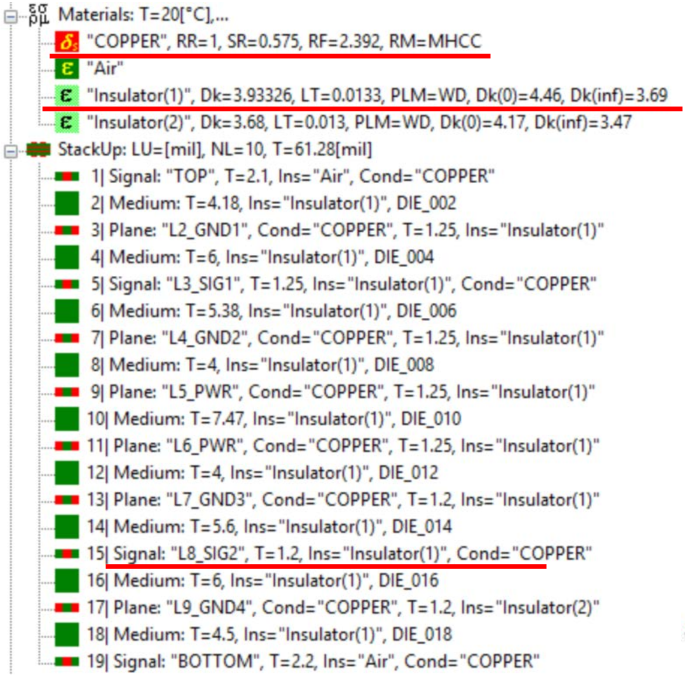
Attenuation

Just noise at the stub resonance location

NO DC defect in phase!

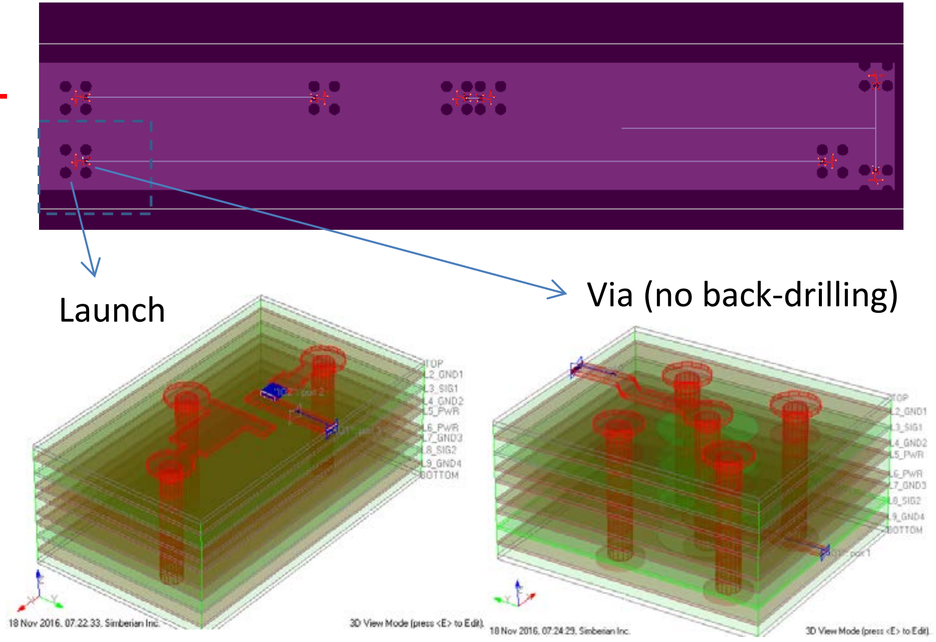
Phase Delay

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



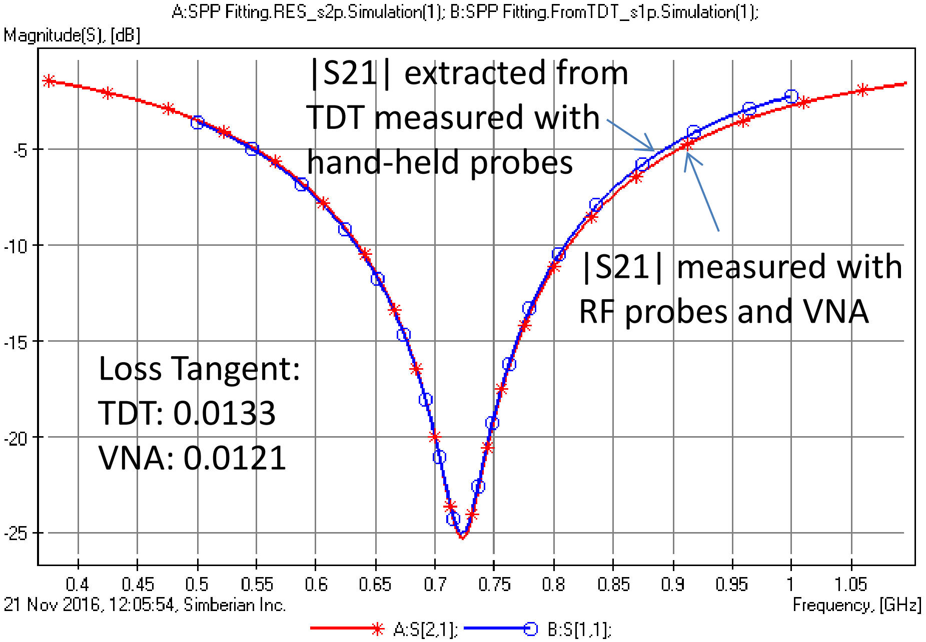
Materials: T=20[°C],...
- "COPPER", RR=1, SR=0.575, RF=2.392, RM=MHCC
- "Air"
- "Insulator(1)", Dk=3.93326, LT=0.0133, PLM=WD, Dk(0)=4.46, Dk(inf)=3.69
- "Insulator(2)", Dk=3.68, LT=0.013, PLM=WD, Dk(0)=4.17, Dk(inf)=3.47

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"


Launch

Via (no back-drilling)

T-resonator results

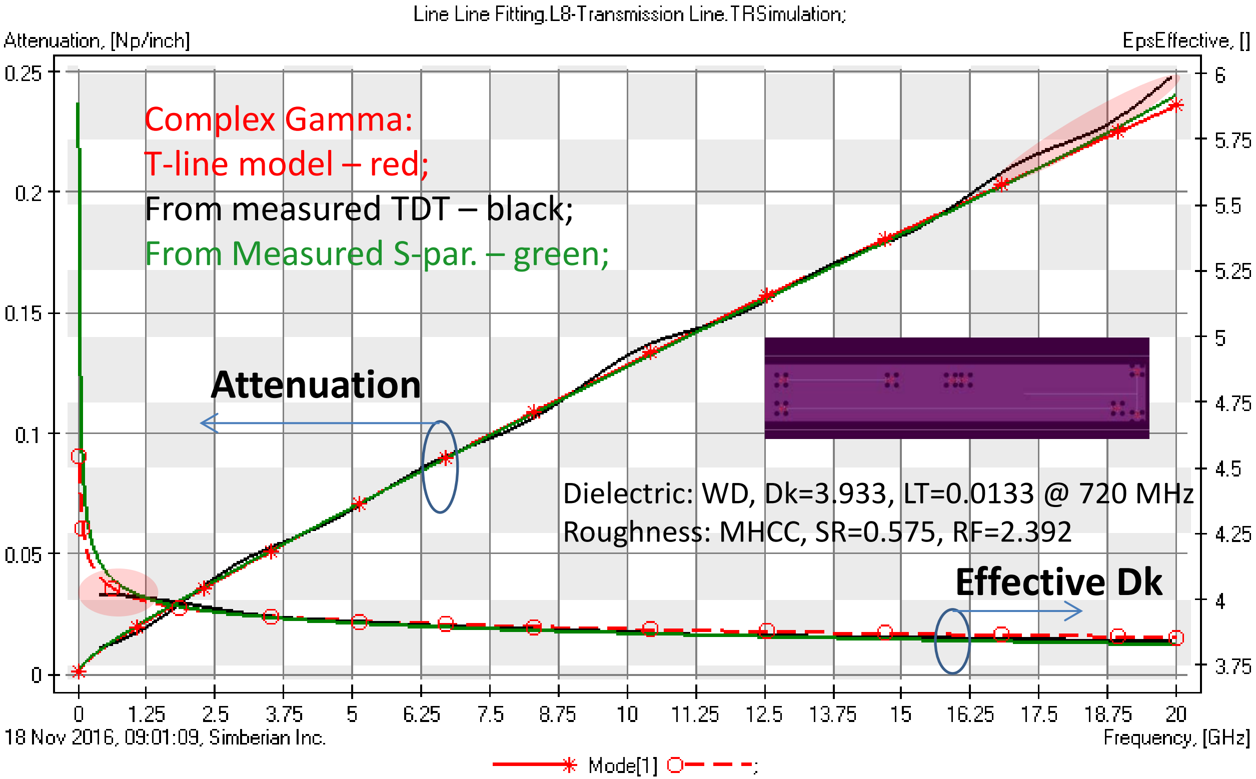


|S21| extracted from TDT measured with hand-held probes

|S21| measured with RF probes and VNA

Loss Tangent:
TDT: 0.0133
VNA: 0.0121

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



Complex Gamma:
T-line model – red;
From measured TDT – black;
From Measured S-par. – green;

Dielectric: WD, Dk=3.933, LT=0.0133 @ 720 MHz
Roughness: MHCC, SR=0.575, RF=2.392

18 Nov 2016, 09:01:09, Simberian Inc.

Procedure Summary

1. T-resonator – tand/Er @low frequency → Wide-band Debye models
2. Two Tlines -- attenuation extraction
3. Once the low-frequency information sets the debye model,

the roughness parameters are adjusted until the measurement-extracted attenuation is close to the model.

Take-Away

- Easy / Fast to measure → hand-held/time-domain
- Accurate enough → Shown by example
- Identifying the material model → surface roughness
- Readily deployable → HW/SW is ready
- Help high-volume manufacturers → monitoring

Conclusion

- Gamma-T technique has been proposed
  - Cost-efficient version with hand-held probes and TDT for production floor
  - Precise version S-parameters measurement for validation in lab
- Key to success is using the right hardware:
  - Introbotix probes
  - Simbeor signal integrity software used for the test fixture design, Gamma extraction and material model identification
- The technique is ready for deployment

Thank you!

QUESTIONS?