

Simplify and validate: A single structure approach for separate PCB dielectric and conductor roughness loss characterization

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Outline

- Introduction
- Dielectric and conductor roughness models
- Identification with single structure and loss separation
- Board design and proof of concept with numerical experiment
- Attempts of extraction with TDR/TDT and S-parameters measurements
- Resistivity evaluation and final extraction results
 - Validation with Gamma-T approach
- Conclusion

Introduction

- Currently, no standard/methodology monitors the material properties in PCB production
- Most of the time, processes are tuned by manufacturers for impedance and insertion loss using trial batches before actual sample production
- To find out the reasons for possible board/manufacturing failure due to losses, a new technique is needed which allows the separation of dielectric, conductor and roughness effects on the production floor

Main objectives

- Use space efficient structure on PCB;
- Time domain method using existing factory testing infrastructure (TDR/TDR equipment);
- High throughput method using handheld probe with TDR scope, no time consuming SMA mounting or VNA calibration;
- Limited cross-sectioning - identification method should tolerate geometric variations;
- 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;

Possible material characterization techniques

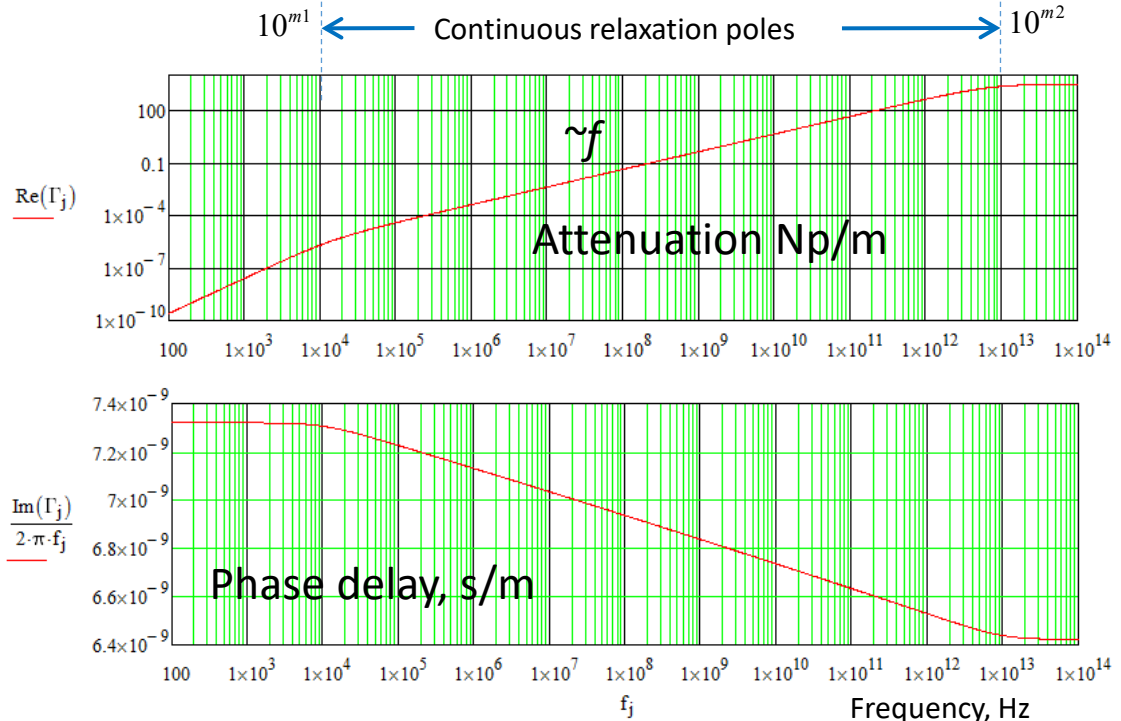
- SET2DIL – pass/fail at a set of frequency points, no material model;
- Delta-L2 – uses S-parameters to extract Γ , loss evaluation only - no material models, requires VNA + measurement skills;
- Complete de-embedding (TRL, AFR, ISD,...) – unnecessary complicated – VNA, test fixture S-parameters are not needed, de-embedded S-parameters have reflections and coupling terms...
- 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)
 - SPP Light with TDT has low-frequency defect preventing separation of conductor and dielectric losses
- Identification with GMS-parameters – similar to SPP Light only with S-parameters (EPEPS'2015, Shlepnev...) – best option, but require VNA and skills;
- T-resonator – simple, uses either TDT or S-parameters, D_k and L_T at a few points;
- Gamma-T - combined identification with Γ (from SPP or GMS-parameters) extraction and T-resonator (Choi, Cheng, Damgaci, Godishala, Shlepnev, DesignCon 2017) – it works, but requires 3 structures (T-resonator and 2 segments)

Dielectric and conductor roughness models and identification with single structure

Dielectric model to identify – Wideband Debye

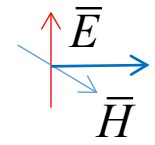
Aka Djordjevic-Sarkar or Swensson-Dermer

$$\epsilon_r(f) = \epsilon_\infty + \sum_{k=1}^K \frac{\Delta\epsilon_k}{1 + i f / f_{rk}} \quad \rightarrow \quad \epsilon_r(f) = \epsilon_\infty + \frac{\Delta\epsilon}{(m_2 - m_1) \cdot \ln(10)} \cdot \ln \left[\frac{10^{m_2} + i f}{10^{m_1} + i f} \right]$$



Example:

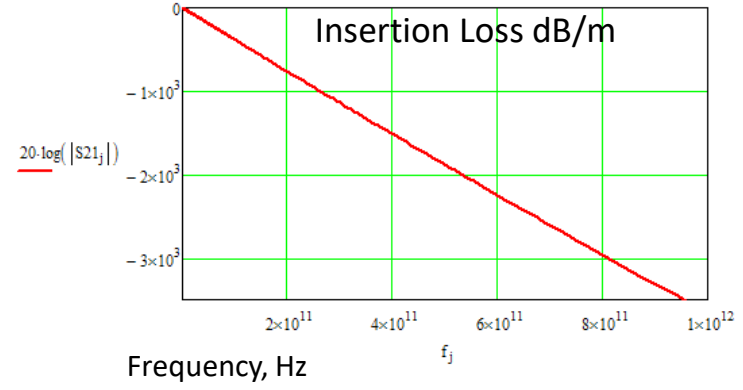
Plane wave propagation constant
 $\Gamma(f) = i 2\pi f \sqrt{\epsilon_r(f) \cdot \epsilon_0 \cdot \mu_0}$



$\epsilon_\infty = 3.707$; $\Delta\epsilon = 1.108$; $m_1 = 4$; $m_2 = 13$;
 $\text{Re}(\epsilon(10^9)) = 4.2$; $\tan \delta(10^9) = 0.02$

Generalized transmission parameter for distance l :

$$S_{21}(\omega) = e^{-\Gamma \cdot l}$$



This model can be defined with Dk and LT measured at 1 frequency point!
 Other wideband model options: Havriliak-Negami

Conductor roughness model to identify – Huray Braken

J. E. Bracken, A Causal Huray Model for Surface Roughness, DesignCon 2012

$$K_{sr} = 1 + \sum_k \left((RF_k - 1) \cdot \left(1 + (1-i) \frac{\delta_s}{2r_i} \right)^{-1} \right) \quad \delta_s = (\pi \cdot f \cdot \mu \cdot \sigma)^{-1/2}$$

RF_i - roughness factor, defines maximal growth of losses due to all balls with radius r_i ;
 r_i - ball radius (SRI parameter in Simbeor);

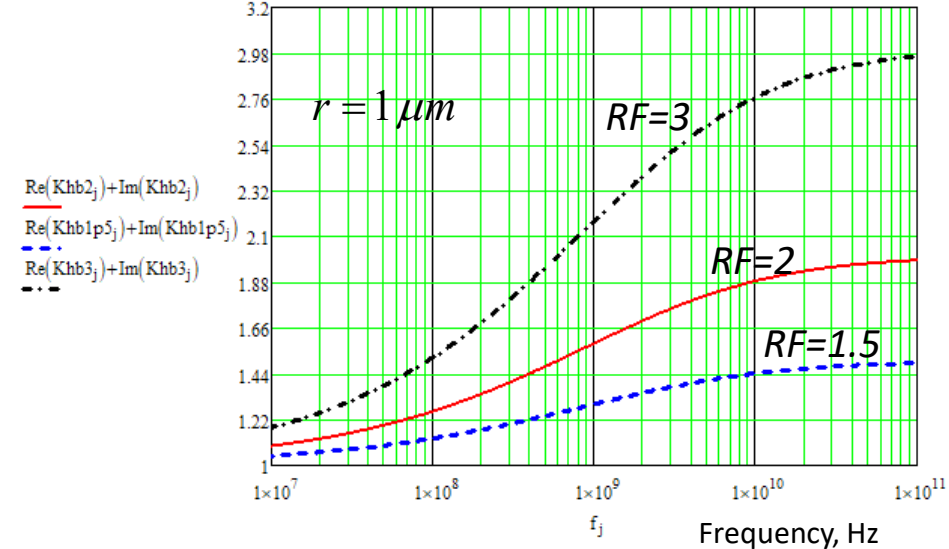
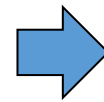
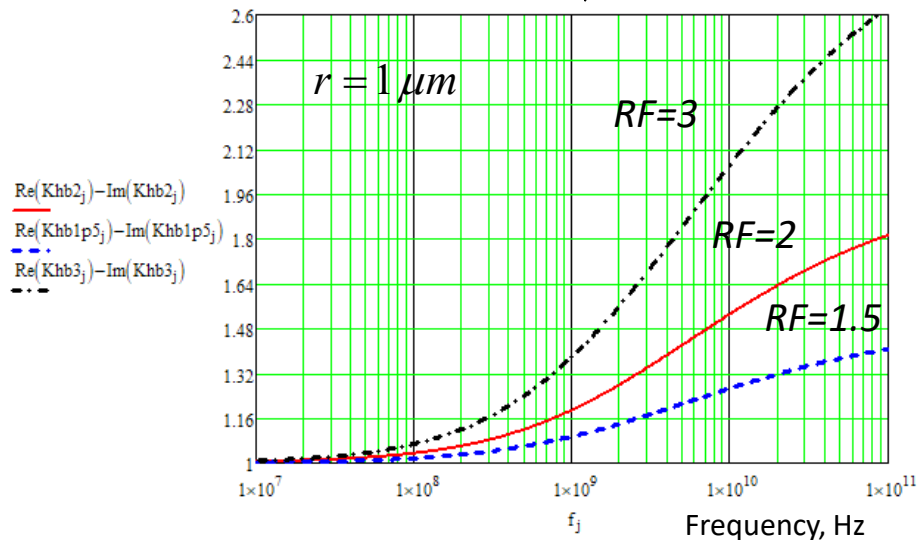
Conductor losses (same as in Huray model)

$$\text{Re}(Z_{rough}) = \underbrace{[\text{Re}(K_{sr}) - \text{Im}(K_{sr})]}_{\text{Additional conductor inductance}} \cdot \frac{1}{\sigma \cdot \delta_s}$$

Makes SIBC causal! $Z_{rough} = \frac{K_{sr}}{\sigma \cdot \delta_s} \cdot (1+i)$

Additional conductor inductance

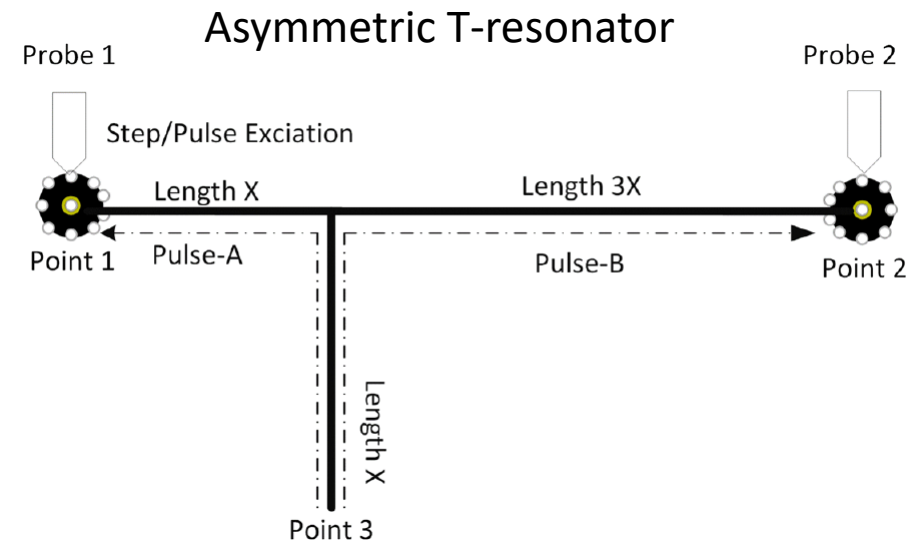
$$\text{Im}(Z_{rough}) = \underbrace{[\text{Re}(K_{sr}) + \text{Im}(K_{sr})]}_{\text{Additional conductor inductance}} \cdot \frac{1}{\sigma \cdot \delta_s}$$



One-level model has 2 parameters: SR (metric) and RF

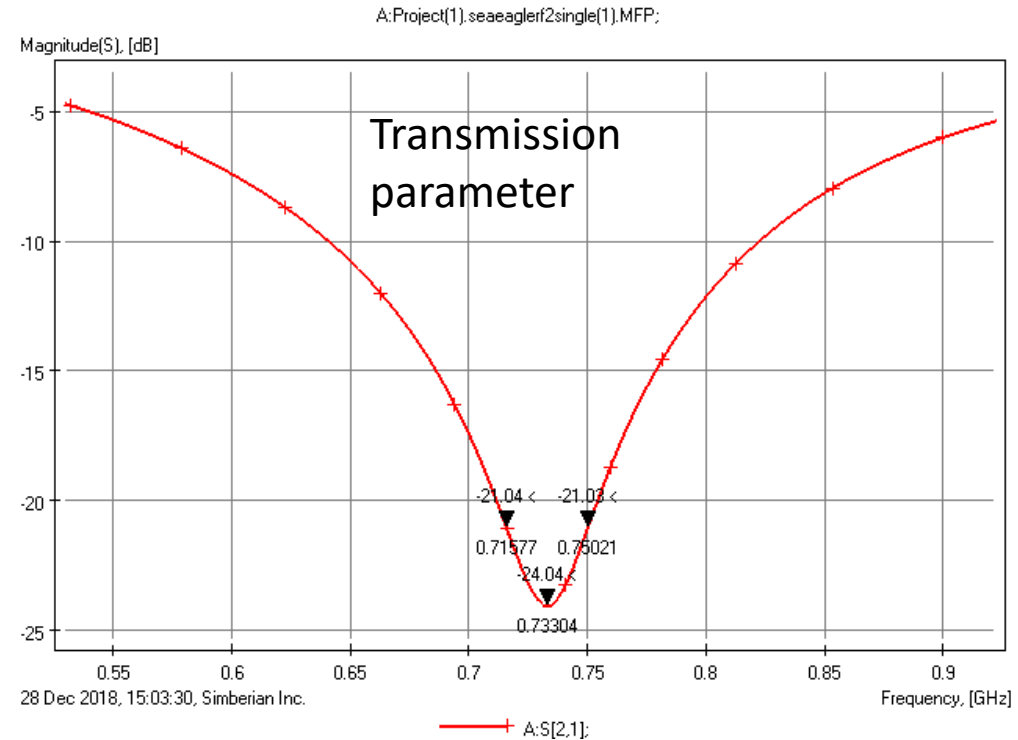
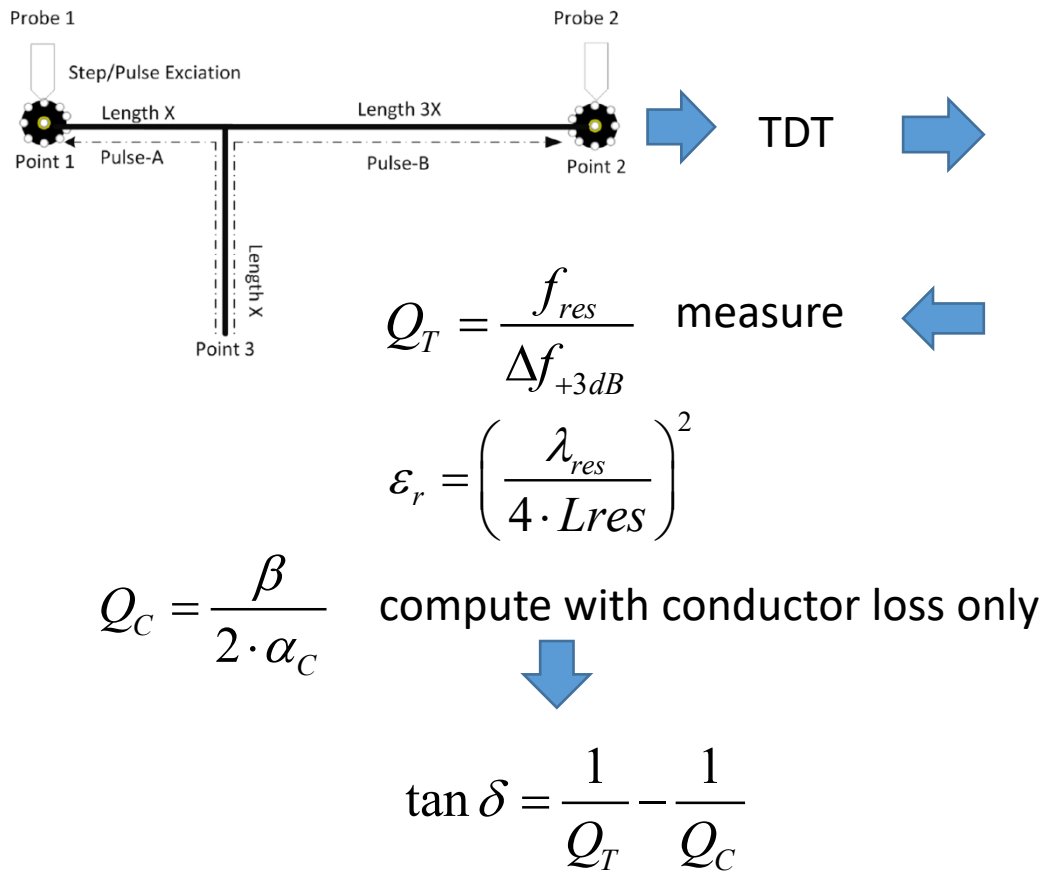
eXtract and MOnitor PCB material properties using only an asymmetrical T-resonator (XMOT) technique

1. Acquire step or pulse response for two port asymmetrical T-resonator (TDR and TDT)
2. Filter the noise with Gaussian filter and, if necessary, convert the step responses into the pulse responses with smoothing derivatives
3. Calculate the first resonance frequency from TDT and identify loss tangent LT and preliminary value of dielectric constant D_k at the resonance frequency
4. Window the pulses reflected from the open end from the TDT and TDR responses
5. Convert windowed pulses reflected from the open-ended stub into frequency domain and calculate the complex propagation constant or Gamma (Attenuation and Phase)
6. Use the field solver to tune D_k and conductor roughness model parameters (SR and RF) to match measured attenuation iteratively and phase delay
7. Optionally adjust the loss tangent by taking into account the identified roughness model in computation of the conductive resonator losses (step 3) and repeat step 6



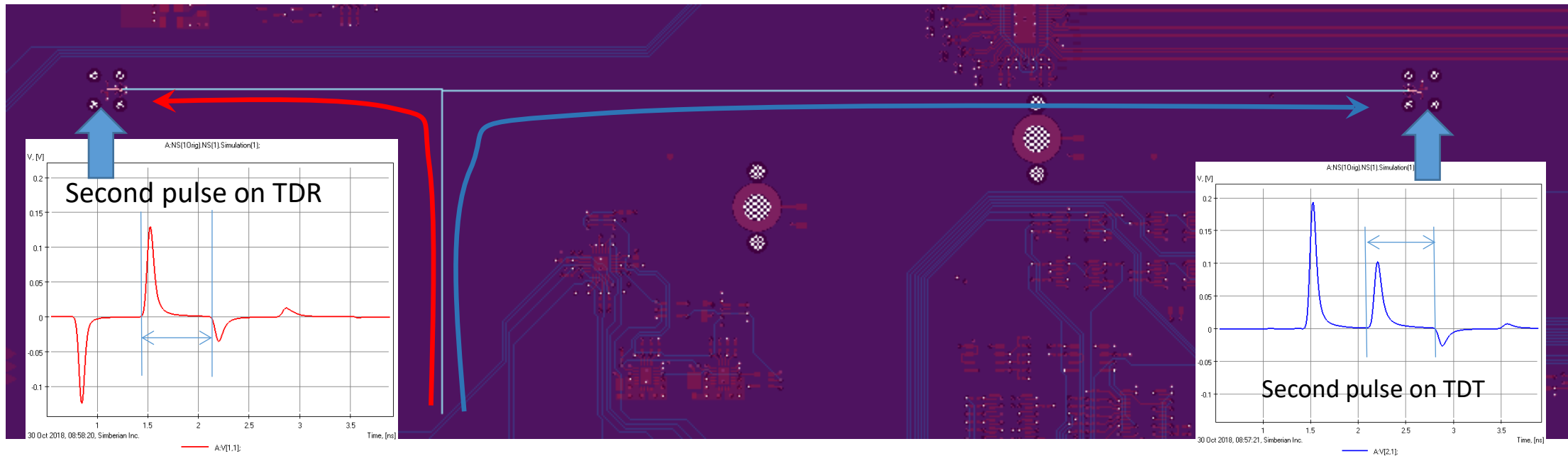
Spoiler – it was not so easy...

Step 3: Preliminary LT and Dk extraction with T-resonator TDT



α_C depends strongly on conductor resistivity – potential problem if resistivity cannot be identified easily...

Steps 4 & 5 - Gamma extraction



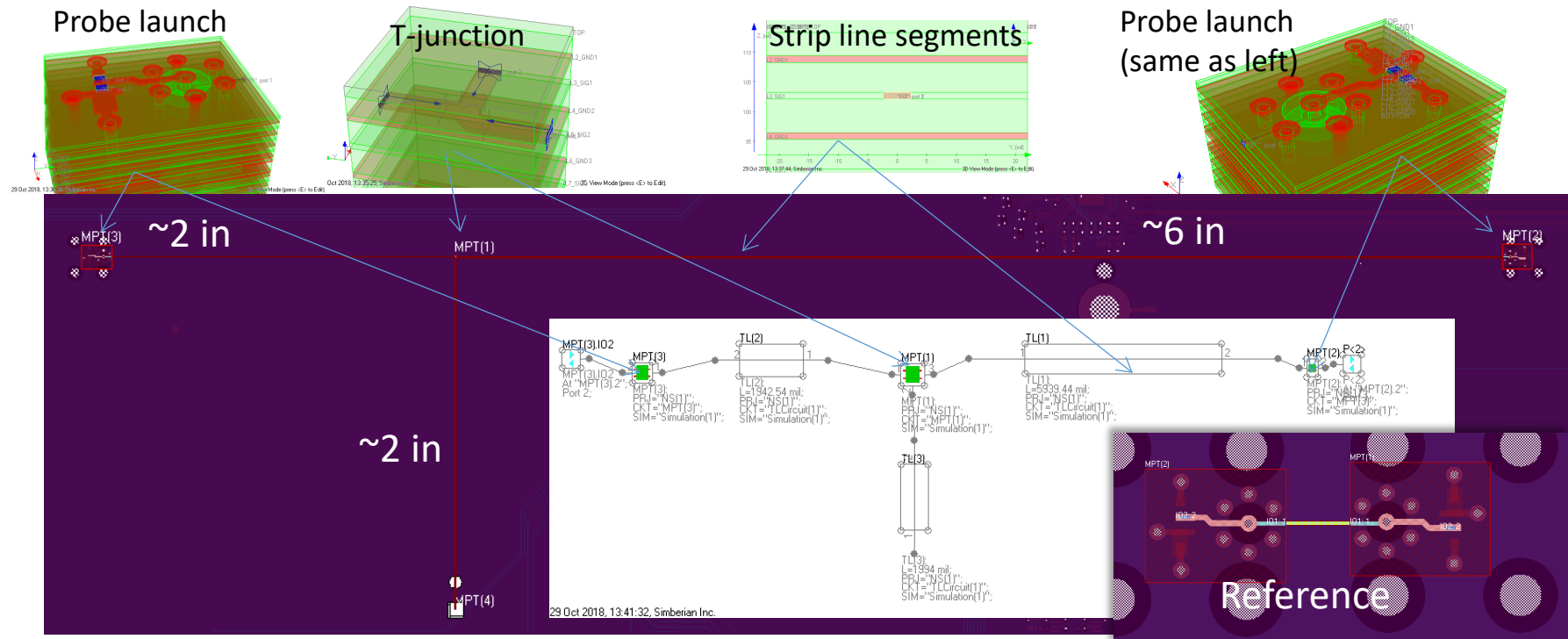
4. Window second pulses from TDR (V_{tdr}) and TDT (V_{tdt})
5. Convert the pulses to frequency domain and compute Gamma:

$$\Gamma(f) = \alpha(f) + j \cdot \beta(f) = \frac{1}{\Delta L} \ln \left(\left| \frac{V_{TDT}(f)}{V_{TDR}(f)} \right| \right) + j \cdot \frac{1}{\Delta L} \arg \left(\frac{V_{TDT}(f)}{V_{TDR}(f)} \right)$$

Board design and proof of concept with numerical experiment

Single T-resonator design and numerical experiment

De-compositional electromagnetic analysis of strip T-resonator



Adjustments from PCB manufacturer:

L3 Cu thickness cross section 1.15 mils – Stack-up 1.2 mils;

L2 Dielectric thickness 4.90 mils – Stack-up 5 mils; L4 Dielectric thickness 5.44 mils – Stack-up 5.6 mils;

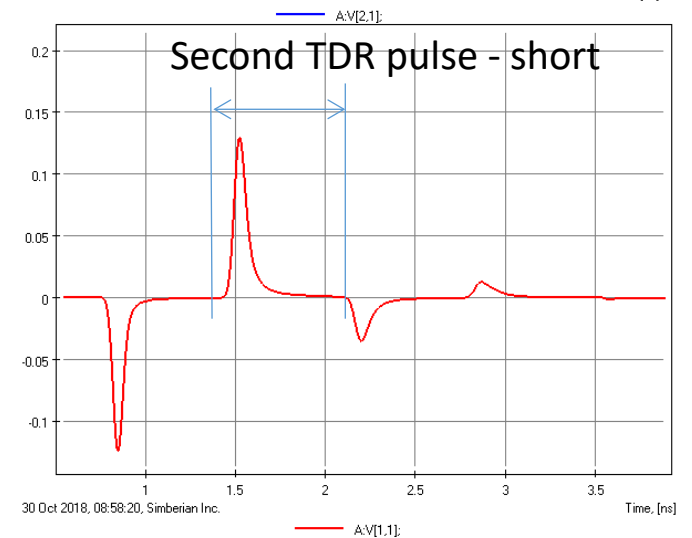
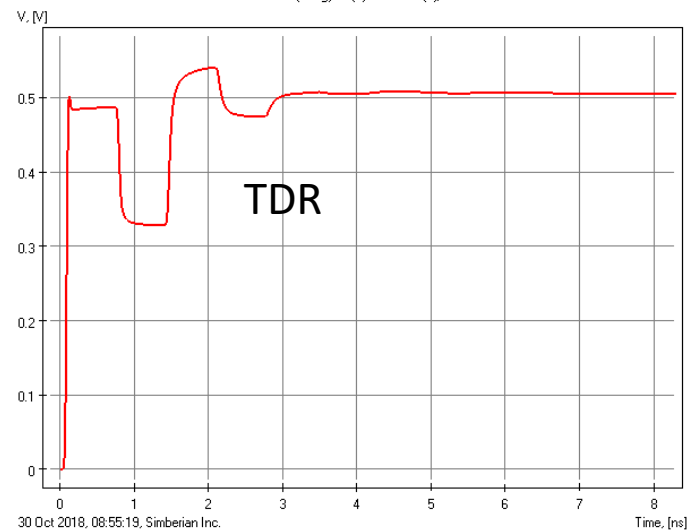
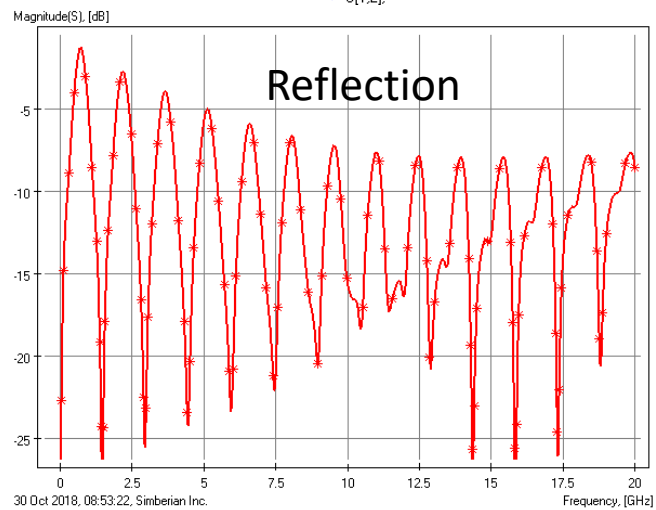
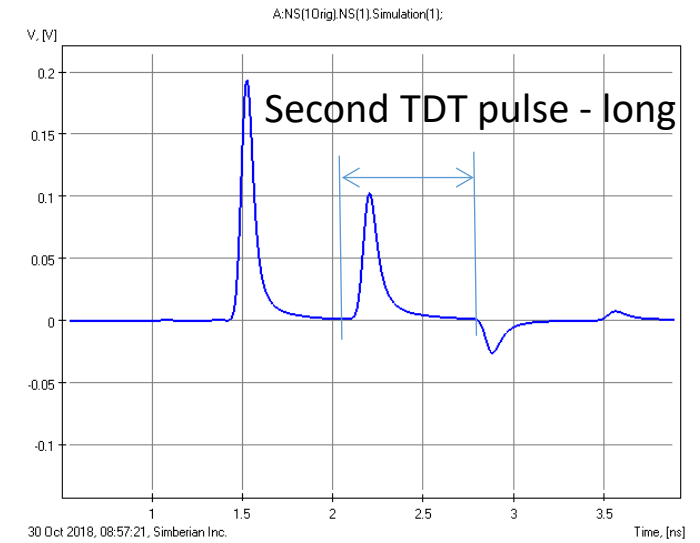
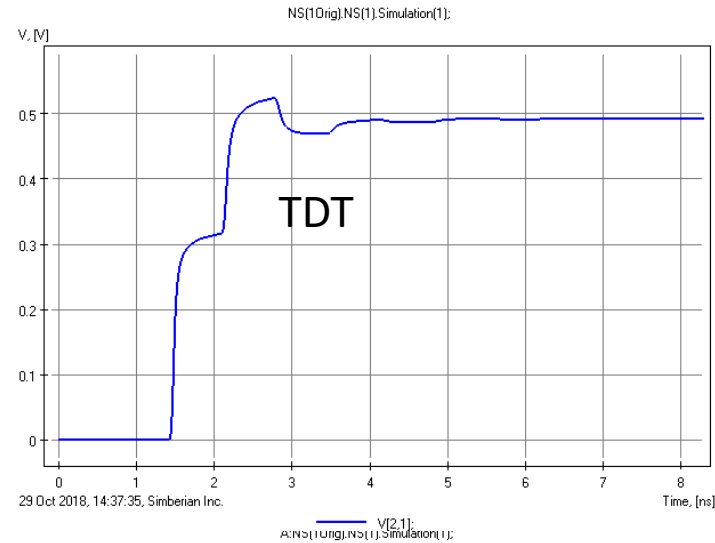
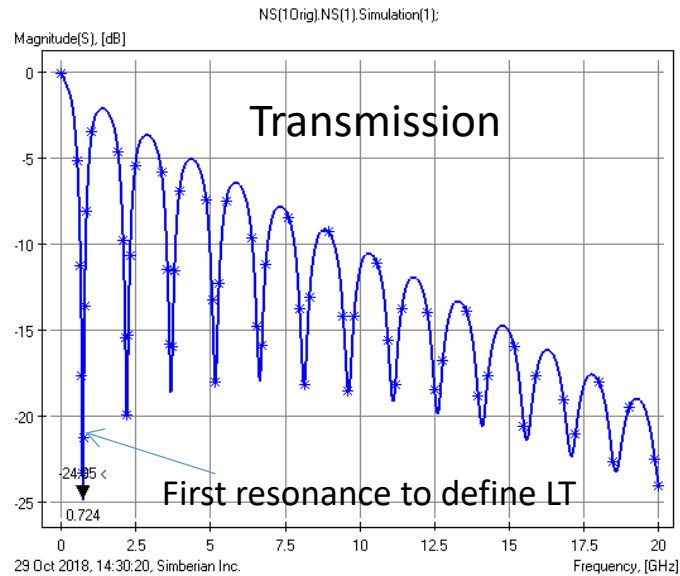
Trace width 4.6 – designed 5 mil; No data on shape – assumed rectangular;

Dk = 4, LT=0.015 – no frequency;

No data on copper resistivity (assumed RR=1) and conductor roughness model (assumed SR=0.1 um, RF=7);

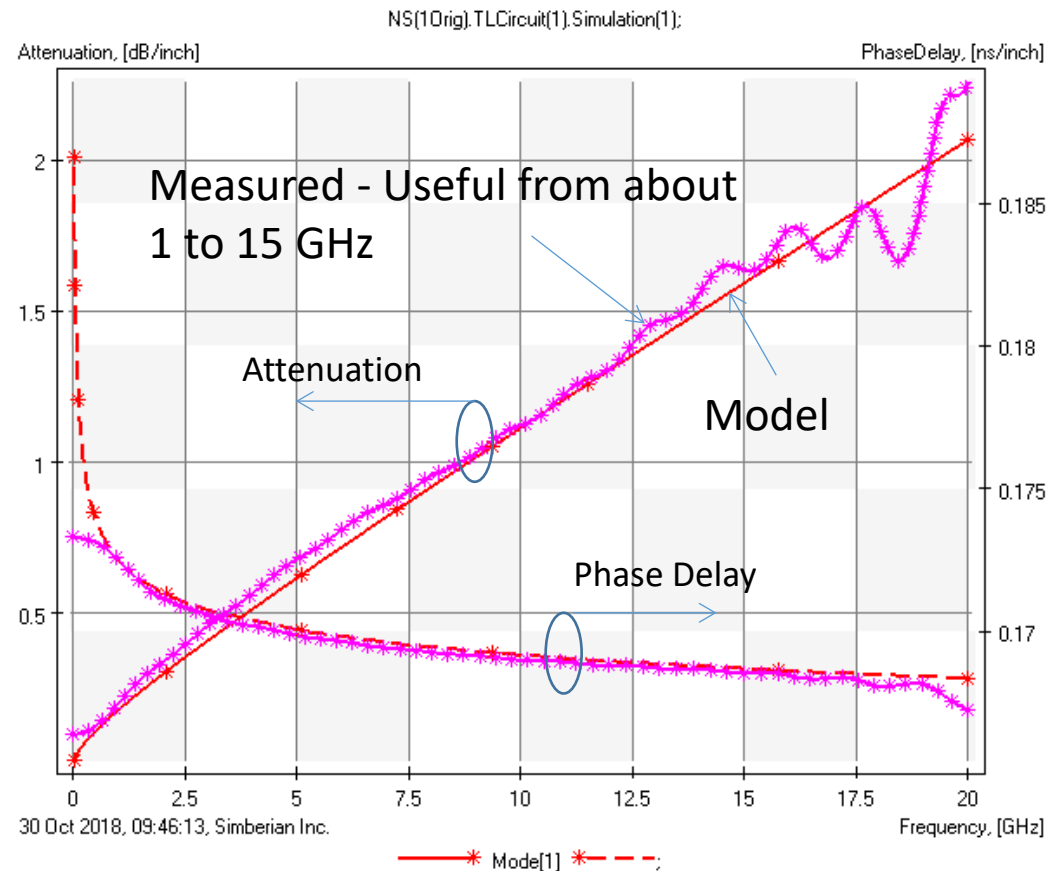
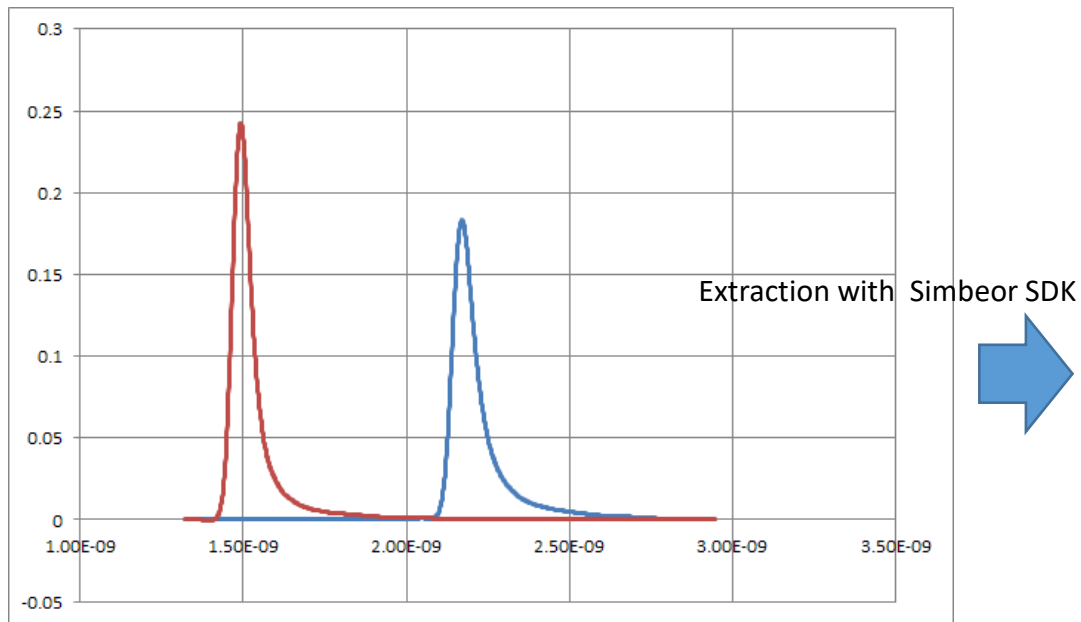
Modeling in Simbeor

Model S-parameters, TDR/TDT and pulse responses



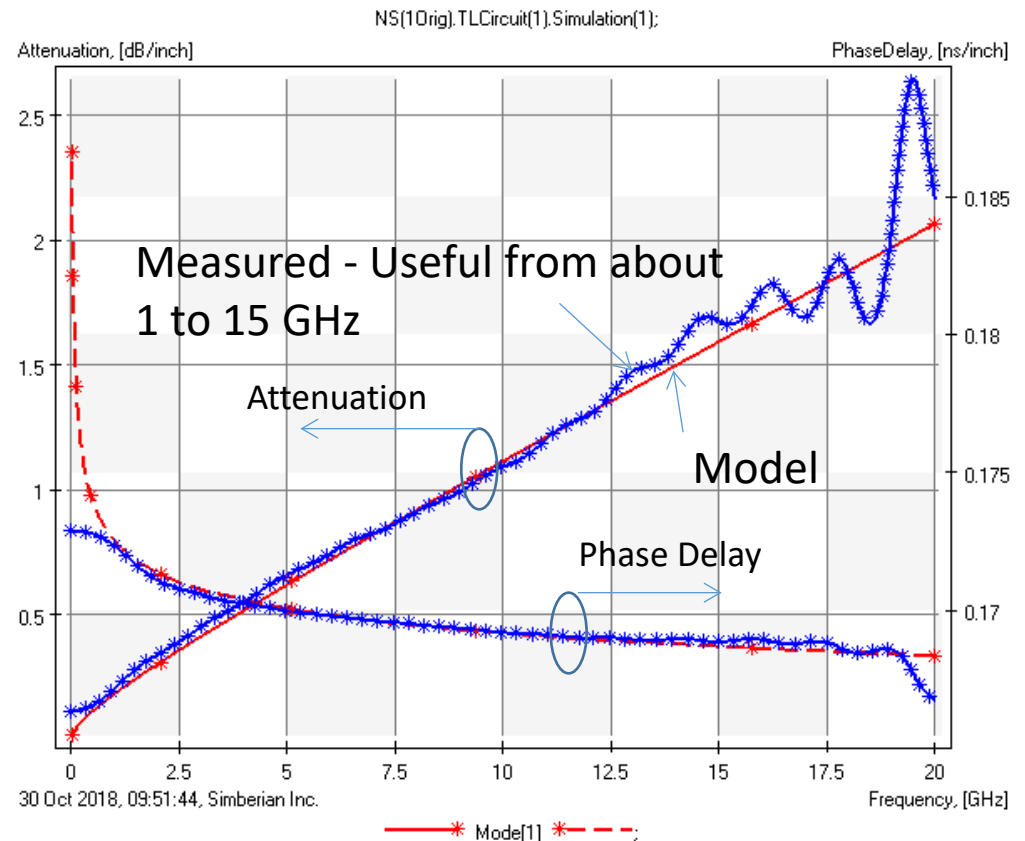
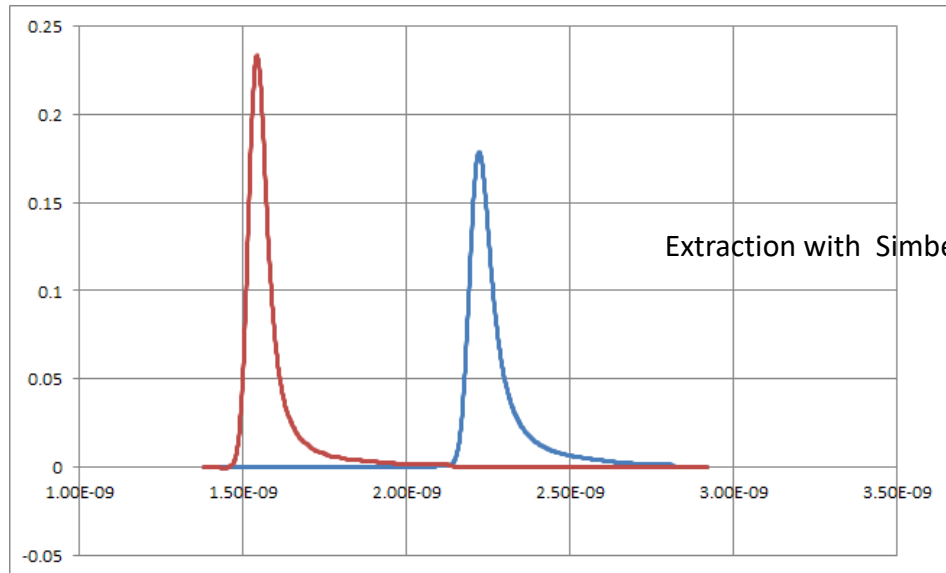
Model extraction results – no launch discontinuities

- Extracted LT=0.0148 @ 723.35 MHz (instead of 0.015)



Model extraction results with launch discontinuities – this is as good as it can get

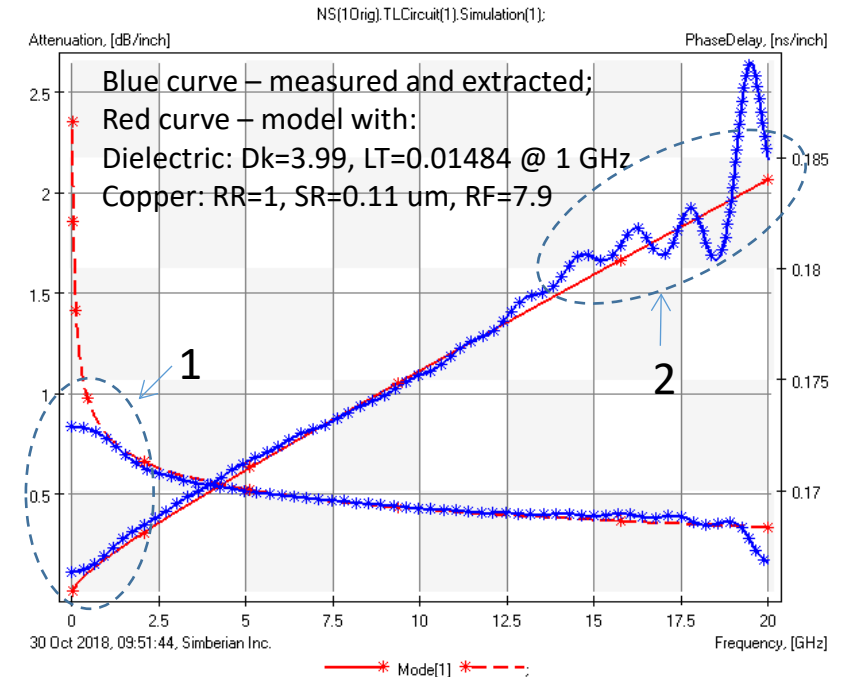
- T-Resonator Analyzer: LT=0.0148 @ 723.35 MHz (instead of 0.015)



Results of numerical experiment

1. Due to the restriction on the window duration, both phase delay and attenuation have defect at lower frequencies
2. Due to the superposition of the first and second pulses and additional reflections from the T-junction and launches there are defects in the extracted Gamma at higher frequencies
3. The phase delay can be used for the Dk identification from about 2 GHz to 17 GHz.
4. To identify the model parameters SR (ball radius in the Huray-Bracken) and RF for conductor roughness model, we use extracted attenuation from 2 to 15 GHz
5. The roughness model has 2 parameters. Because of this, multiple outcomes with slightly different results are possible. One of the outcomes with SR=0.11 μm , RF=7.8 is used in the model (reasonable)

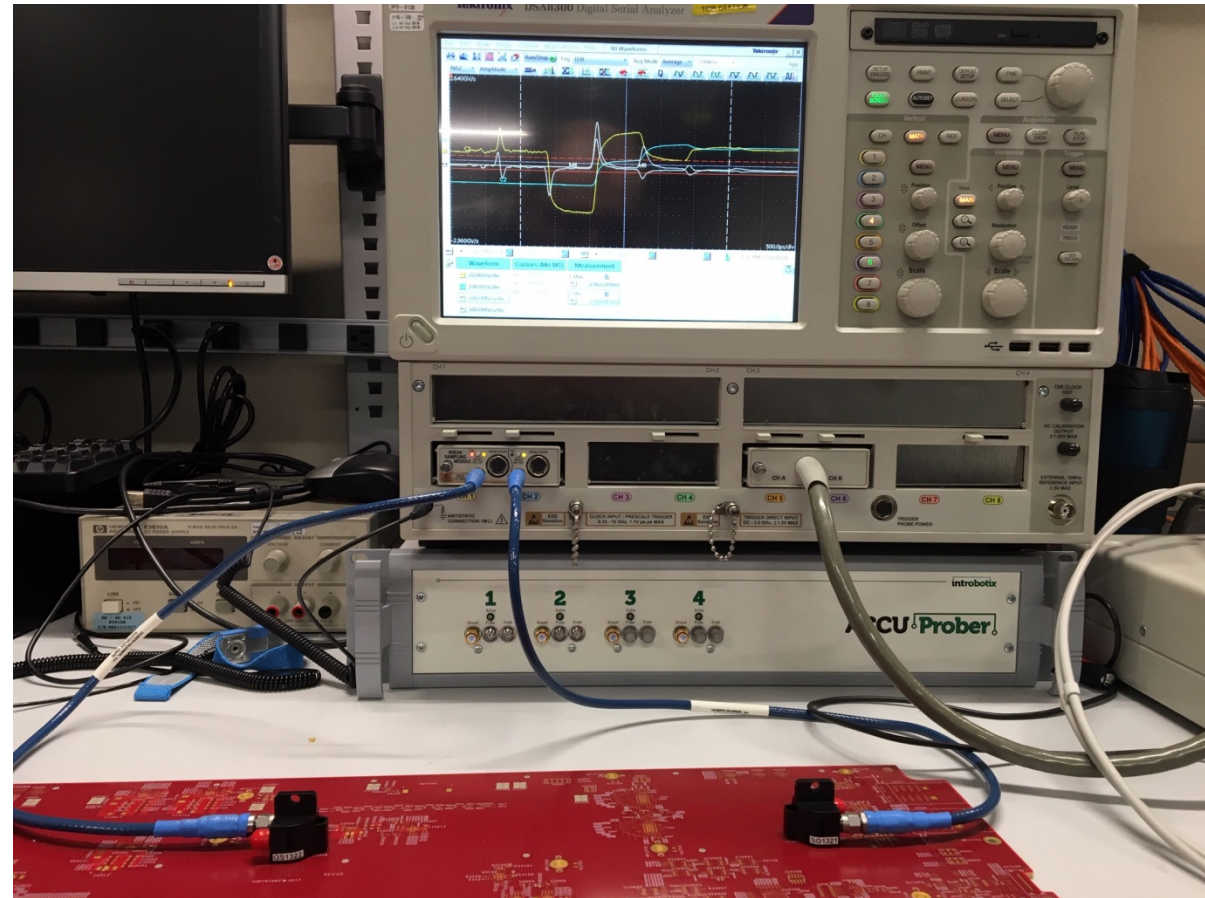
Model parameter	Original	Identified	Difference
Dk @ 1 GHz	4.0	3.99	0.25%
LT @ 1 GHz	0.015	0.01484	1%
SR, μm	0.1	0.11	10%
RF	7	7.8	11%



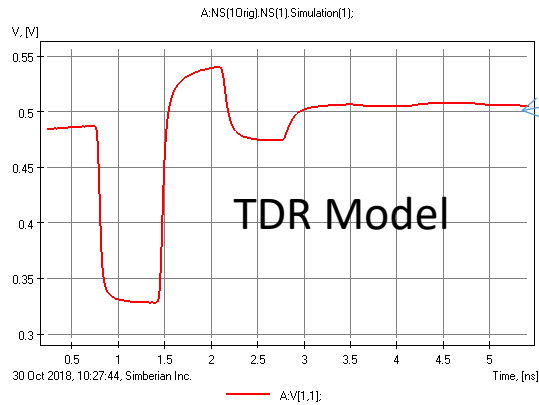
Attempt of extraction with TDR/TDT and S-parameters measurements

TDR/TDT measurements with hand-held probes

Test board with Introbotix hand-held probes. Launch is optimized for the probe footprint for single-ended transmission line. Tektronix DSA 8300 with 80E04 sampling modules used for measurements

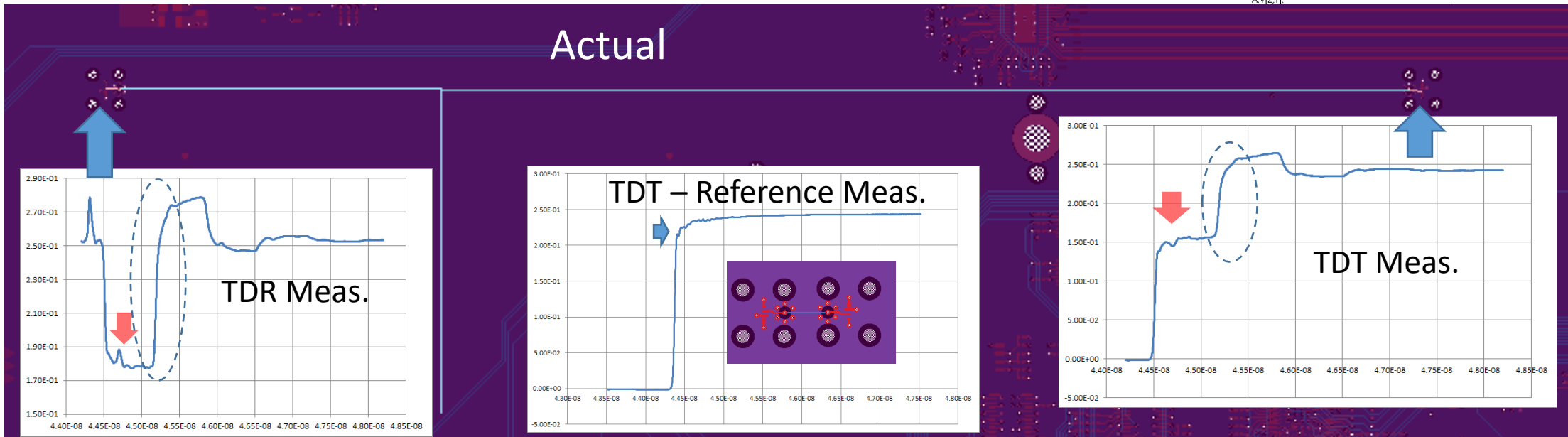
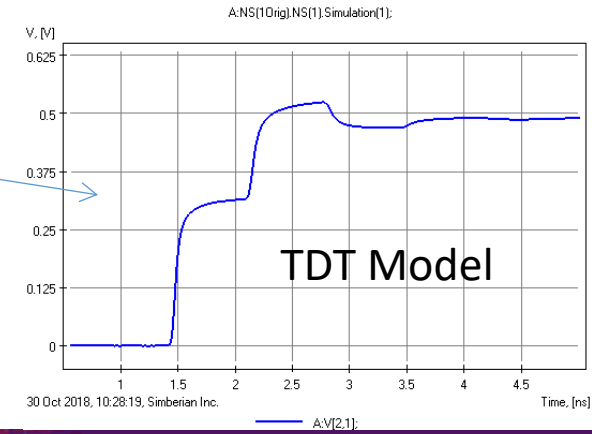


TDR/TDT measurements



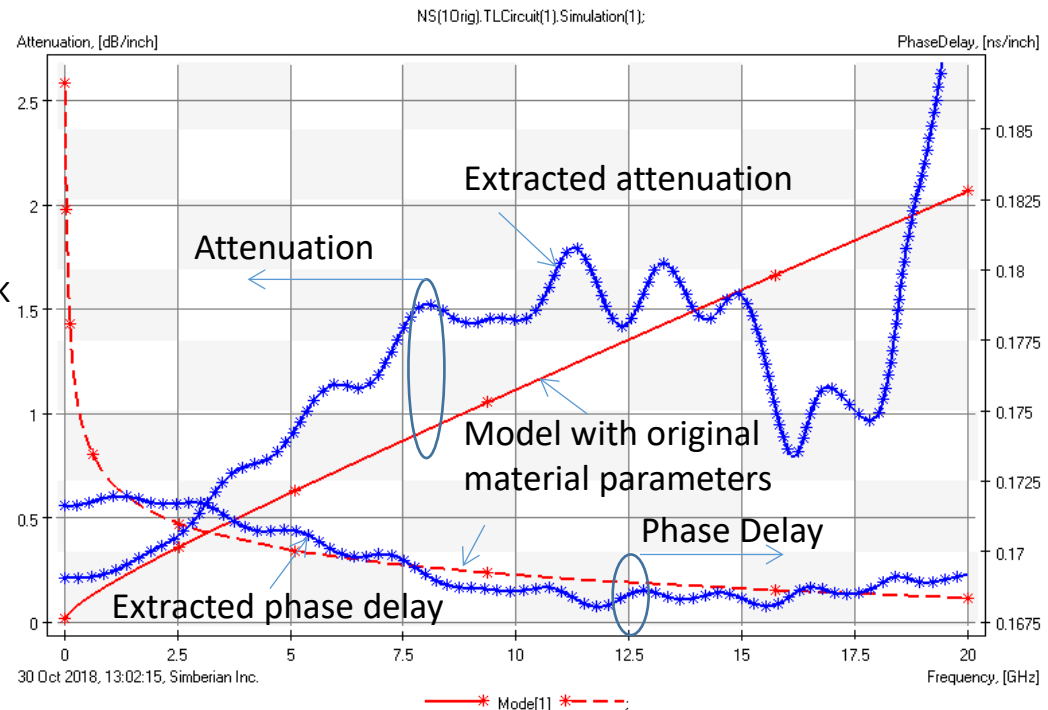
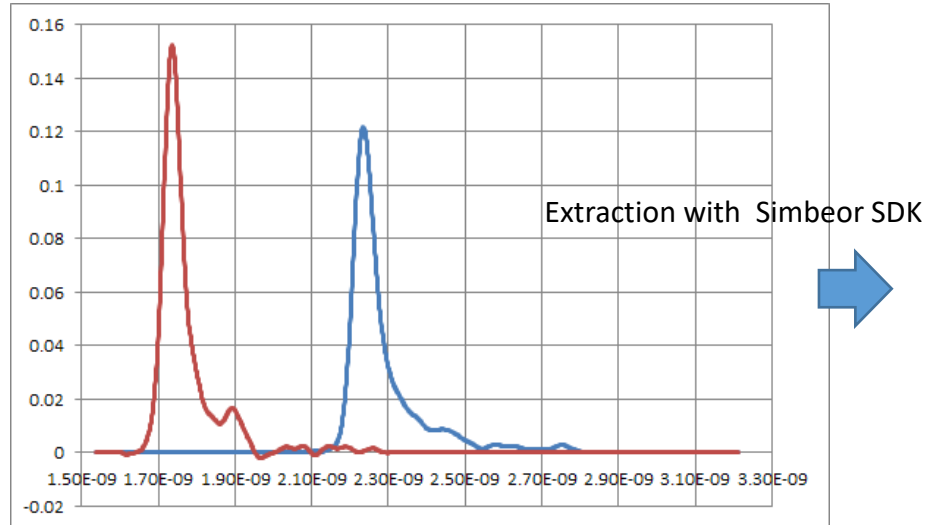
Expected

Problem – multiple reflections – ripples
Meas.: Oct. 15, 2018 – 1 ps time step,
hand-held probes



TDR/TDT Meas.: Processed data

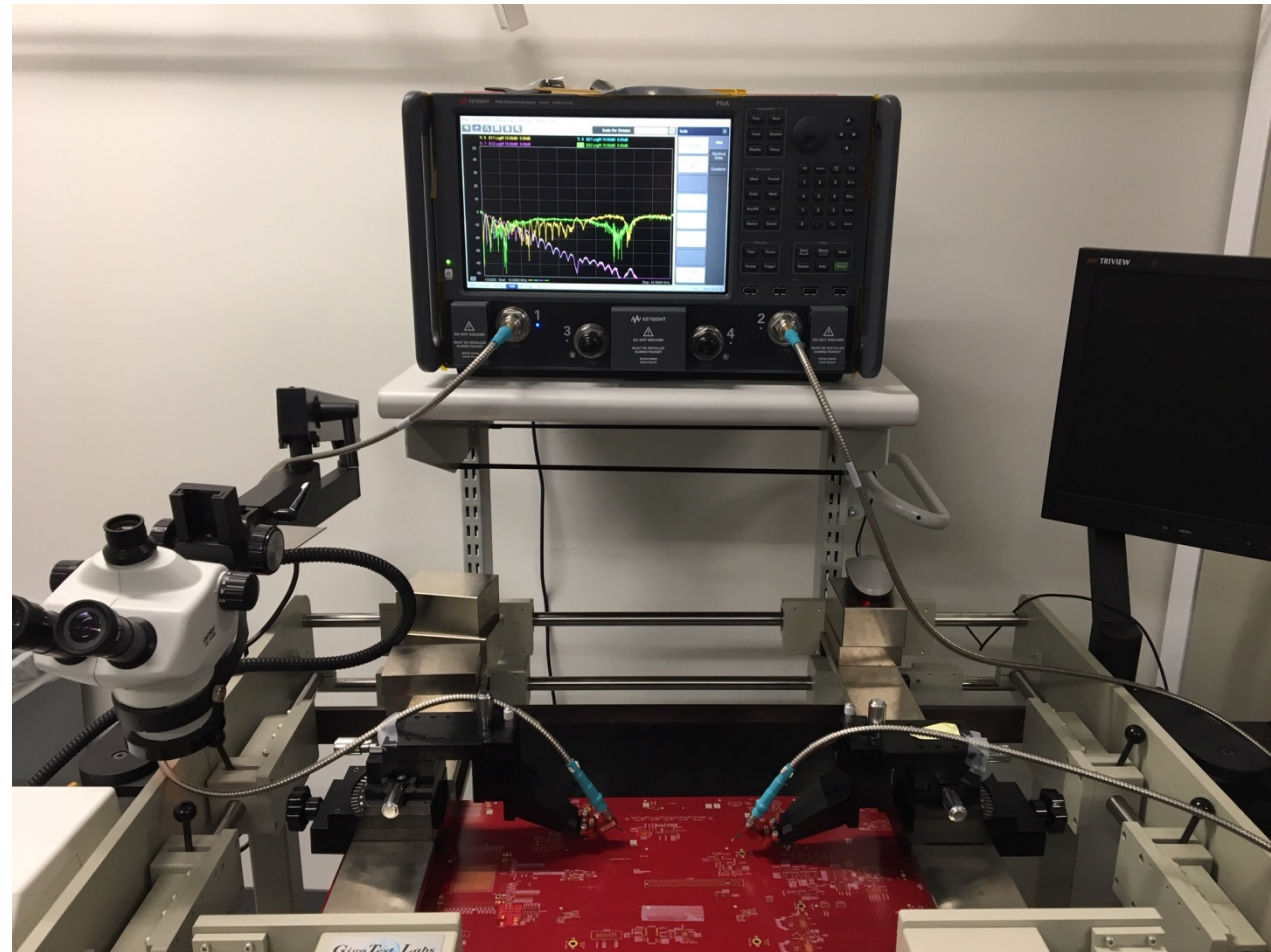
- T-Resonator Analyzer LT=0.021 @ 715.86 MHz



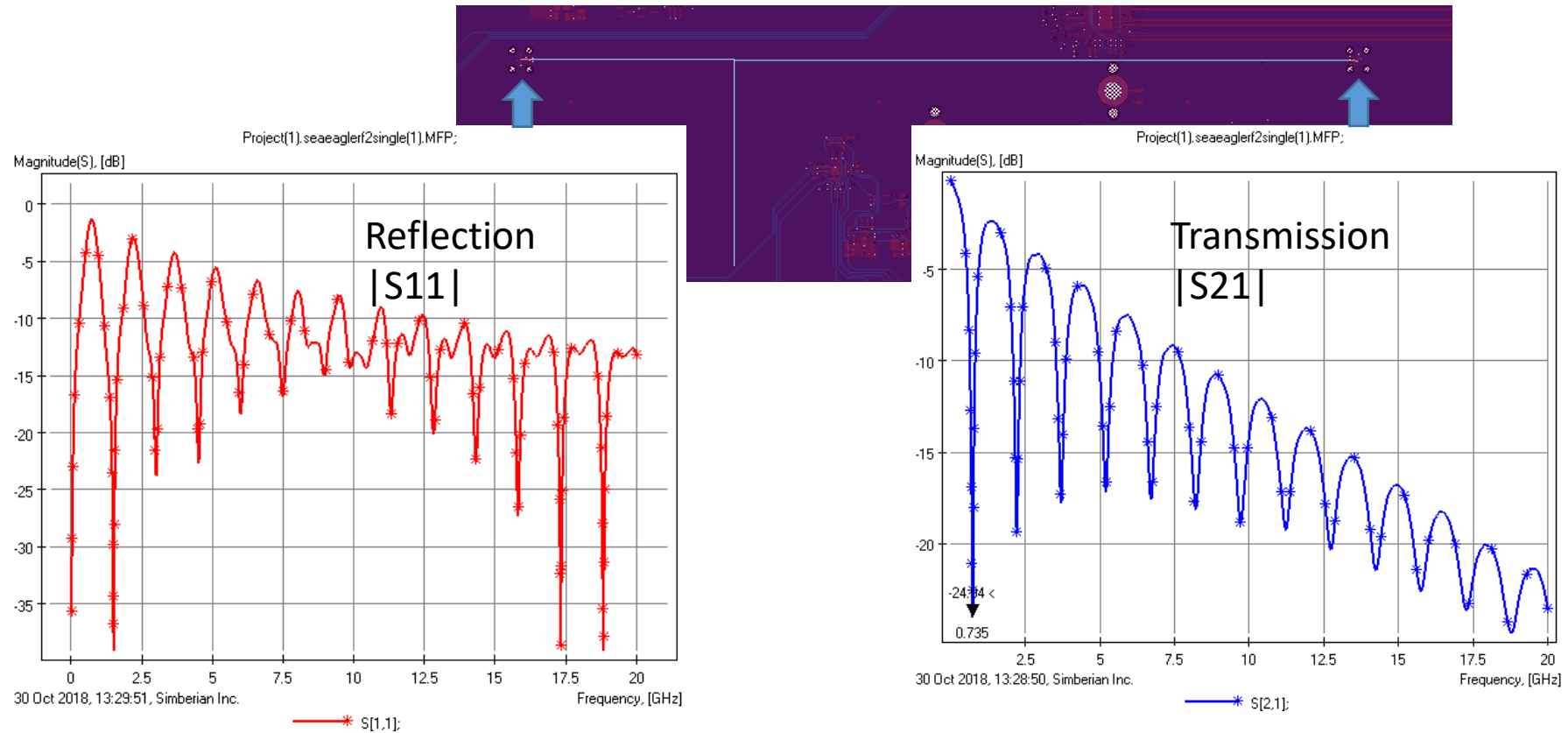
Multiple reflections on pulses distorts Gamma – the result is not suitable for the identification
The problem can be reproduced in numerical experiment with additional reflections from probes

S-parameters measurement with RF probes

Test board with GigatestLabs RF probes. GigatestLabs calibration substrate used for VNA calibration

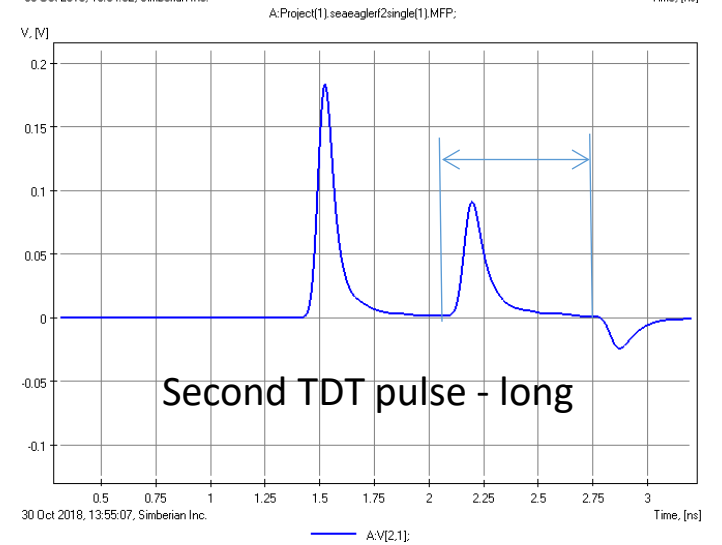
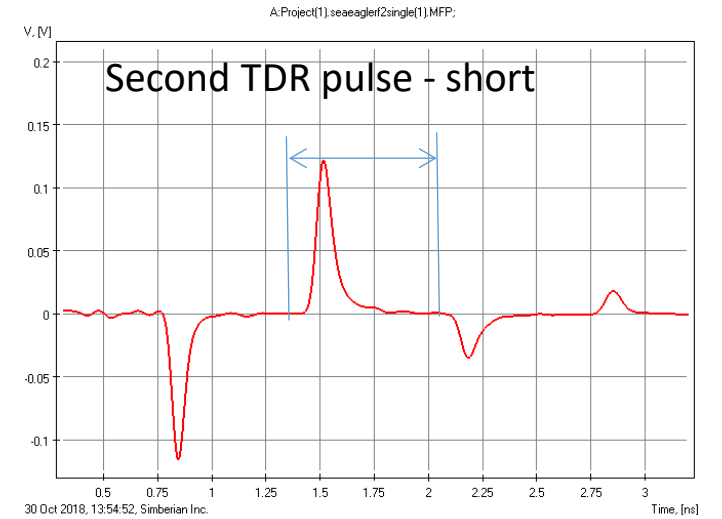
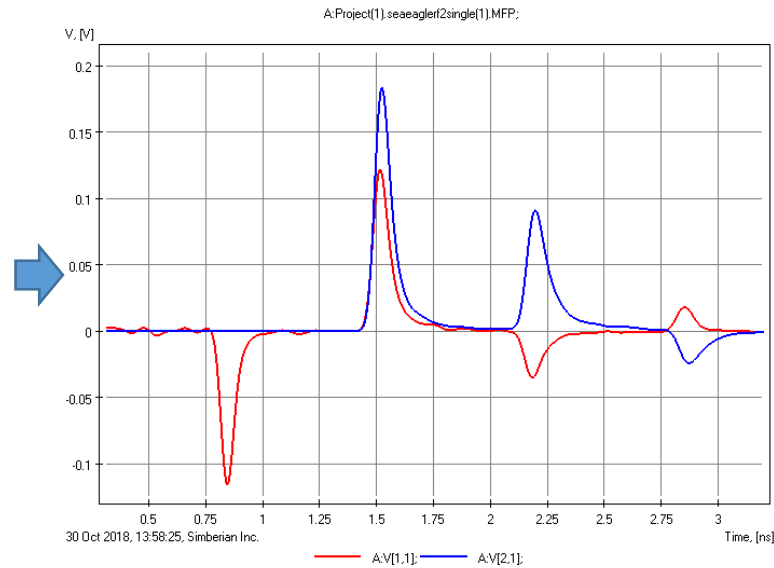
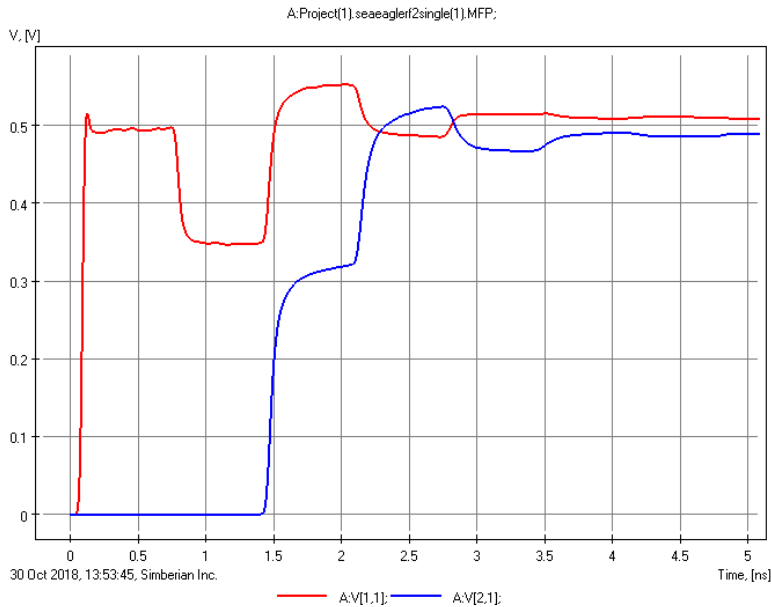


S-parameters measurement with RF probes



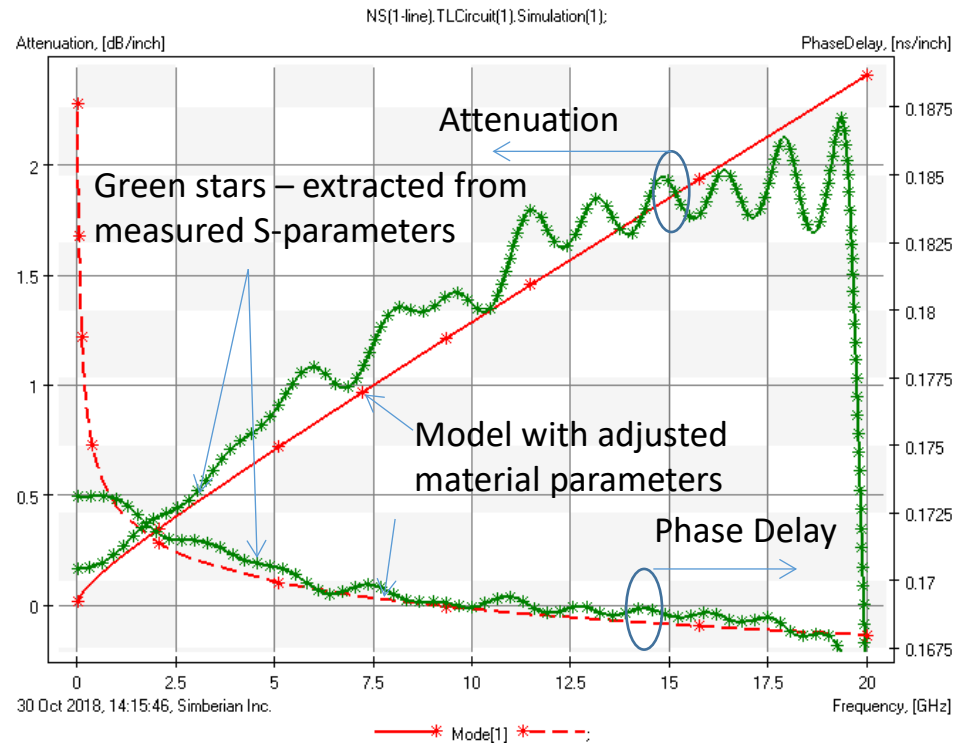
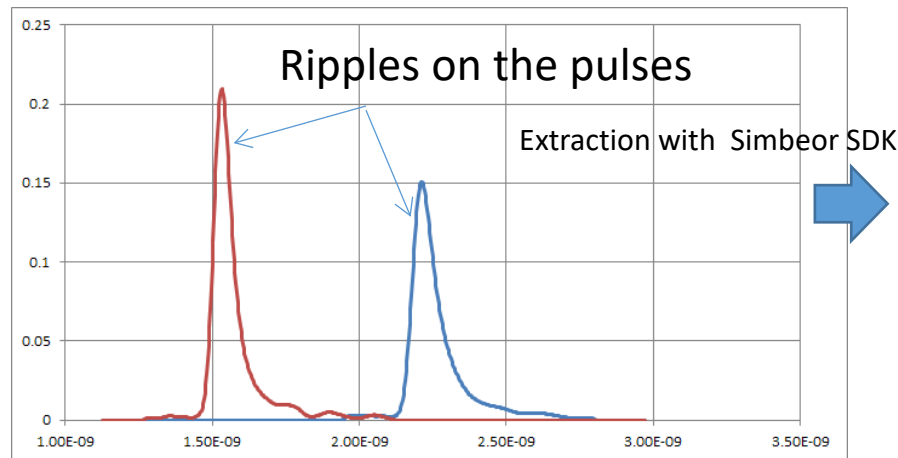
TD Response from S-parameters

Computed with rational approximation with RMS Error 0.0028
(quality 99.76%), Gaussian step rise time 20 ps (10-90%)



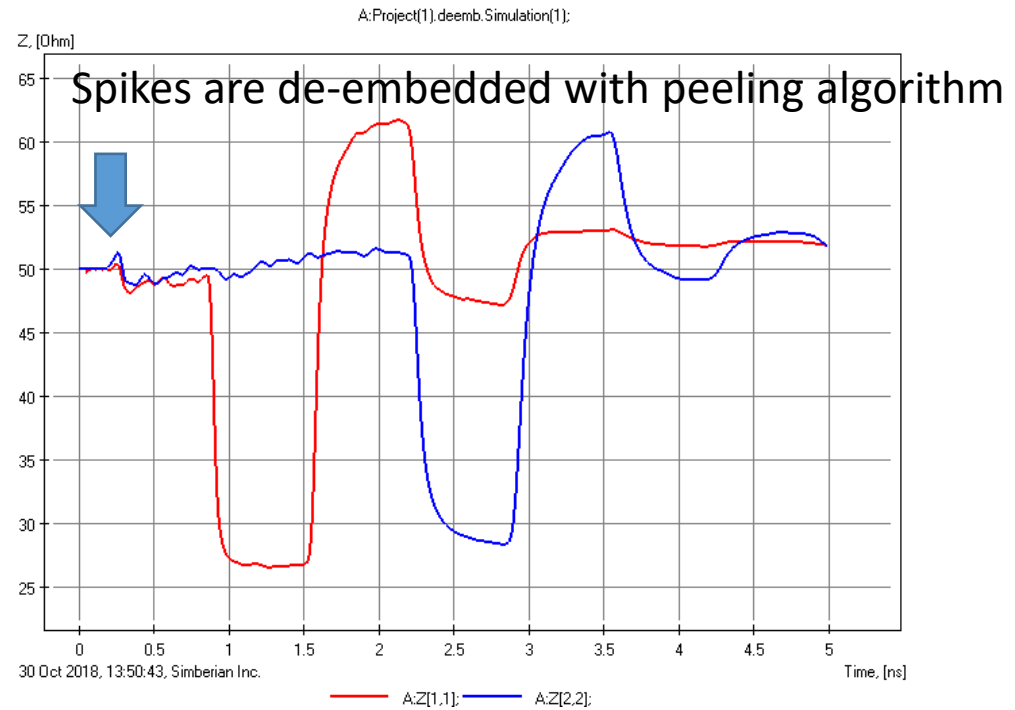
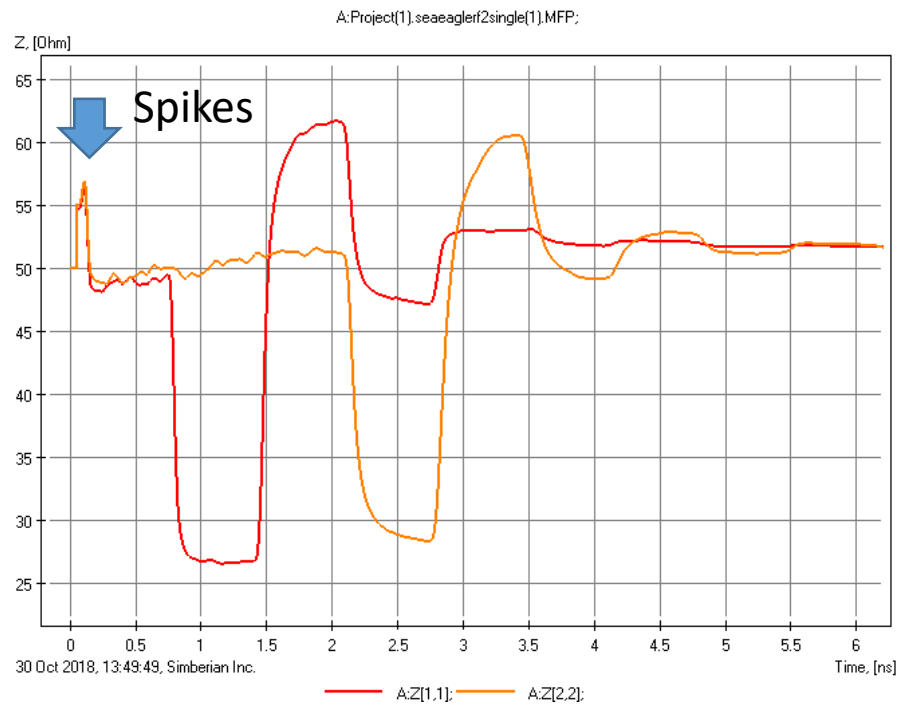
Extraction from S-parameters, RF probes

- T-Resonator Analyzer: $LT=0.0189$ @ 733.06 MHz



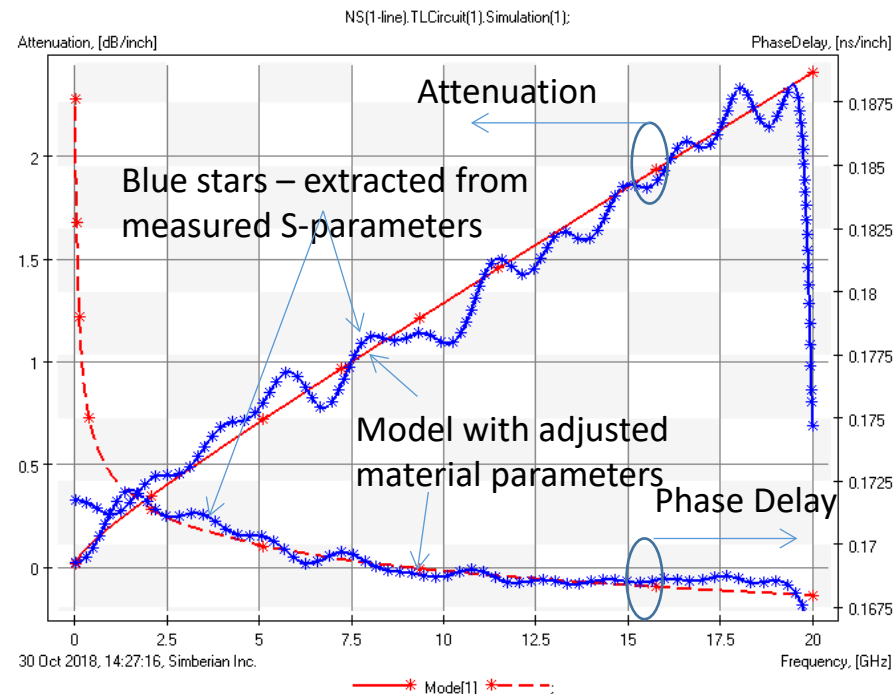
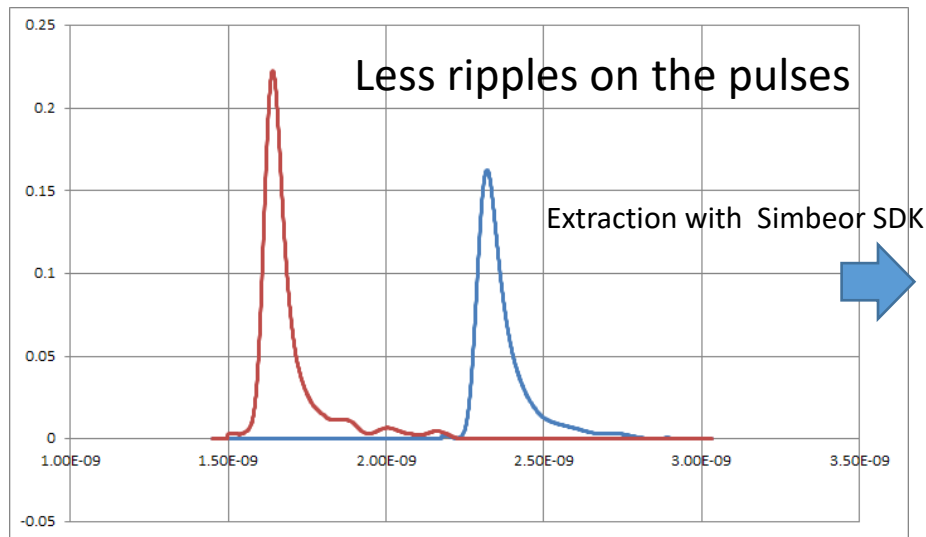
2 problems:
Ripples on the TD response or pulse shifts produce noisy Attenuation
Loss tangent seems too large

Post-processing, to improve quality



Extraction from de-embedded S-parameters

- T-Resonator Analyzer: $LT=0.0189$ @ 733.06 MHz



Best possible so far

Attenuation is marginally suitable

Loss tangent seems too large – dielectric includes almost all observed losses – not possible

Possible sources of discrepancies

- Cross-sectioning – we rely on the data from PCB manufacturer
- Resistivity of copper – nominal value $1.724e-8$ Ohm*meter is assumed (relative resistivity $RR=1$)
- Possible effect of roughness at 733 MHz (RTF copper is used)
- Additional data are needed
 - We tried to identify the resistivity with measurements of S-parameters for t-line segment at very low frequencies...

Resistivity evaluation and final results

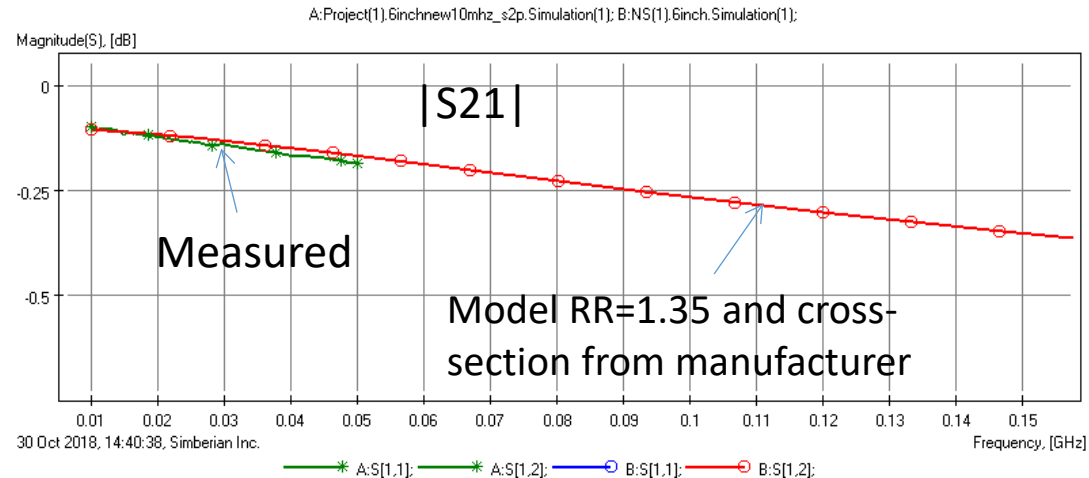
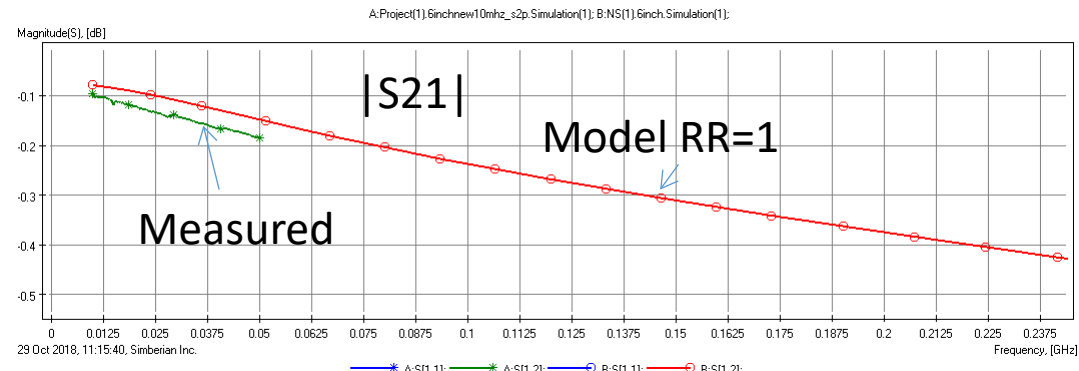
Identification of bulk resistivity of copper

6-inch T-line segment attenuation at lower frequencies is used to identify relative resistivity (RR)

Identified RR=1.35 (much higher than expected)

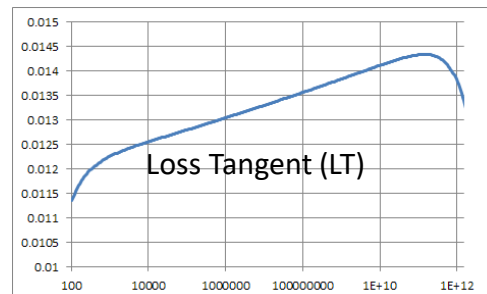
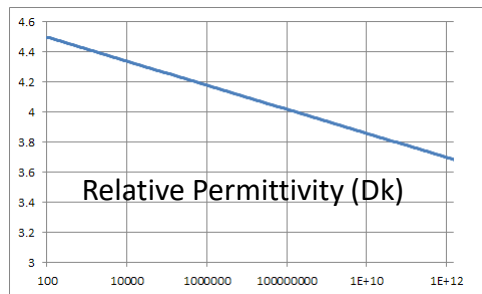
With RR=1.35, extracted loss tangent:
LT=0.0147 @ 733 MHz with SR=0.1 um, RF=7
LT=0.0138 @ 733 MHz with SR=0.2 um, RF=7

Roughness slightly changes the result – the process of the identification may require iterative refinement

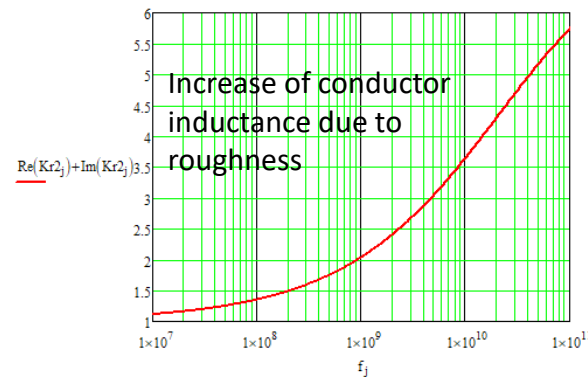
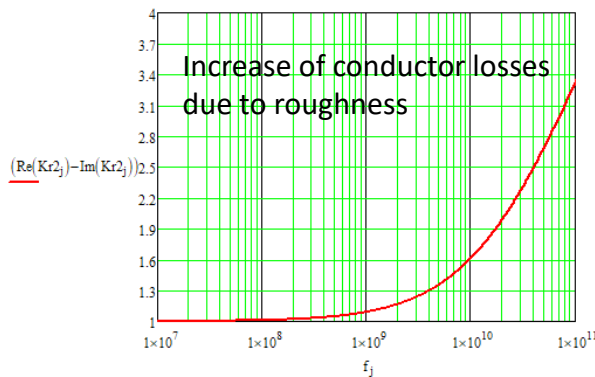


Final single structure extraction results

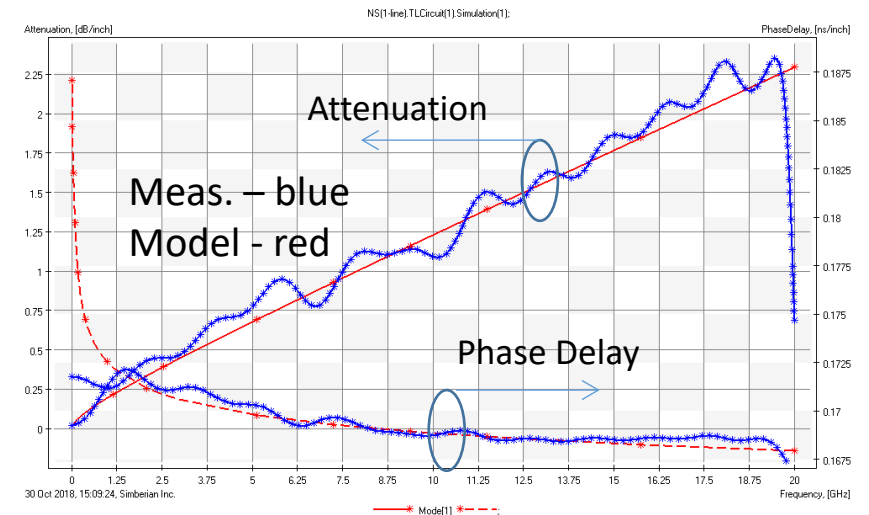
- Dielectric: Wideband Debye Dk=3.95 LT=0.0138 @ 733 MHz



- Conductor: Relative Resistivity 1.35, Huray-Bracken roughness model with SR=0.2 um, RF=7

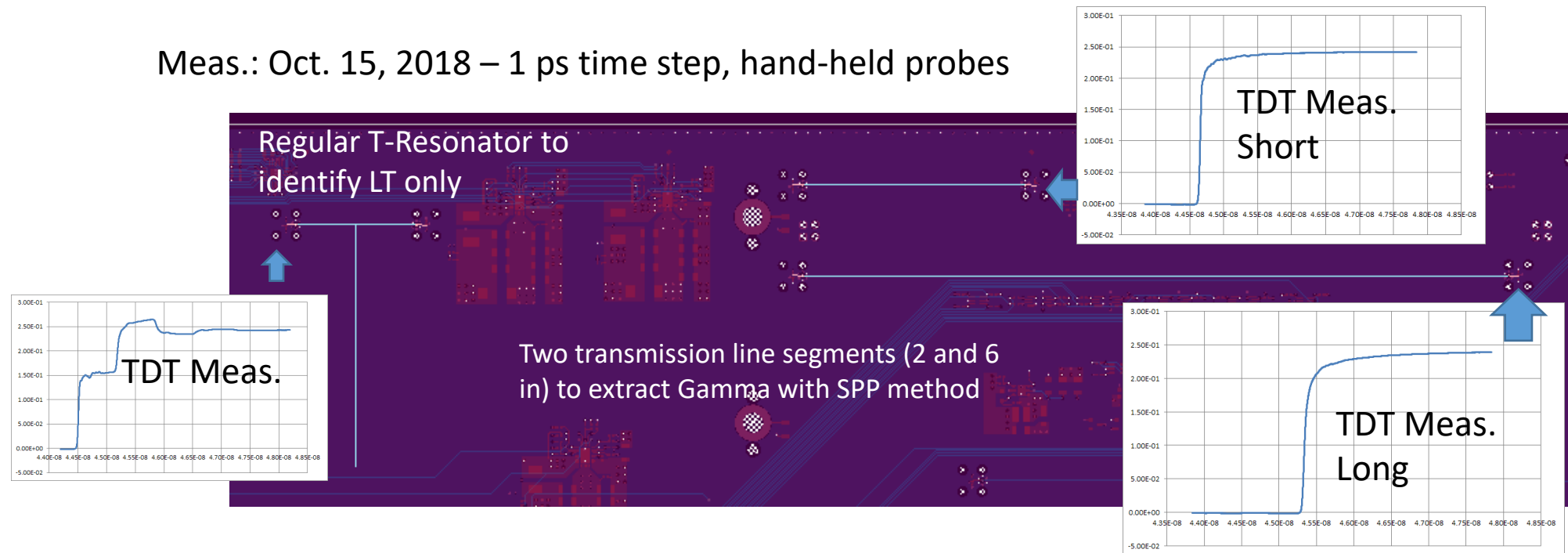


Loss tangent is identified with T-resonator Q-factor
 Dielectric constant is identified by matching Phase Delay
 Roughness model is identified by matching attenuation (by minimization of RMS deviation)



Validation with Gamma-T approach

Meas.: Oct. 15, 2018 – 1 ps time step, hand-held probes



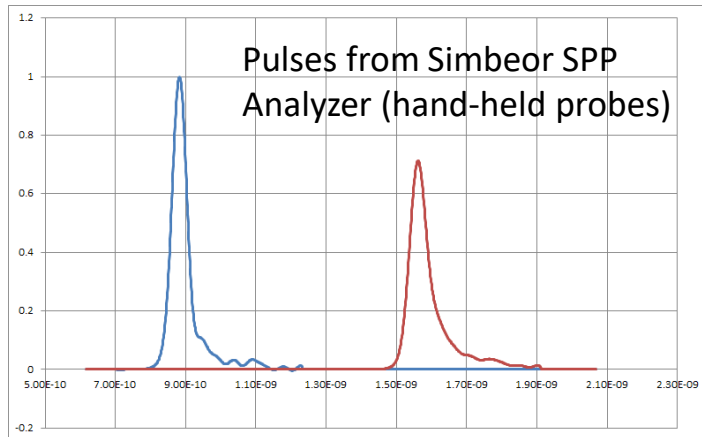
Y. Choi, C. Cheng, Y. Damgaci, N. Godishala, Y. Shlepnev, Cost-effective PCB Material Characterization for High-volume Production Monitoring, DesignCon 2017, Santa Clara, CA. - the award-winning paper from DesignCon2017.

Y. Shlepnev, Y. Choi, C. Cheng, Y. Damgaci, Drawbacks and Possible Improvements of Short Pulse Propagation Technique, 2016 IEEE 25th Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS'2016), pp. 141-143, October 23-26, 2016, San Diego, CA.

Validation results

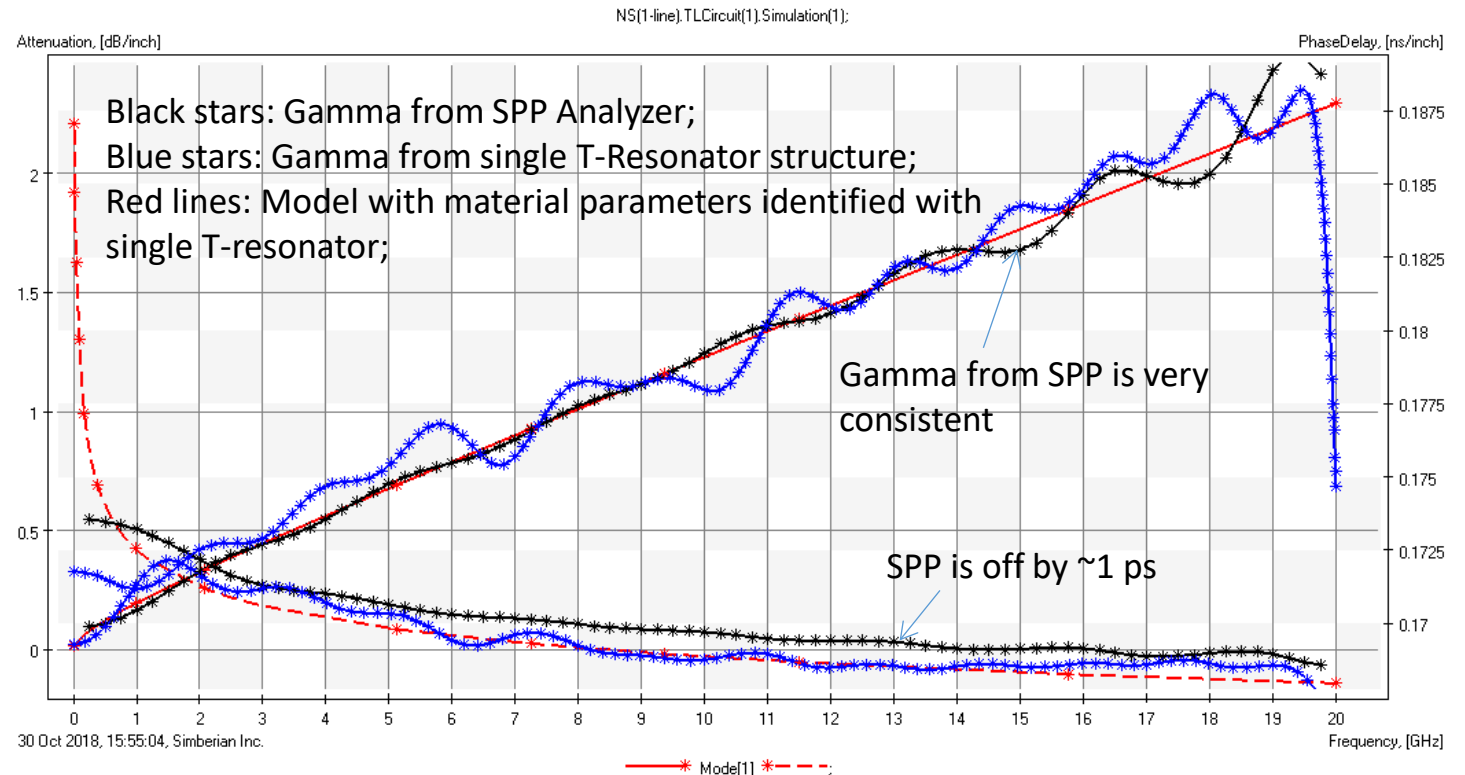
- Short T-Resonator, hand-held probes, TDT (RR=1.3, SR=0.2, RF=7): LT=0.0165 @ 715.8 MHz
- Short T-Resonator, RF probes, S-parameters (RR=1.3, SR=0.2, RF=7): LT=0.0128 @ 718.8 MHz
- Single T-Resonator RF probes, S-parameters (RR=1.3, SR=0.2, RF=7): LT=0.0138 @ 733.0 MHz

Extracted with Simbeor T-Resonator Analyzer (complete T-resonator model is used for computation of Q_c)



Ripples in pulses on t-line segment do not have such Gamma distortion effect as on single T-resonator

Acceptable correspondence!



Conclusion

- Single T-Resonator extraction method may be used to extract material parameters with the dielectric and conductor loss separation up to ~15 GHz
- However, the approach is very sensitive to the reflections at the probes/launches – required RF probes and de-embedding in this case to get usable results
- Loss tangent extraction depends on conductor resistivity (cross-section) and roughness (large roughness losses)
 - Separate measurement of the bulk resistivity is required
 - Iterative refinement of the loss tangent extraction should be used in case of large conductor roughness
- Gamma-T approach is less sensitive to the reflection and can be used with the hand-held probes – it also allows separation of the losses and should be recommended at this point as more reliable technique (the result also depends on resistivity)