# Practical Identification of Dispersive Dielectric Models with Generalized Modal S-parameters for Analysis of Interconnects in 6-100 Gb/s Applications

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# Outline

- Project goals
- Computation of generalized modal S-parameters
- Measurement of generalized modal S-parameters
- Identification of dielectric models
- Practical examples
- Conclusion

# Why do we need broadband dielectric models?

- Insulators or dielectrics are the media where signals propagate along the conductors of interconnects
- PCB dielectrics exhibit strong **dependency on frequency**
- Dielectric constant and loss tangent changing substantially over the frequency band of multi-gigabit signal spectrum
  - From DC up to 20 GHz for 10-20 Gb/s
  - From DC up to 40 GHz  for 20-40 Gb/s

- *Dielectric models are the requisite foundation for performing meaningful electromagnetic verification of multi-gigabit interconnects*

# Why are obtaining accurate dielectric models so difficult?

- Manufacturers of dielectrics and PCBs provide measurements for dielectric constant and loss tangent typically at **one frequency point or at 2-3 points in the best cases**
- Only frequency-continuous models can describe dispersive behavior of PCB dielectrics over very wide bandwidth
- Simplified TDR-based methods and advanced microwave resonator-based methods do not produce dispersive dielectric models
- *Multi-gigabit interconnect design and compliance analysis must start with the identification of the dielectric properties over the frequency band of interest*

# Project goals

- Develop **simple and accurate method** for dispersive dielectric parameters identification
  - Use VNA and SOLT calibration only (no TRL)
  - Suitable both for test and production boards

- Verify it on low-cost high-loss FR-4 and on low-loss high-performance composite dielectrics

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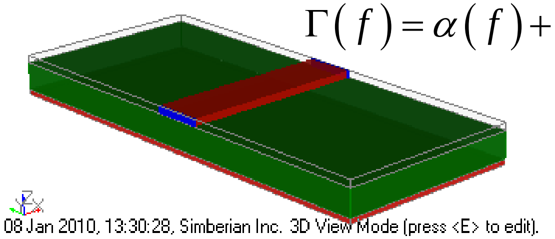
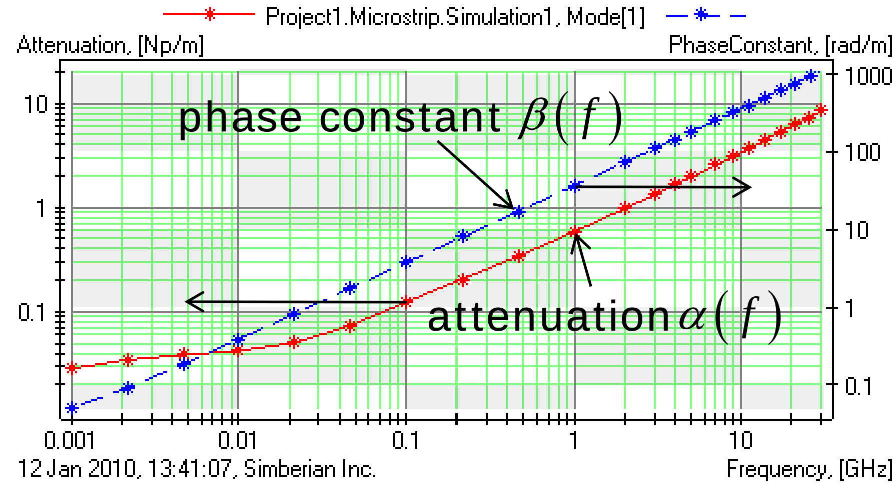
# Generalized modal S-parameters for single conductor line

1. Compute propagation constant (Gamma)

$$\Gamma(f) = \alpha(f) + i \cdot \beta(f)$$

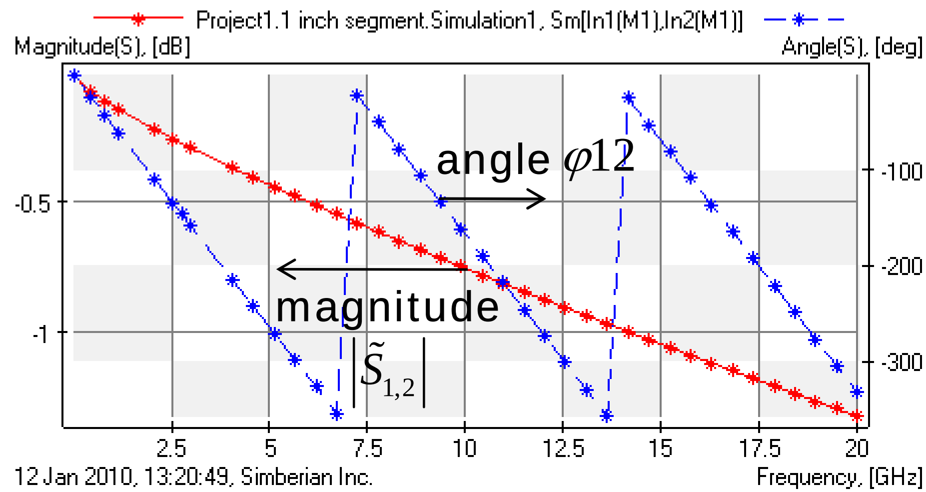



2. Compute 2x2 Sg of line segment with length $l$

$$\tilde{S}g(f,l) = \begin{bmatrix} 0 & \tilde{S}_{1,2} \\ \tilde{S}_{1,2} & 0 \end{bmatrix}$$

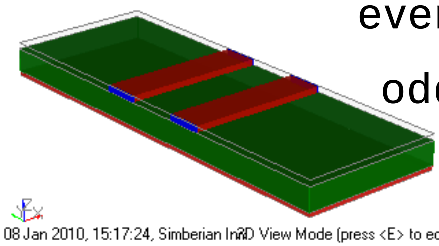
$$\tilde{S}_{1,2} = e^{-\Gamma(f) \cdot l} = \left|\tilde{S}_{1,2}\right| e^{i \cdot \varphi 12}$$




*Very simple!*

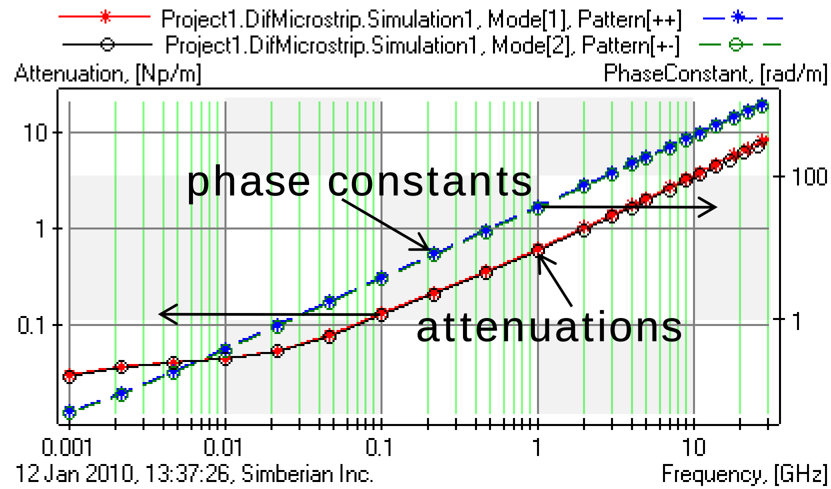
# Generalized modal S-parameters for two-conductor line

1. Compute propagation constants for 2 modes




even $\Gamma_1(f) = \alpha_1(f) + i \cdot \beta_1(f)$

odd $\Gamma_2(f) = \alpha_2(f) + i \cdot \beta_2(f)$

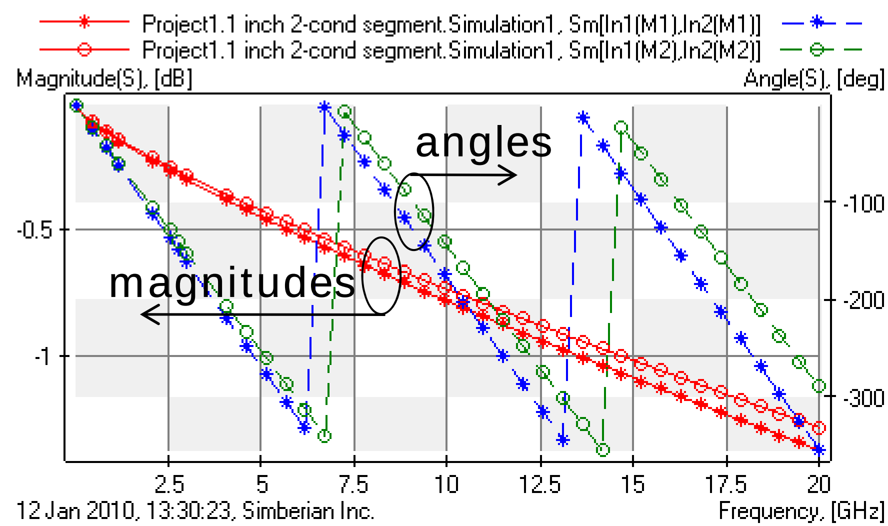



2. Compute 4x4 Sg of line segment with length $l$

$$\tilde{S}g(f,l) = \begin{bmatrix} 0 & 0 & \tilde{S}_{1,3} & 0 \\ 0 & 0 & 0 & \tilde{S}_{2,4} \\ \tilde{S}_{1,3} & 0 & 0 & 0 \\ 0 & \tilde{S}_{2,4} & 0 & 0 \end{bmatrix}$$

$$\tilde{S}_{1,3} = e^{-\Gamma_1(f) \cdot l}$$

$$\tilde{S}_{2,4} = e^{-\Gamma_2(f) \cdot l}$$

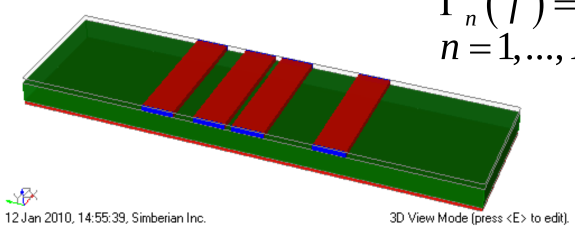


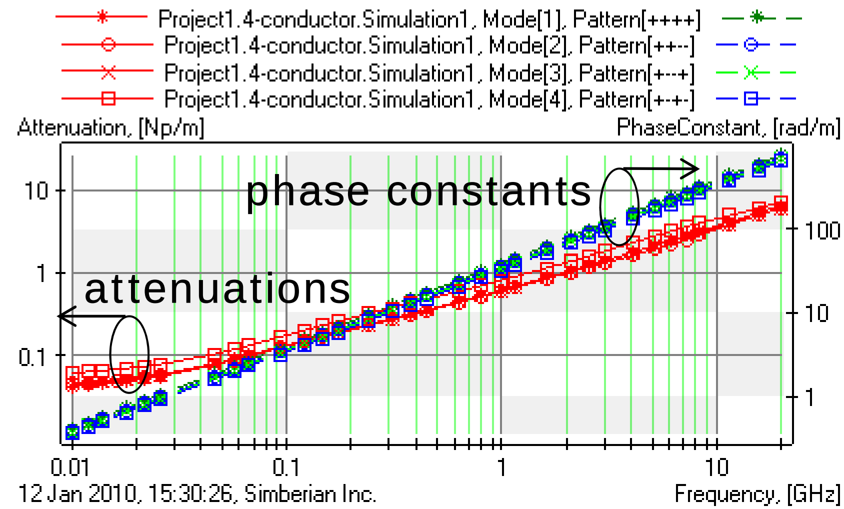

*Simple!*

# Generalized modal S-parameters for N-conductor line

1. Compute propagation constants for N modes

$$\Gamma_n(f) = \alpha_n(f) + i \cdot \beta_n(f),$$
$$n = 1, \ldots, N$$



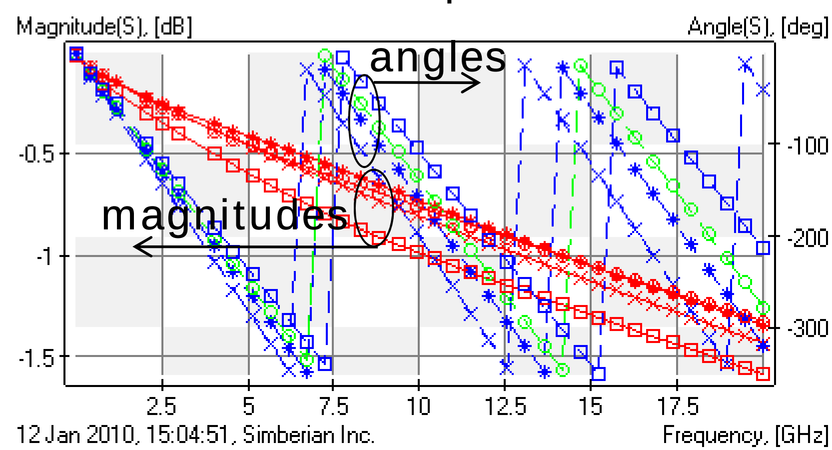




2. Compute NxN Sg of line segment with length $l$

$$\tilde{S}g(f,l) = \begin{bmatrix} 0 & Sm \\ Sm & 0 \end{bmatrix}$$

$$Sm = diag\left(e^{-\Gamma_n(f)\cdot l},\ n = 1, \ldots, N\right)$$

4 non-zero S-parameters




*Simple too!*

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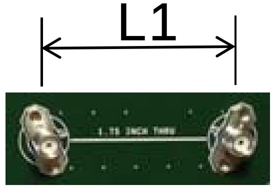
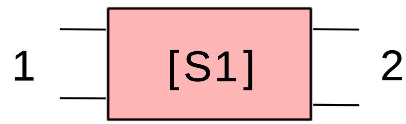
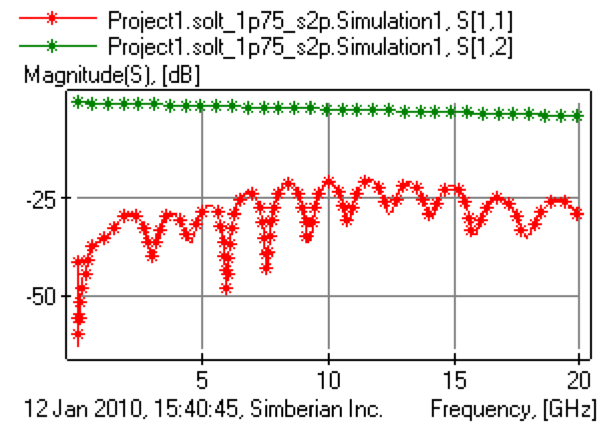
# Measure S-parameters of two line segments

- S1 for line with length L1



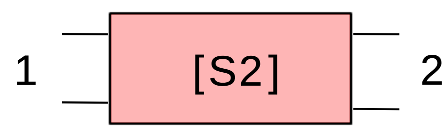

$$S1 = \begin{bmatrix} S1_{1,1} & S1_{1,2} \\ S1_{2,1} & S1_{2,2} \end{bmatrix}$$

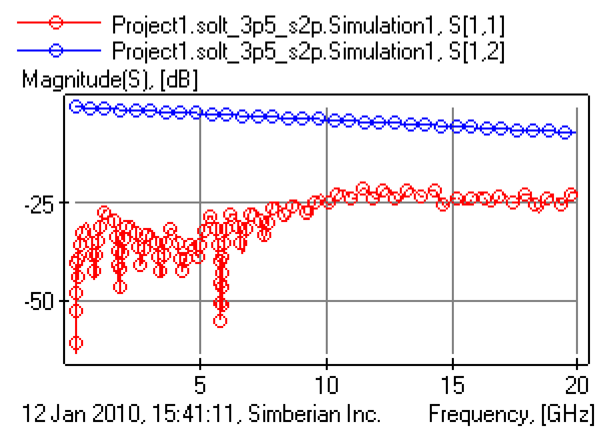


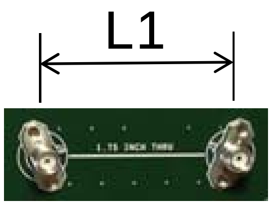

- S2 for line with length L2


$$S2 = \begin{bmatrix} S2_{1,1} & S2_{1,2} \\ S2_{2,1} & S2_{2,2} \end{bmatrix}$$



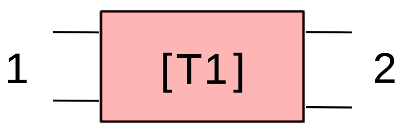
# Convert S-parameters of line segments into T-parameters

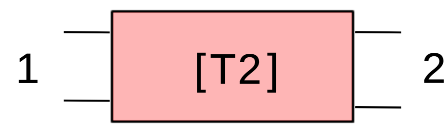




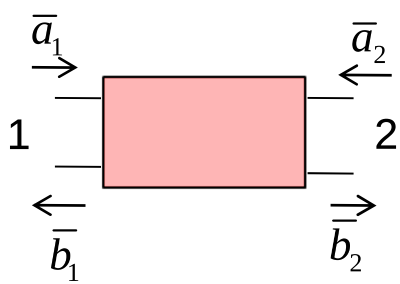
$$S1=\begin{bmatrix} S1_{1,1} & S1_{1,2} \\ S1_{2,1} & S1_{2,2} \end{bmatrix} \Rightarrow T1=\begin{bmatrix} T1_{1,1} & T1_{1,2} \\ T1_{2,1} & T1_{2,2} \end{bmatrix}$$

$$S2=\begin{bmatrix} S2_{1,1} & S2_{1,2} \\ S2_{2,1} & S2_{2,2} \end{bmatrix} \Rightarrow T2=\begin{bmatrix} T2_{1,1} & T2_{1,2} \\ T2_{2,1} & T2_{2,2} \end{bmatrix}$$




conversion equations



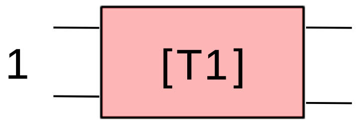

$$\begin{vmatrix} \bar{b}_1 \\ \bar{b}_2 \end{vmatrix} = \begin{bmatrix} S_{1,1} & S_{1,2} \\ S_{2,1} & S_{2,2} \end{bmatrix} \cdot \begin{vmatrix} \bar{a}_1 \\ \bar{a}_2 \end{vmatrix} \Rightarrow \begin{vmatrix} \bar{b}_1 \\ \bar{a}_1 \end{vmatrix} = \begin{bmatrix} T_{1,1} & T_{1,2} \\ T_{2,1} & T_{2,2} \end{bmatrix} \cdot \begin{vmatrix} \bar{a}_2 \\ \bar{b}_2 \end{vmatrix}$$

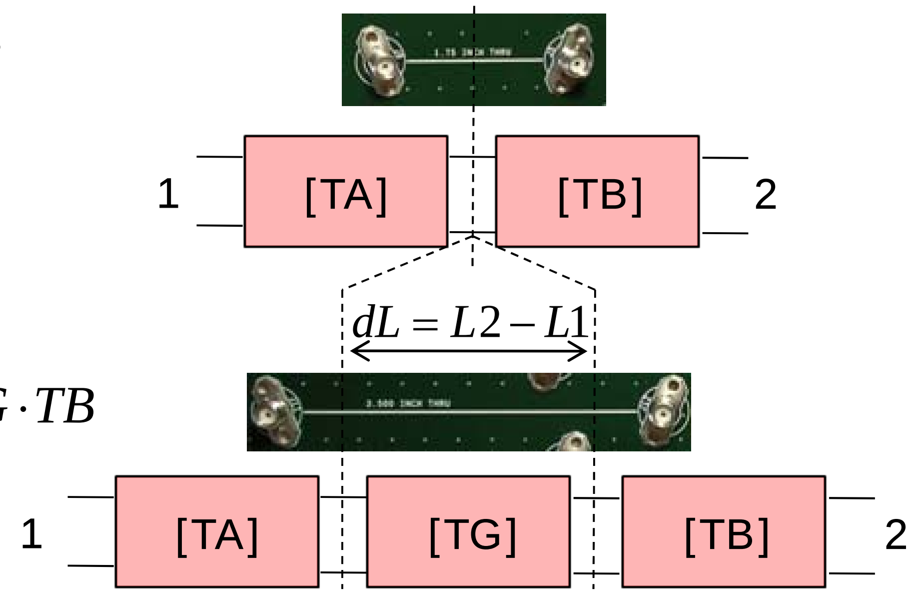
$$T_{1,1} = S_{2,1} - S_{1,1} \cdot S_{2,1}^{-1} \cdot S_{2,2} \qquad T_{2,1} = -S_{2,1}^{-1} \cdot S_{2,2}$$

$$T_{1,2} = S_{1,1} \cdot S_{2,1}^{-1} \qquad T_{2,2} = S_{2,1}^{-1}$$

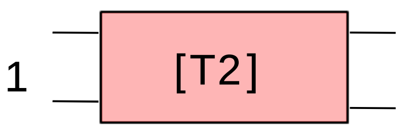
# T-matrices decomposition and TG

Segment L1 $T1 = TA \cdot TB$




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




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

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

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

*Easy to compute!*

$$TG = \begin{bmatrix} e^{-\Gamma(f) \cdot dL} & 0 \\ 0 & e^{\Gamma(f) \cdot dL} \end{bmatrix}$$ 1-conductor line

$$TG = \begin{bmatrix} Tm & 0 \\ 0 & (Tm)^{-1} \end{bmatrix}$$

$$Tm = diag\left(e^{-\Gamma_n(f) \cdot dL},\ n = 1, ..., N\right)$$

N-conductor line

# Convert TG into generalized modal S-parameters of the line difference

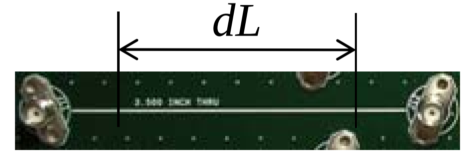
- 1-signal conductor case

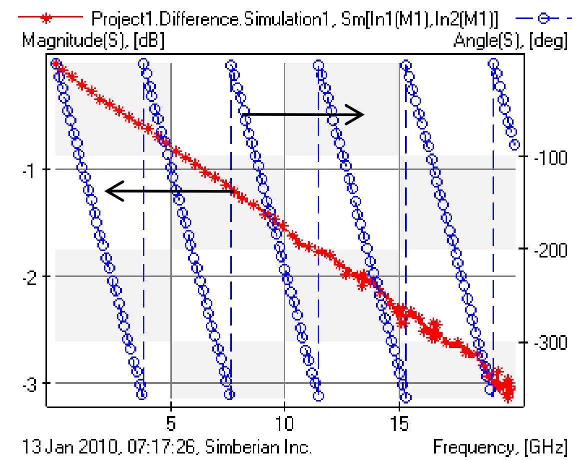
$$TG = \begin{bmatrix} e^{-\Gamma(f)\cdot dL} & 0 \\ 0 & e^{\Gamma(f)\cdot dL} \end{bmatrix} \Rightarrow SG = \begin{bmatrix} 0 & e^{-\Gamma(f)\cdot dL} \\ e^{-\Gamma(f)\cdot dL} & 0 \end{bmatrix}$$

- N-conductor case

$$TG = \begin{bmatrix} Tm & 0 \\ 0 & (Tm)^{-1} \end{bmatrix} \Rightarrow SG = \begin{bmatrix} 0 & Sm \\ Sm & 0 \end{bmatrix}$$

$$Sm = Tm = diag\left(e^{-\Gamma_n(f)\cdot dL},\ n = 1,...,N\right)$$




- Measured SG of the difference segment can be directly compared with calculated generalized modal S-parameters for dielectric parameters identification

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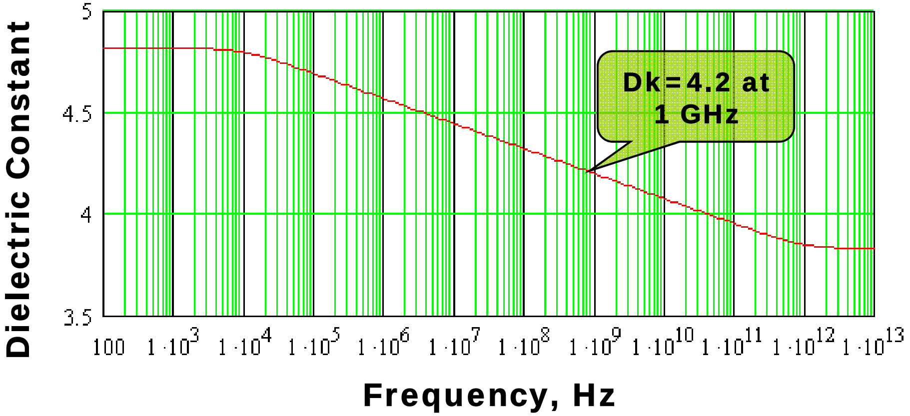
# Possible continuous dielectric model: Wideband Debye model

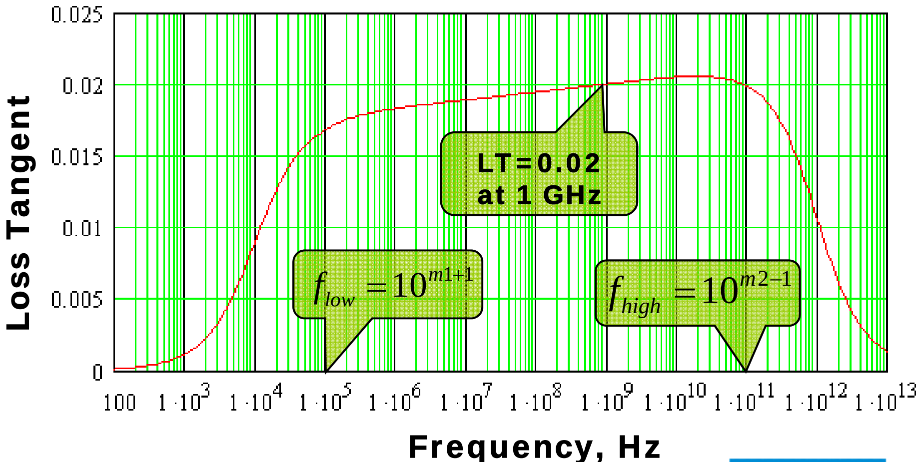
$$\varepsilon_{wd}(f) = \varepsilon_r(\infty) + \varepsilon_{rd} \cdot F_d(f)$$

$$F_d(f) = \frac{1}{(m_2 - m_1)\cdot \ln(10)} \cdot \ln\left[\frac{10^{m2} + if}{10^{m1} + if}\right]$$

- Continuous-spectrum model
- Requires specification of DK and LT at one frequency point
- Good match for high-loss FR-4 dielectrics (LT>0.01)
- Unfortunately does not provide good match for low-loss, high-frequency composites (LT<0.01)

Djordjevic, R.M. Biljic, V.D. Likar-Smiljanic, T.K.Sarkar, IEEE Trans. on EMC, vol. 43, N4, 2001, p. 662-667.

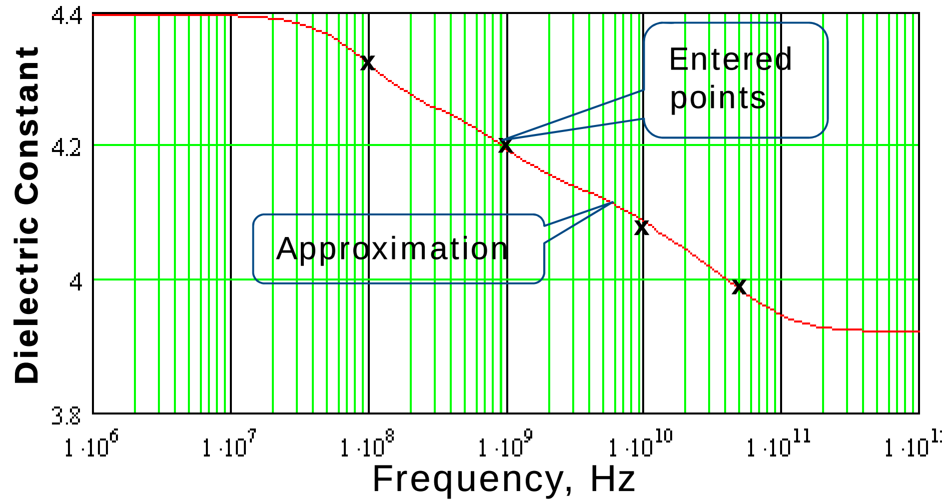


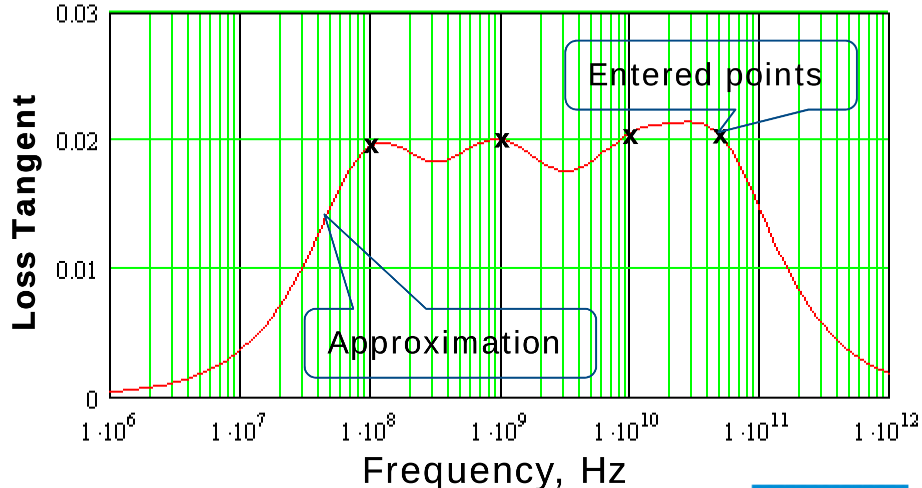



# Possible continuous dielectric model: Multi-pole Debye model

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

- Discrete-spectrum model
- Requires specification of DK and LT at multiple frequency points
- Can be used for any dielectric without resonances
- At least 4 poles (usually 10) are required for composite dielectrics for multi-gigabit signals



# Dielectric model identification procedure

- Measure S-parameters for two line segments S1 and S2
- Transform S1 and S2 to the T-matrices T1 and T2, diagonalize the product of T1 and inversed T2 and compute generalized modal S-parameters of the line difference SG
- Select dielectric model and guess values of the model parameters
- Compute generalize modal S-parameters Sg of the line difference segment by solving Maxwell's equation for t-line cross-sectioin (only propagation constants are needed)
- Compare simulated Sg and measured SG modal transmission parameters and adjust dielectric model until simulated data match the measured data

*Simberian's patent pending (application #61296237)*

# The technique is the simplest possible

- Needs SOLT-calibrated 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 zeros

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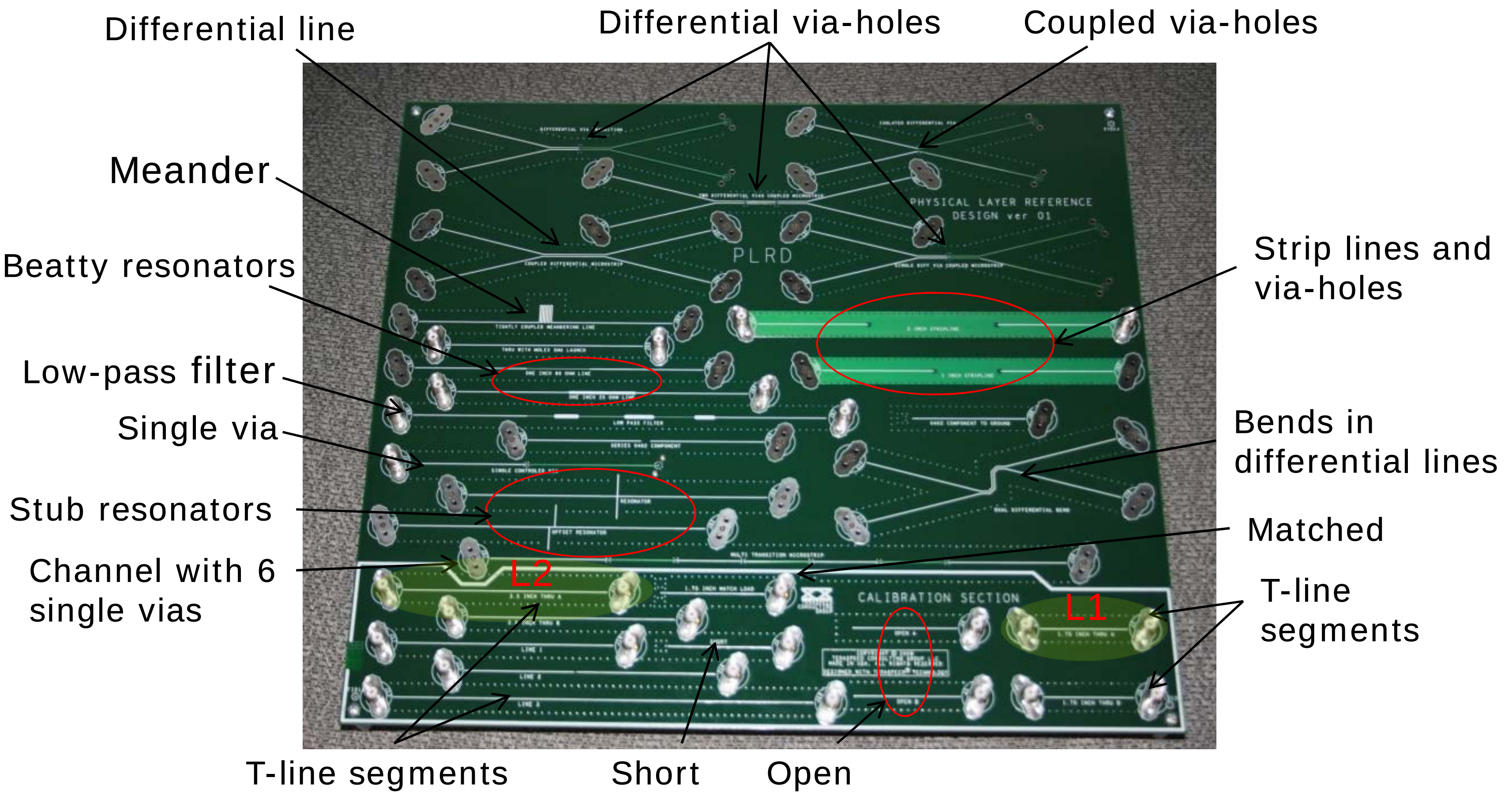
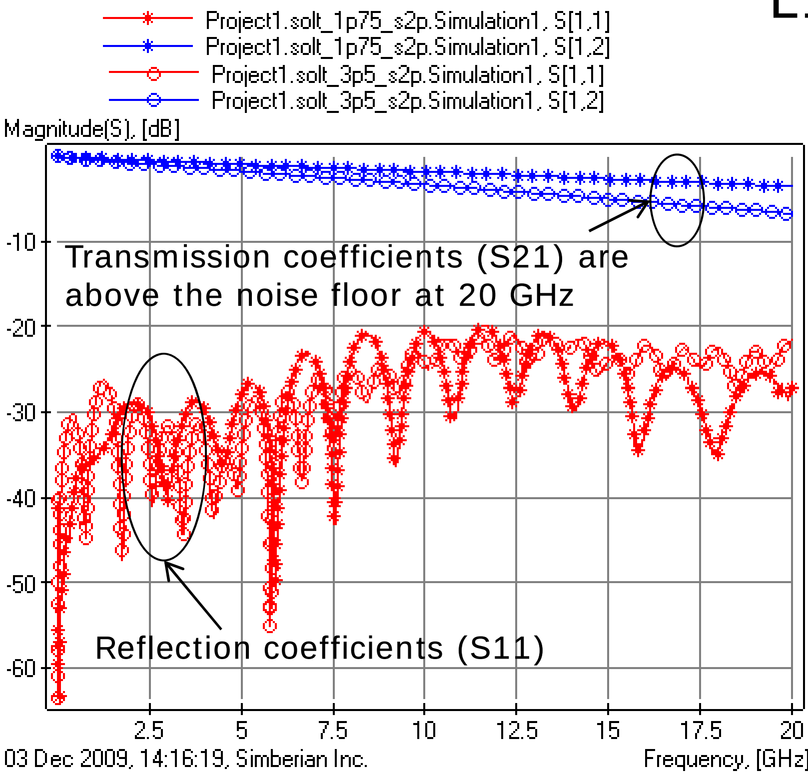
# PLRD-1 Physical Layer Test Vehicle

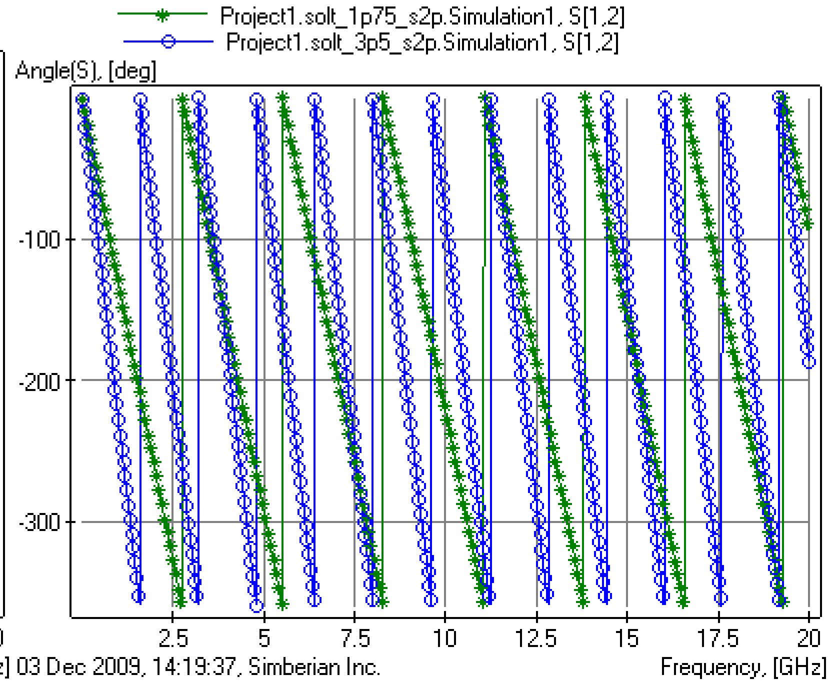
- 30 test structures – all equipped with SMA connectors with optimized launch



# S-parameters of line segments

L1 – stars, L2 – circles

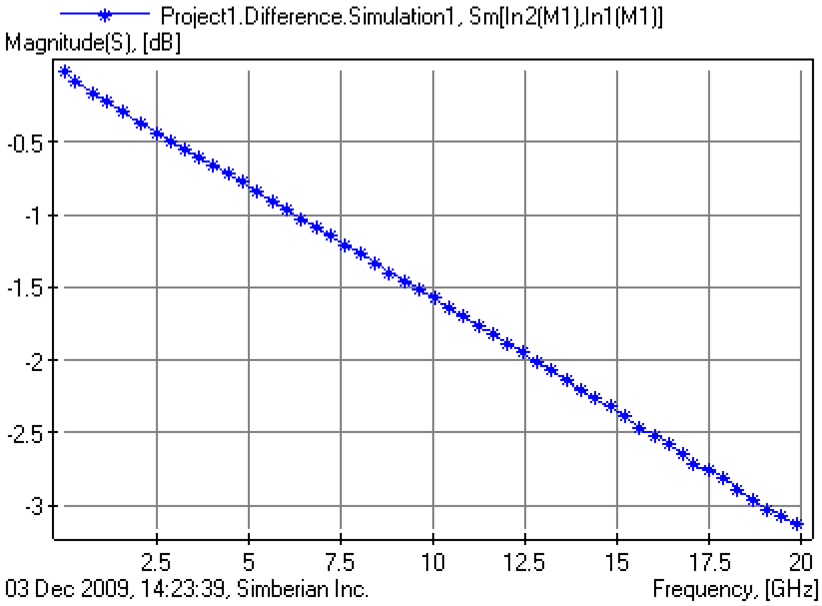


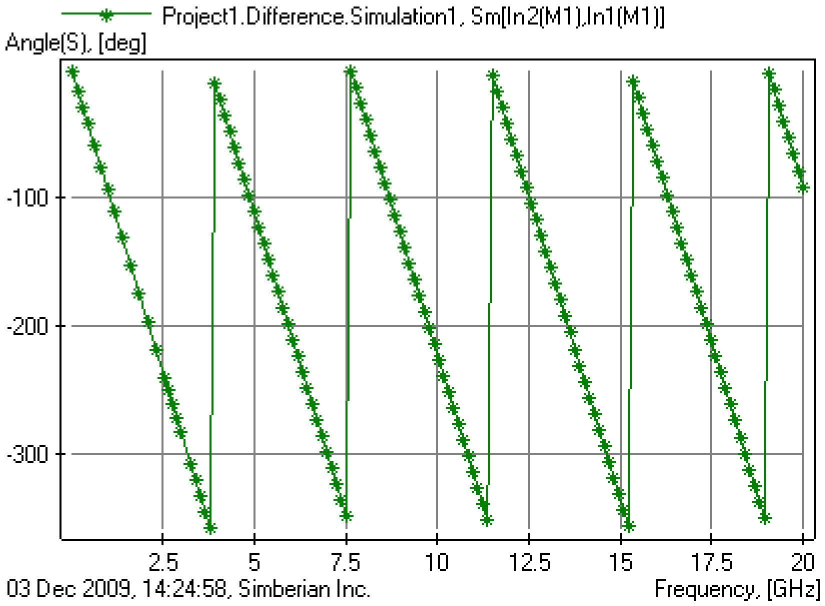




To use this data directly for the material parameters identification, we need to model transitions from/to the connectors or de-embed the launches

# Generalized S-parameters of dL segment

- Conversion to the modal generalized S-parameters gives us only the transmission coefficient (S12=S21) of the dominant micro-strip mode through the dL=1.75 inch segment

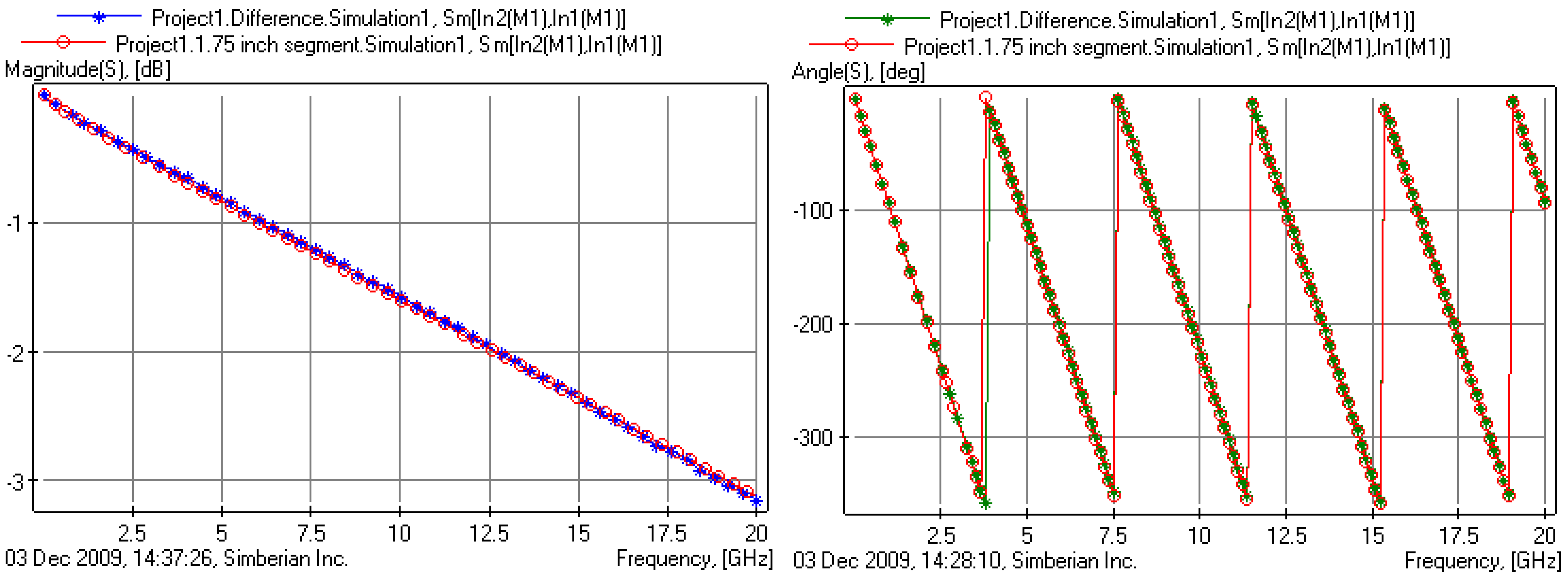



These data are suitable for the dielectric identification!

# DK and LT identification by comparison

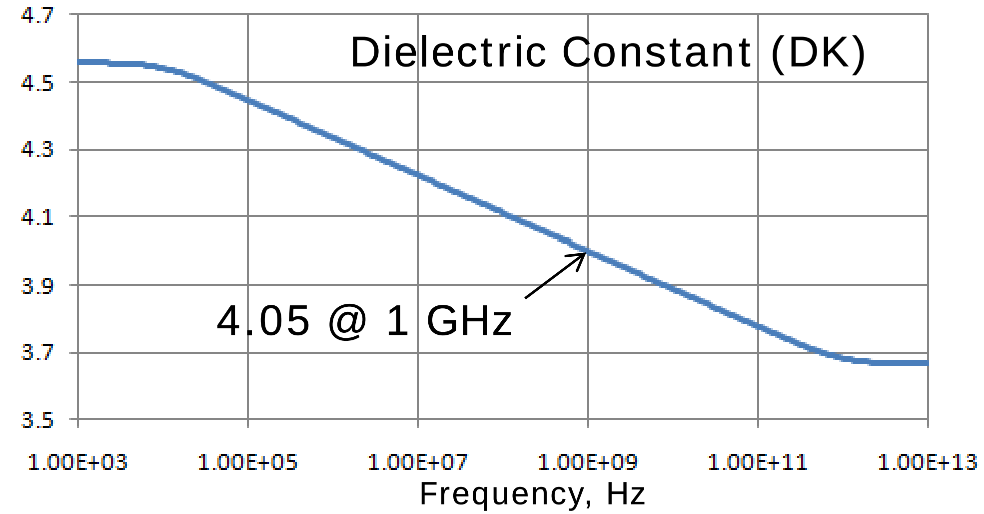
- Wide-band Debye dielectric model is used to compute S-parameters
- DK is adjusted to 4.05 @ 1 GHz to match the phase (right graph), and LT to 0.0195 @ 1GHz to match the attenuation (left graph)

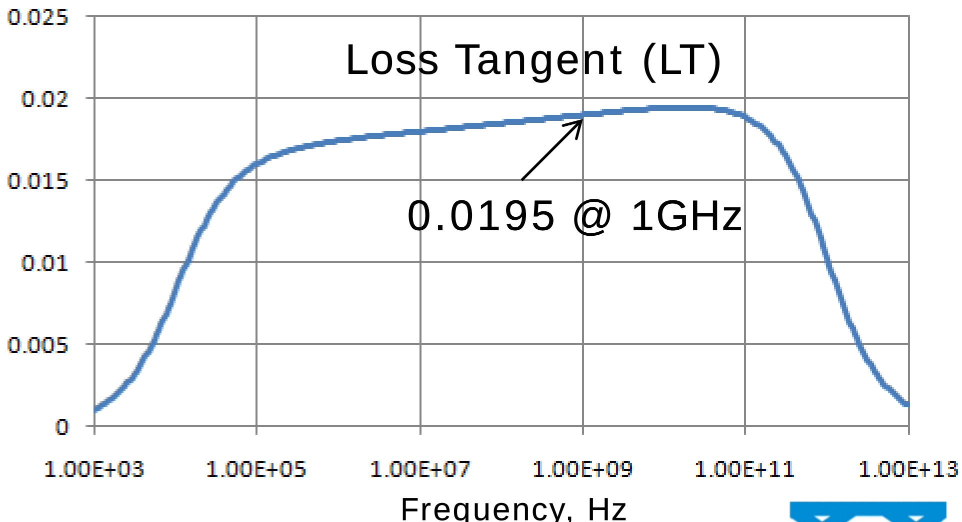



Stars – measured and circles are simulated modal generalized S-parameters of 1.75 inch micro-strip line segment

# Final dielectric model for PLRD-1 board

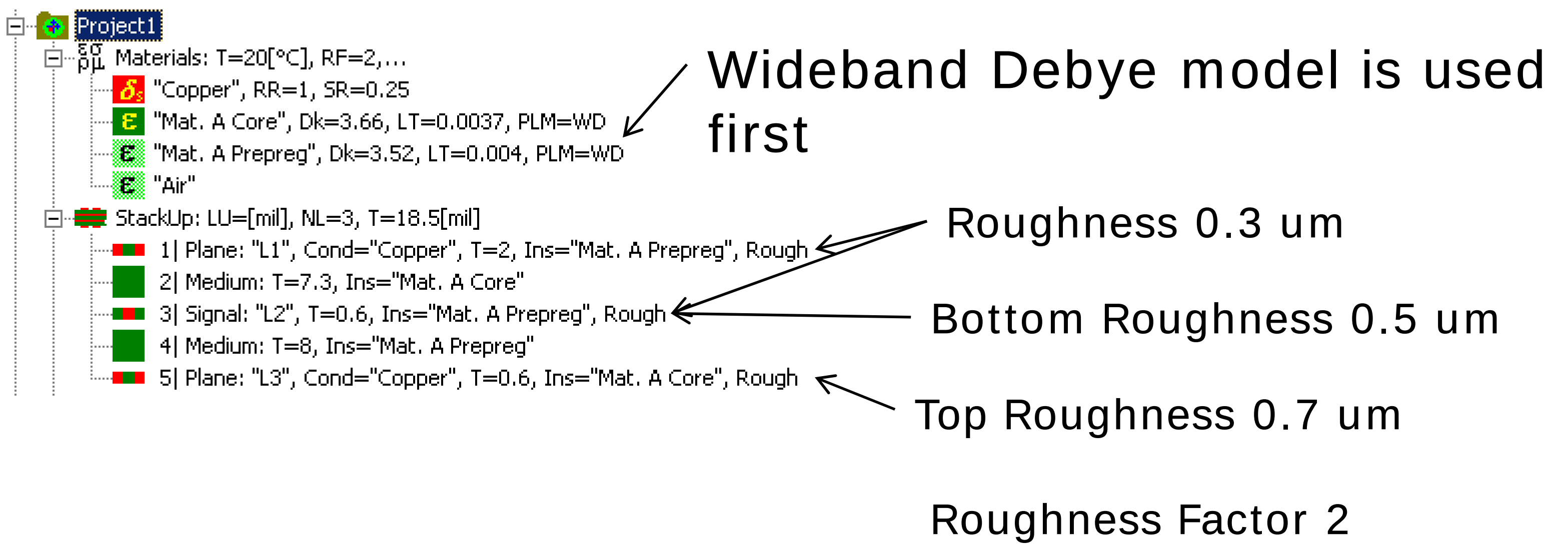
- Frequency-continuous wide-band Debye model
- DK is decreasing linearly on the log scale
- LT is almost constant
- Suitable for applications up to 100 Gb/s



# Material A specifications and stackup for strip-line structures

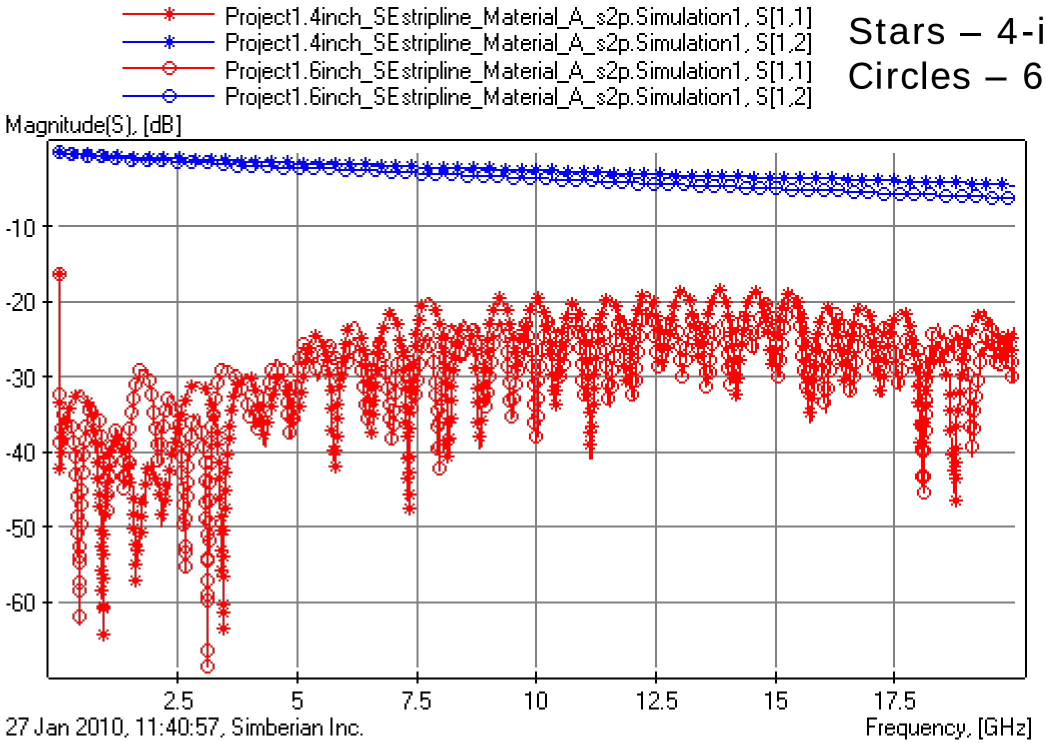
- Core (measured with clamped strip-line, IPC TM-650, #2.5.5.5):
  - DK=3.48, LT=0.0037 @ 10 GHz, 0.0031 @ 2.5 GHz
  - DK=3.66 is recommended for analysis
- Prepreg:
  - DK=3.52, LT=0.004 @ 10 GHz



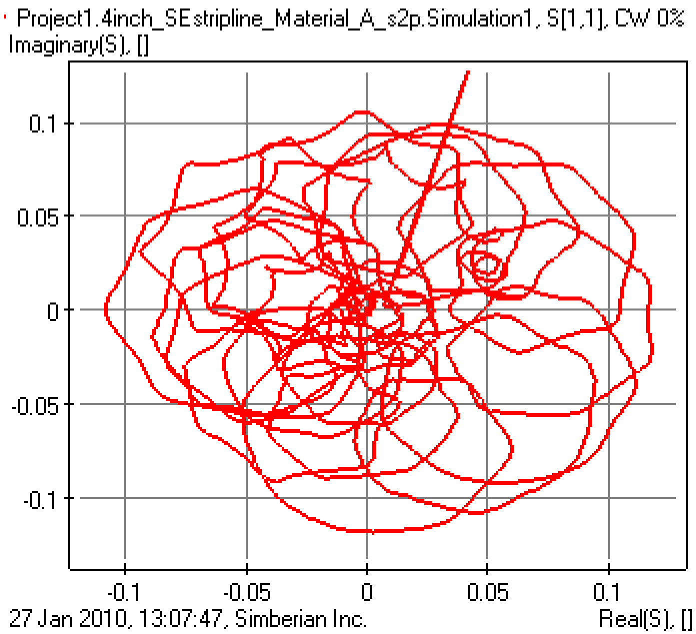
# 4 and 6 inch 50-Ohm strip-line segments with optimized launch

- 4-inch segment (stars): PQM=99.99%, RQM=96.27%, SQM=74%, CQM=0%
- 6-inch segment (circles): PQM=99.99%, RQM=96.8%, SQM=78%, CQM=0%



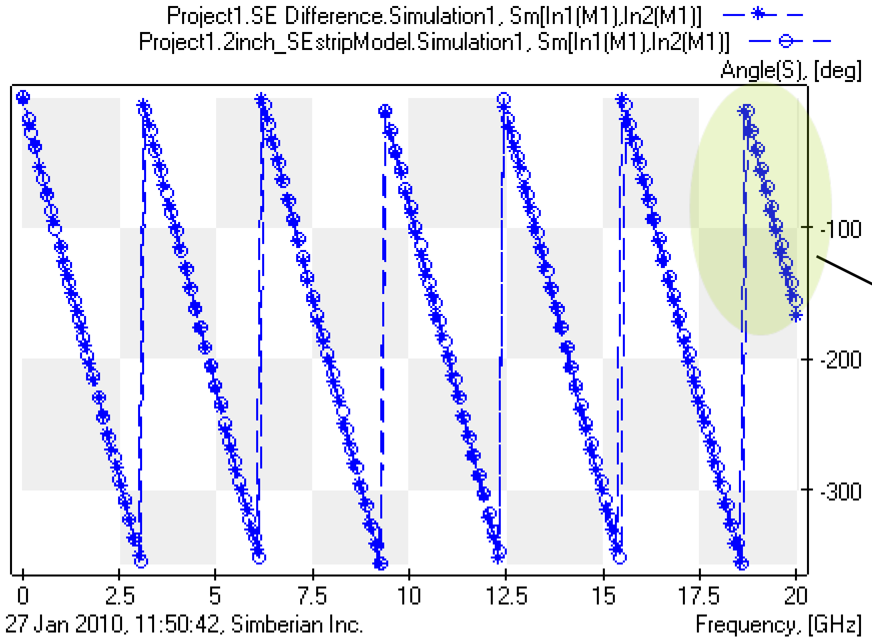

Stars – 4-inch line
Circles – 6-inch line

Causality measure is low due to noise in the return loss

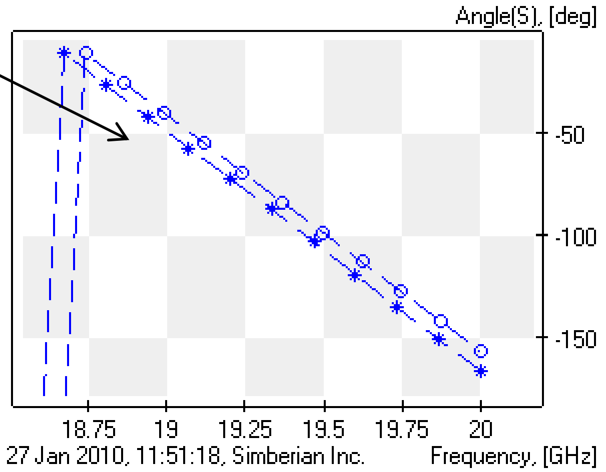


# Generalized modal transmission phase

- Computed angle is consistently smaller over the frequency band



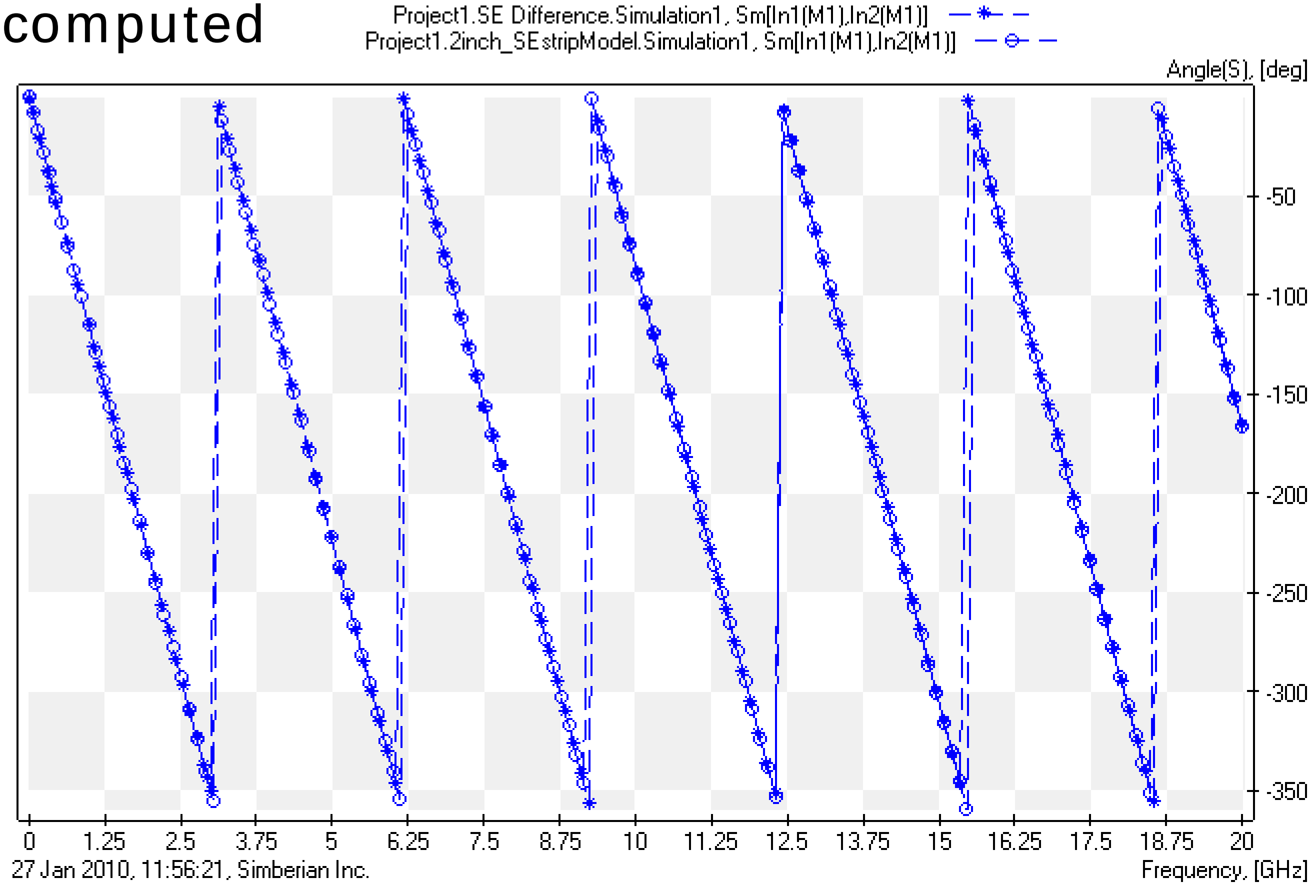

Stars - measured
Circles – computed




DK may be adjusted from 3.48 to 3.62 @ 10 GHz for core and prepreg for perfect match

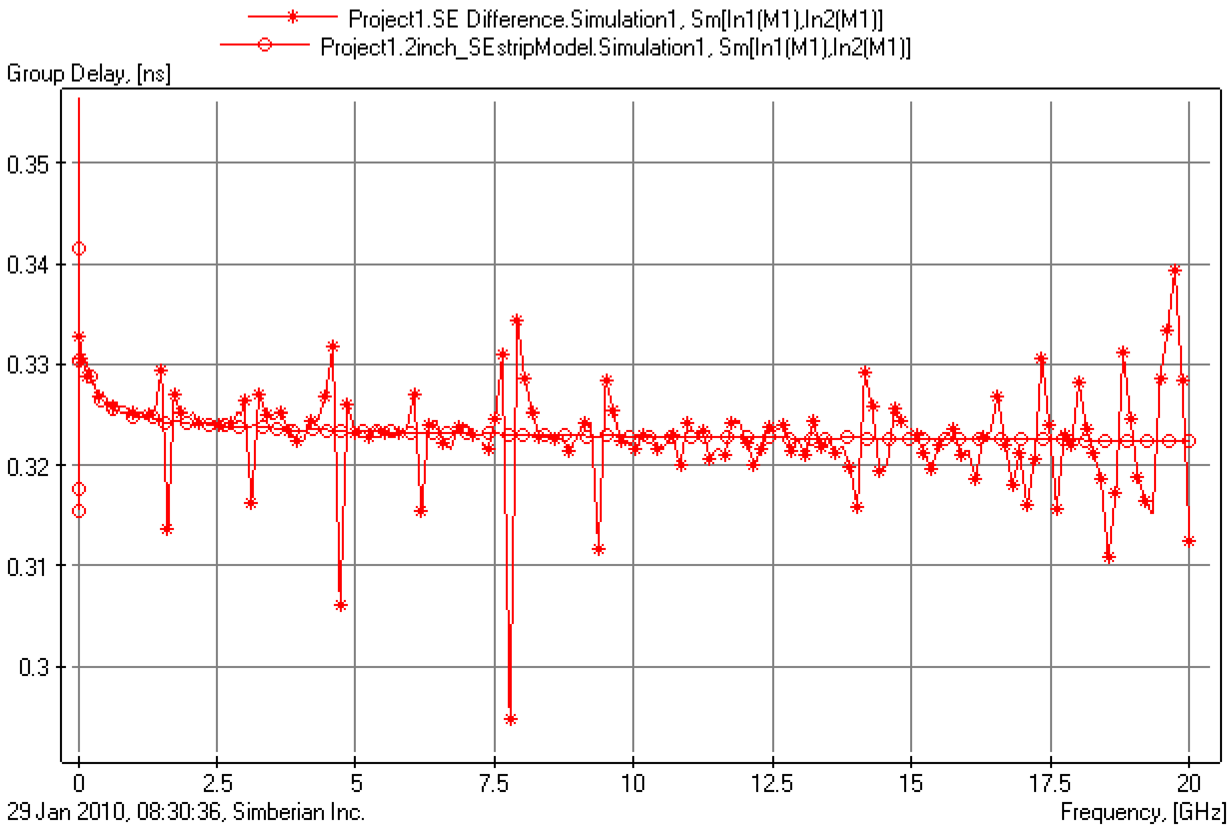
# Generalized modal transmission phase match with DK=3.62 @ 10 GHz

Stars - measured
Circles – computed



# Generalized modal group delay with DK=3.62 @ 10 GHz

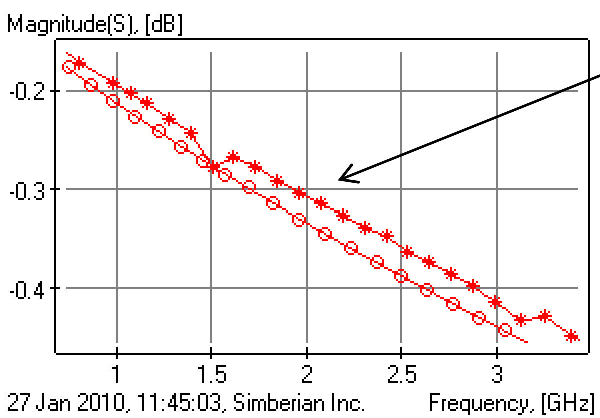
Stars - measured
Circles – computed

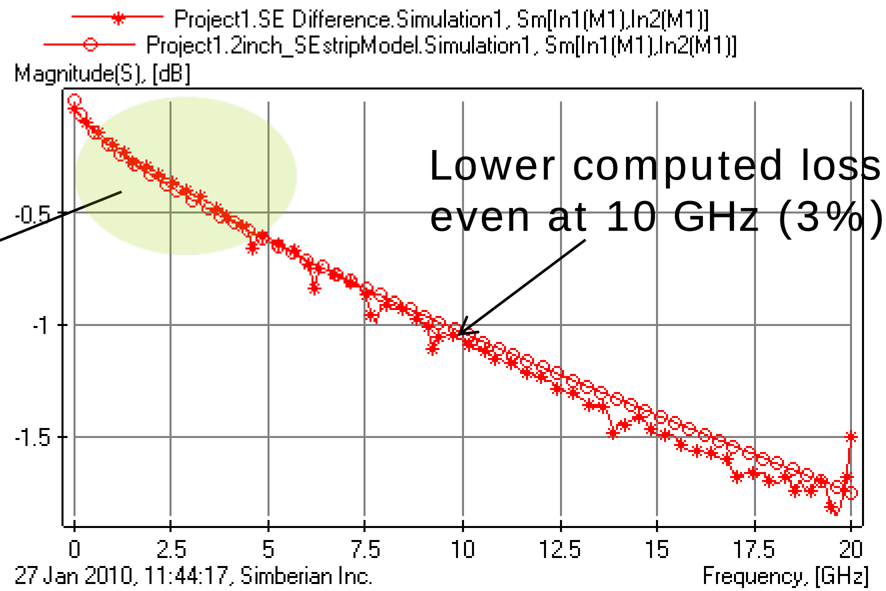


# Generalized modal attenuation parameter

- Computed attenuation is slightly larger then measured at lower frequencies and smaller at high frequencies

Stars - measured
Circles – computed




Lower computed loss even at 10 GHz (3%)

LT is smaller at lower frequencies and larger at higher
Roughness is probably too large too

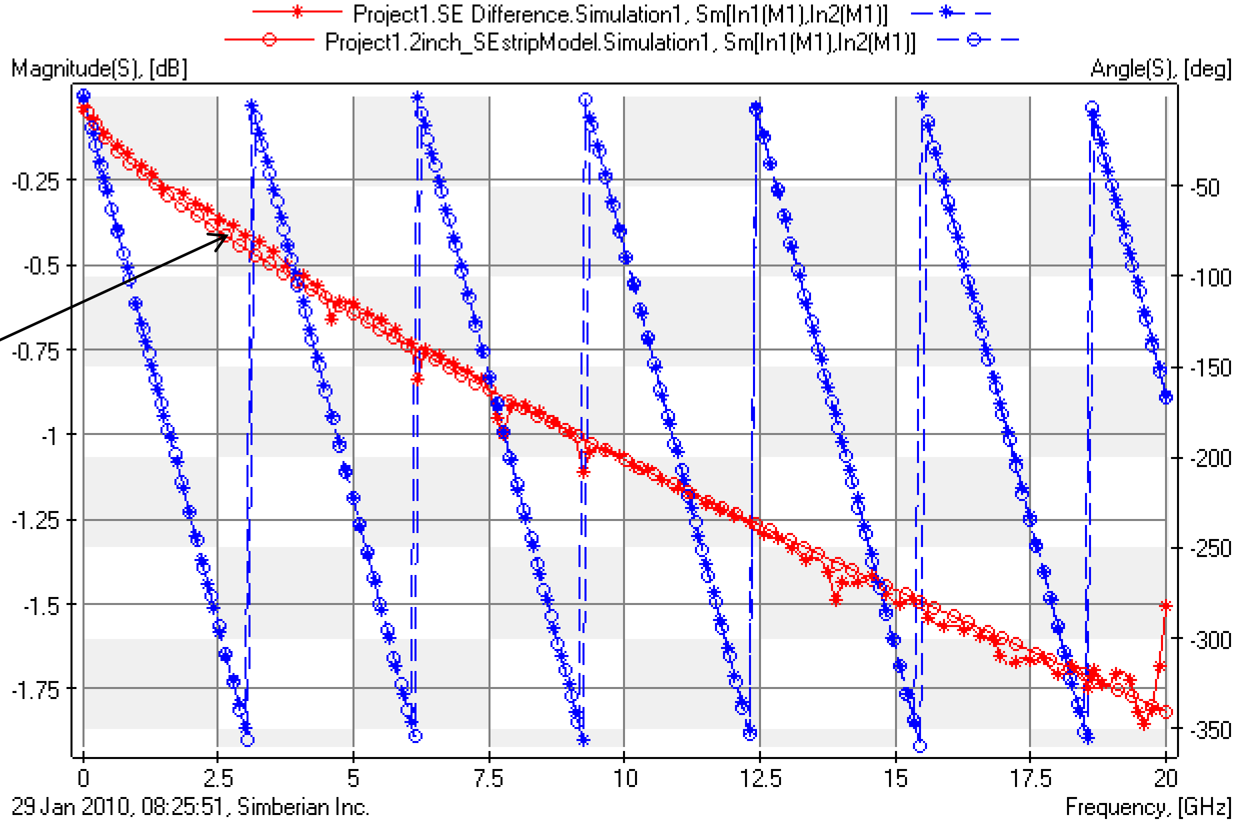
# Possible WD model adjustment

- Use wideband Debye model with DK=3.62 and LT=0.0038 @ 10 GHz both for core and prepreg
- Adjust roughness to 0.5 um (RF=2) for all conductor surfaces

Stars - measured
Circles – computed

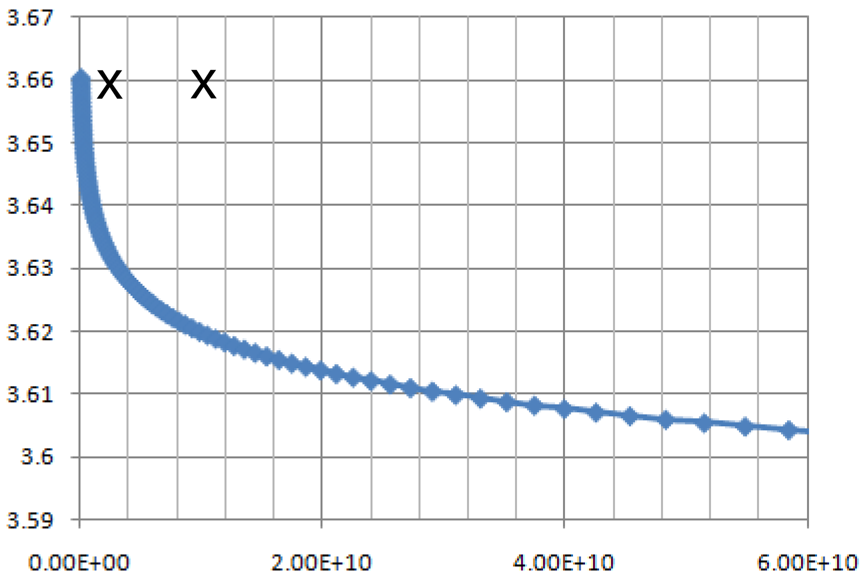
Minor deviation at lower frequencies

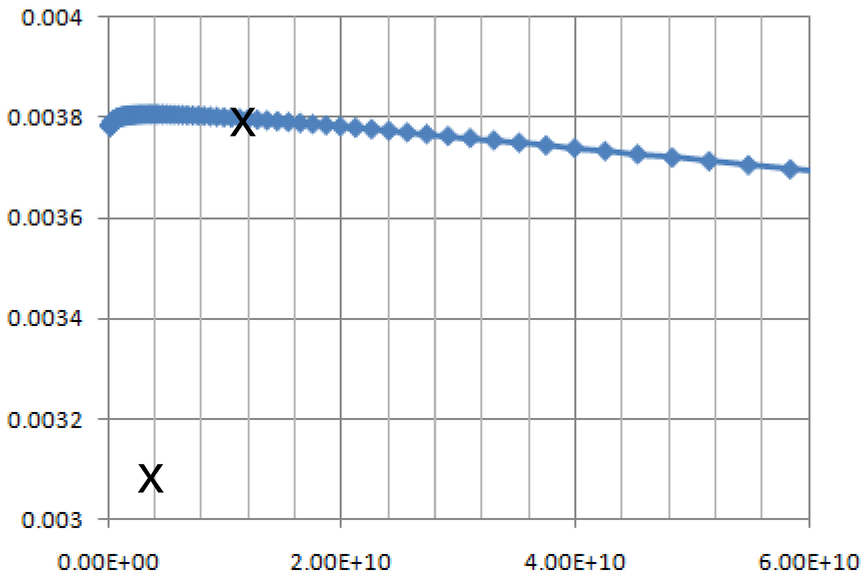
Phase and group delays are not changed



# Final Wideband Debye (WD) model

- Conductor model: RR=1; SR=0.5 um; RF=2

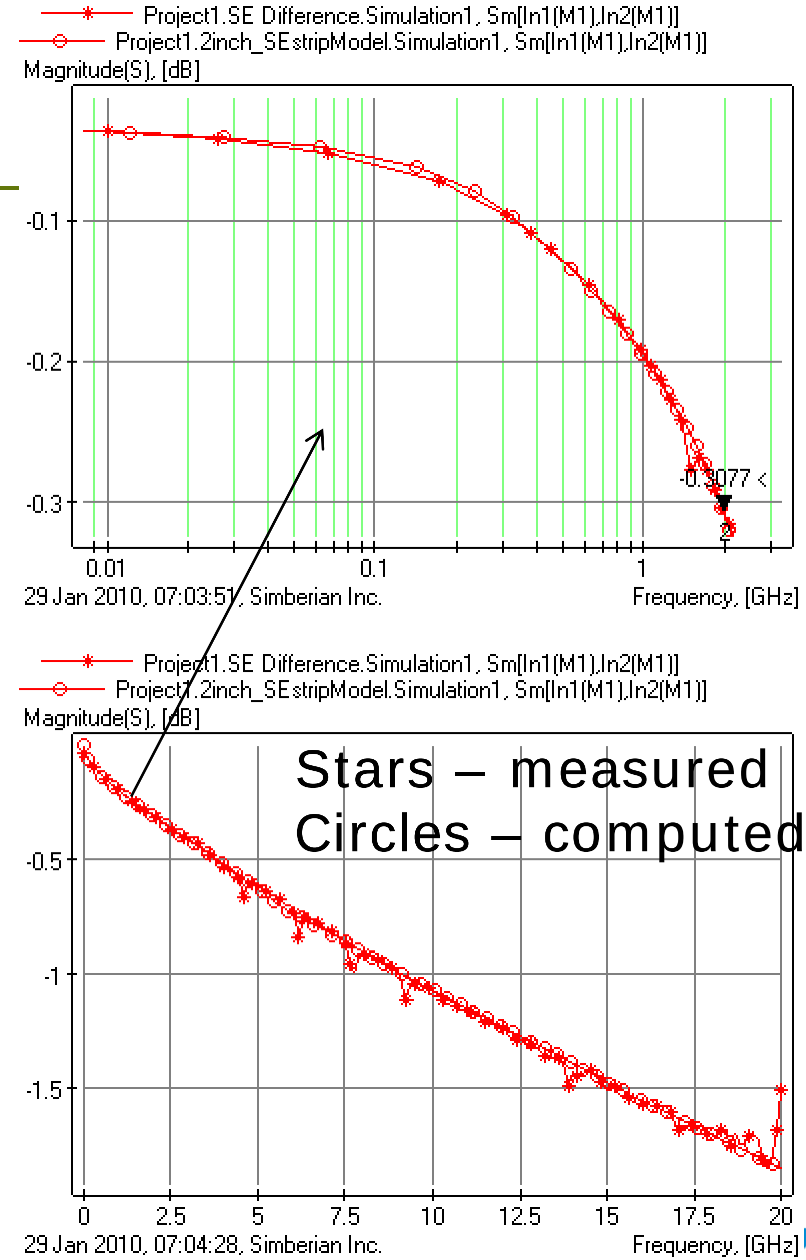



x – values from dielectric specifications

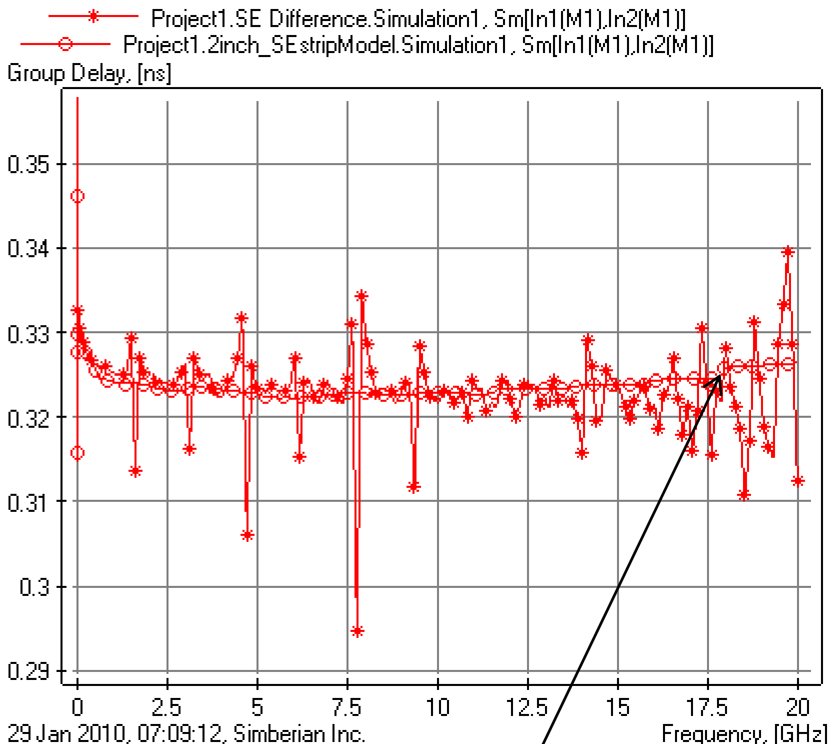
# Model adjustments (2)

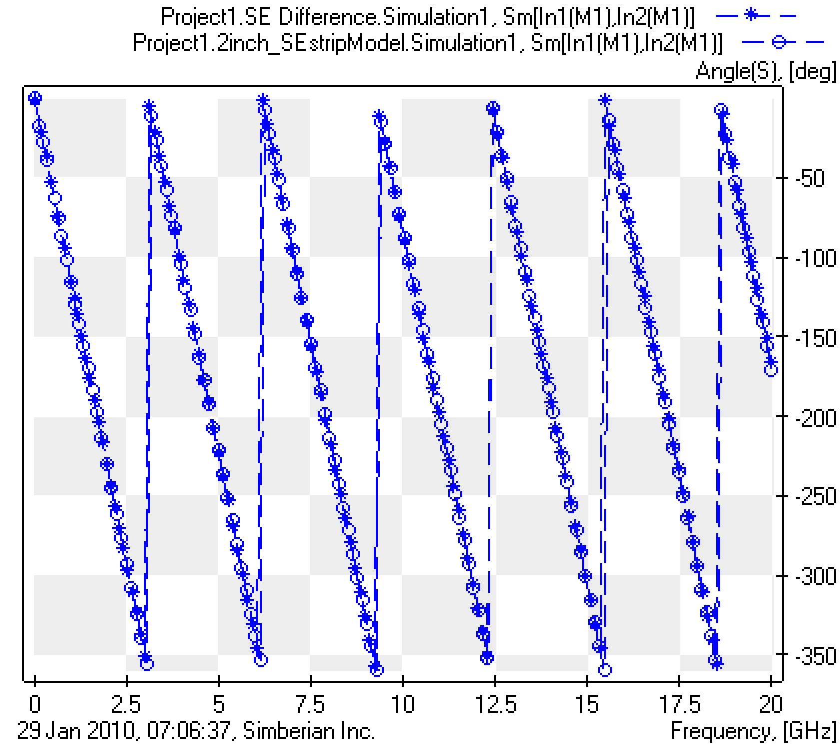
- To match DC to 1-2 GHz
  - Copper bulk resistivity relative to annealed copper is increased from 1 to 1.1
  - Roughness is adjusted to 0.25 um, RF=2 for all surfaces
- Debye model with 16 poles constructed to match transmission from 1-2 GHz to 20 GHz



# Phase and group delay for 16-pole Debye model

Stars – measured
Circles – computed

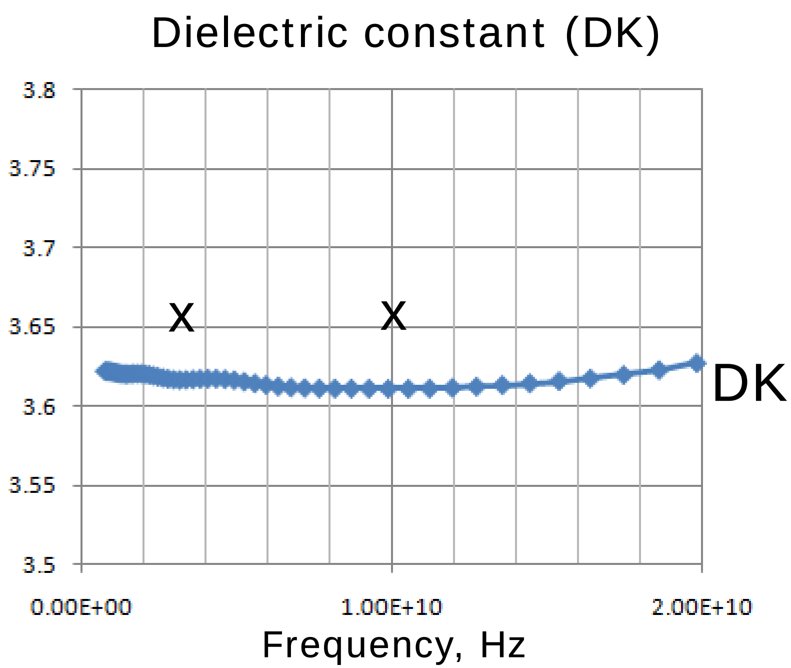


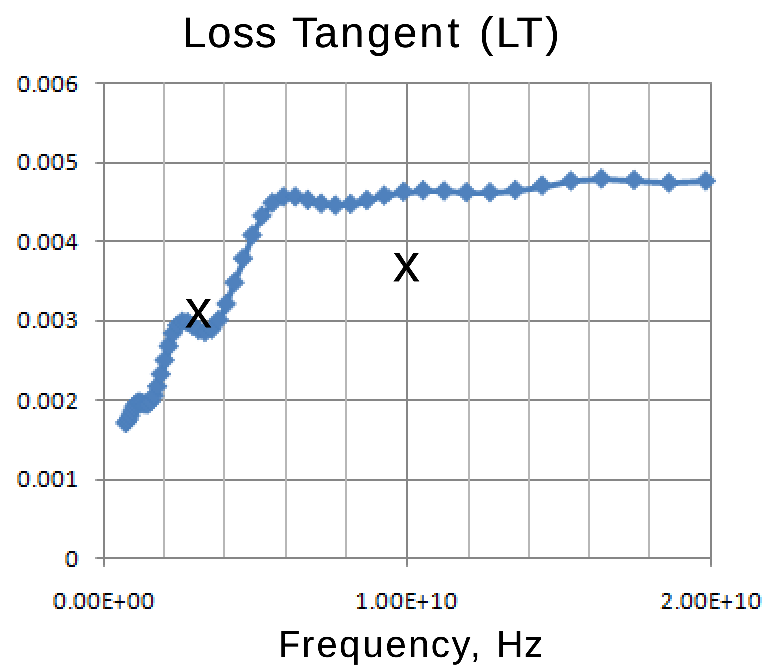




Slight upward trend in the model

# Final 16-pole Debye model

- Conductor model: RR=1.1; SR=0.25 um; RF=2

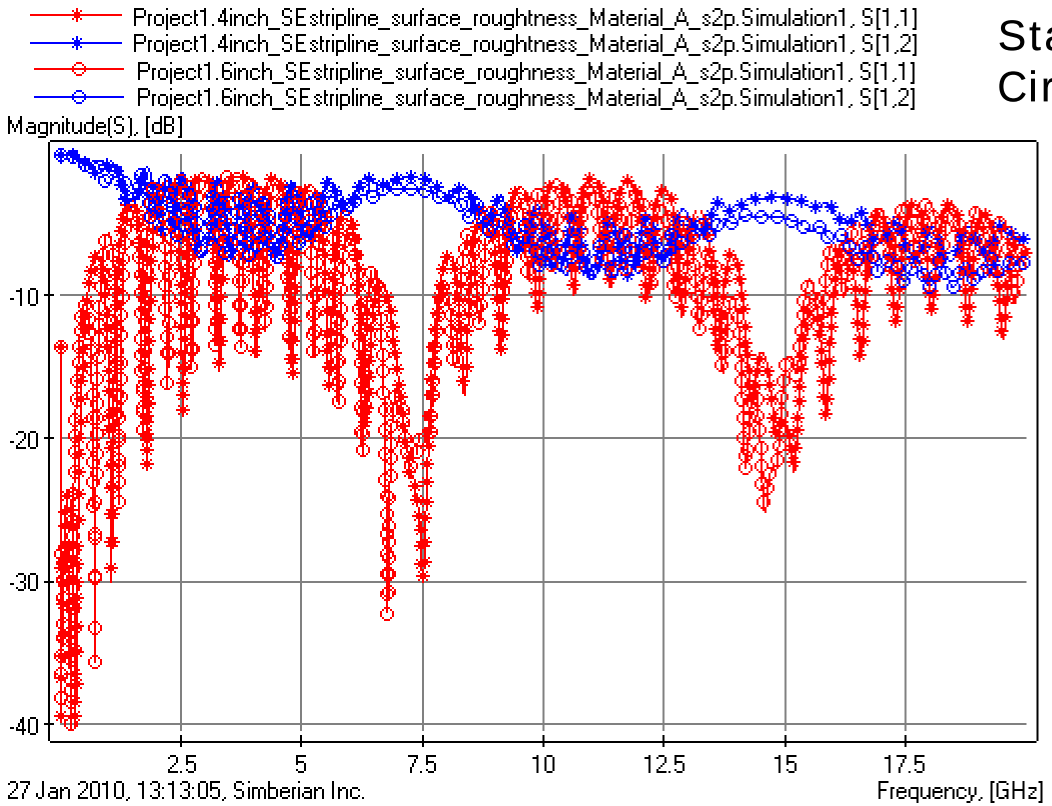



x – values from dielectric specifications

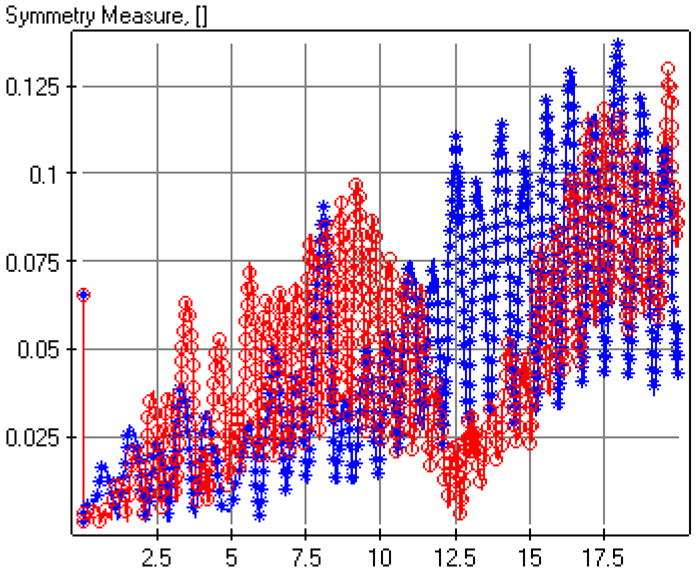
# 4 and 6 inch 25-Ohm strip-line segments (normalized to 25 Ohm)

- 4-inch segment (stars): PQM=99.99%, RQM=96.3%, SQM=51%, CQM=77%
- 6-inch segment (circles): PQM=99.99%, RQM=96.6%, SQM=52%, CQM=88%



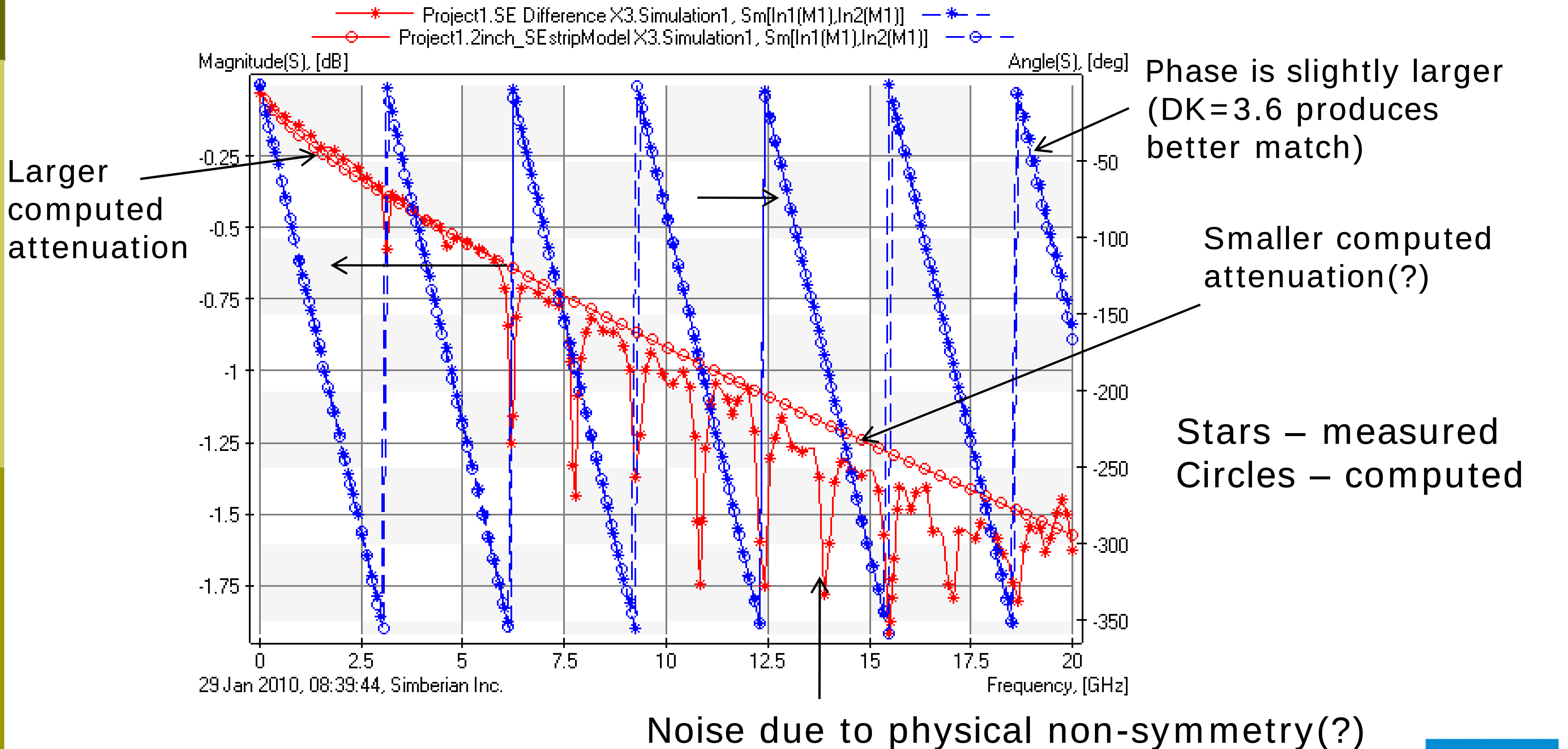

Stars – 4-inch line
Circles – 6-inch line

Symmetry quality measure is low due to physical non-symmetry



# Generalized modal transmission parameter for 25-Ohm strip-line

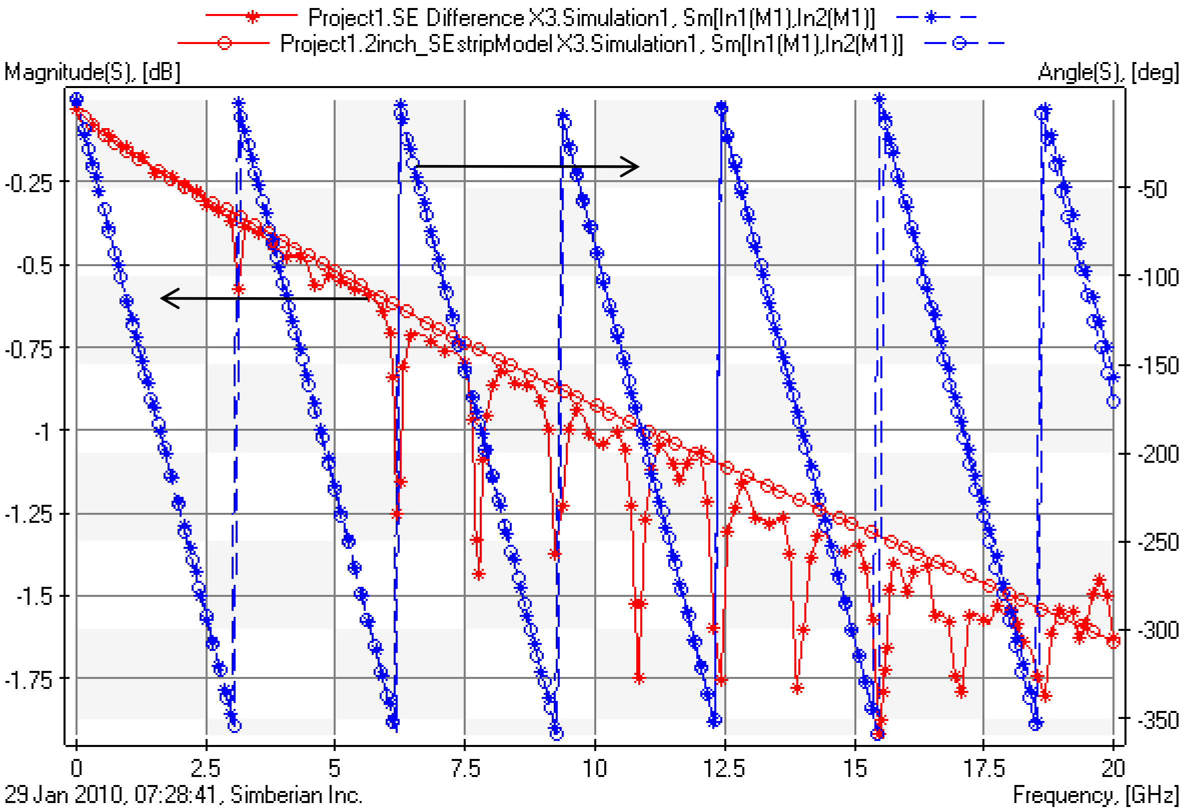
- Wideband Debye model: DK=3.62, LT=0.0038 @ 10 GHz
- Conductor: RR=1.0; SR=0.5 um; RF=2



# Generalized modal transmission parameter for 25-Ohm strip-line

- 16-pole Debye model
- RR=1.1; SR=0.25 um; RF=2

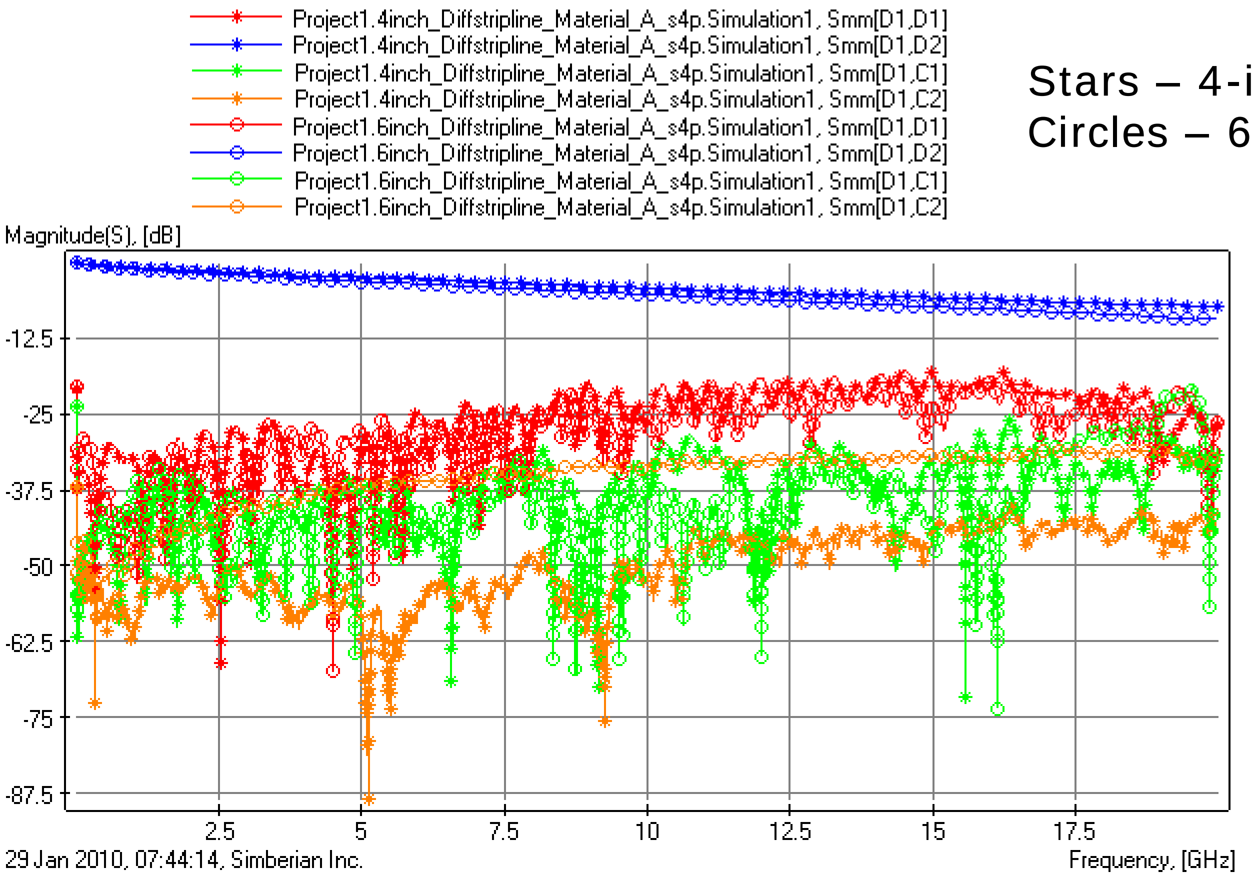
Good correspondence at lower frequencies, not conclusive at high frequencies due to noise




Stars – measured
Circles – computed

# 4 and 6 inch 100-Ohm differential strip-line segments

- 4-inch segment (stars): PQM=99.98%, RQM=99.1%, SQM=58%, CQM=9%
- 6-inch segment (circles): PQM=99.99%, RQM=99.3%, SQM=64%, CQM=17%

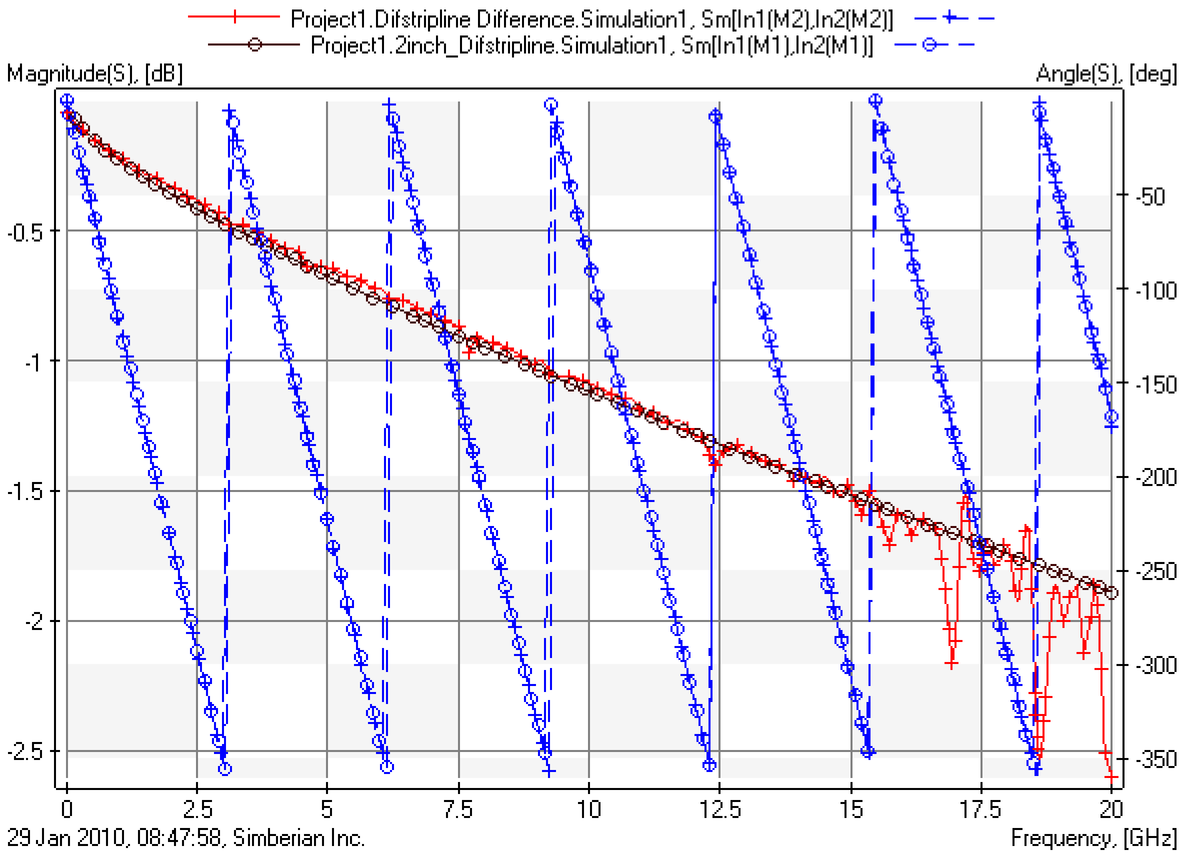



Stars – 4-inch line
Circles – 6-inch line

Mixed-Mode S-parameters

# Generalized odd mode transmission parameter with WD model

- Wideband Debye model: DK=3.62, LT=0.0038 @ 10 GHz
- Conductor: RR=1.0; SR=0.5 um; RF=2

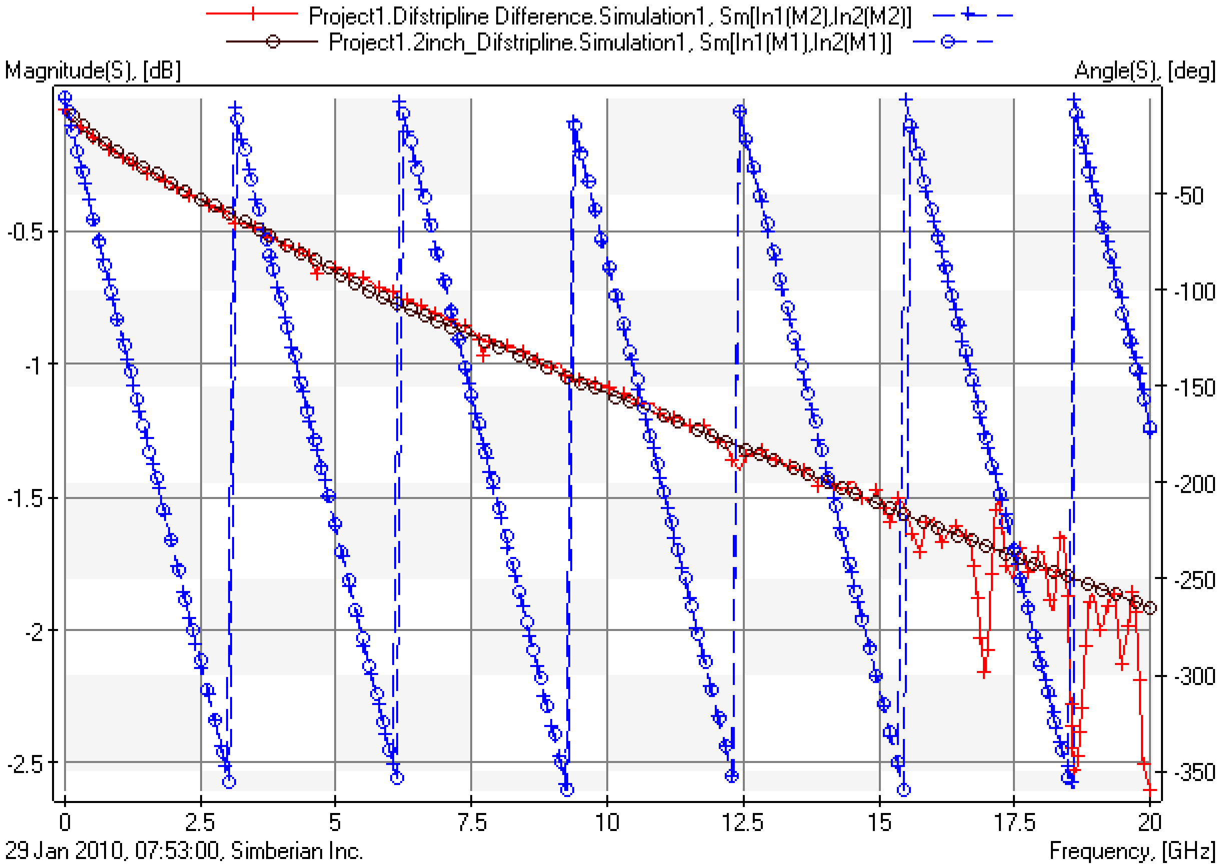



Pluses – measured;
Circles – computed;

Good correspondence!

# Generalized odd mode transmission parameter with 16-pole Debye model

- 16-pole Debye model
- RR=1.1; SR=0.25 um; RF=2

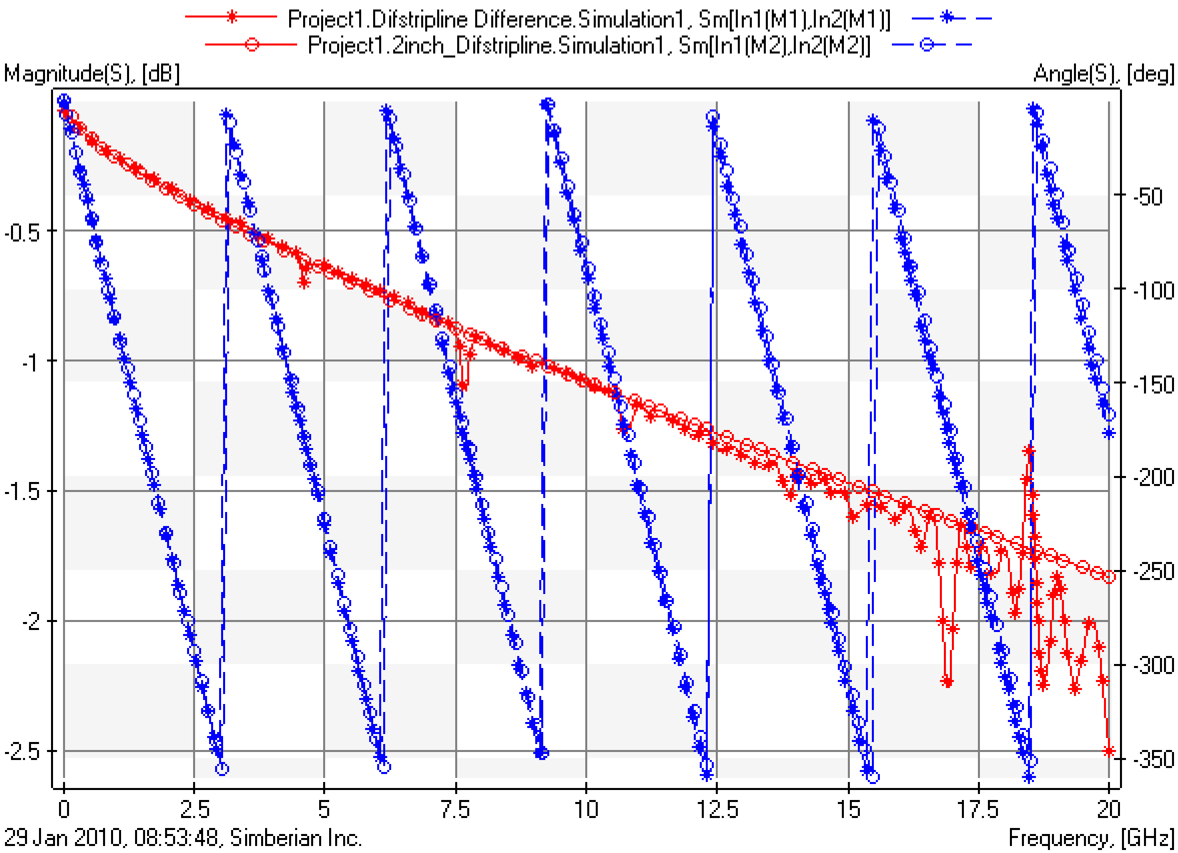



Pluses – measured;
Circles – computed;

Good correspondence!

# Generalized even mode transmission parameter with WD model

- Wideband Debye model: DK=3.62, LT=0.0038 @ 10 GHz
- Conductor: RR=1.0; SR=0.5 um; RF=2

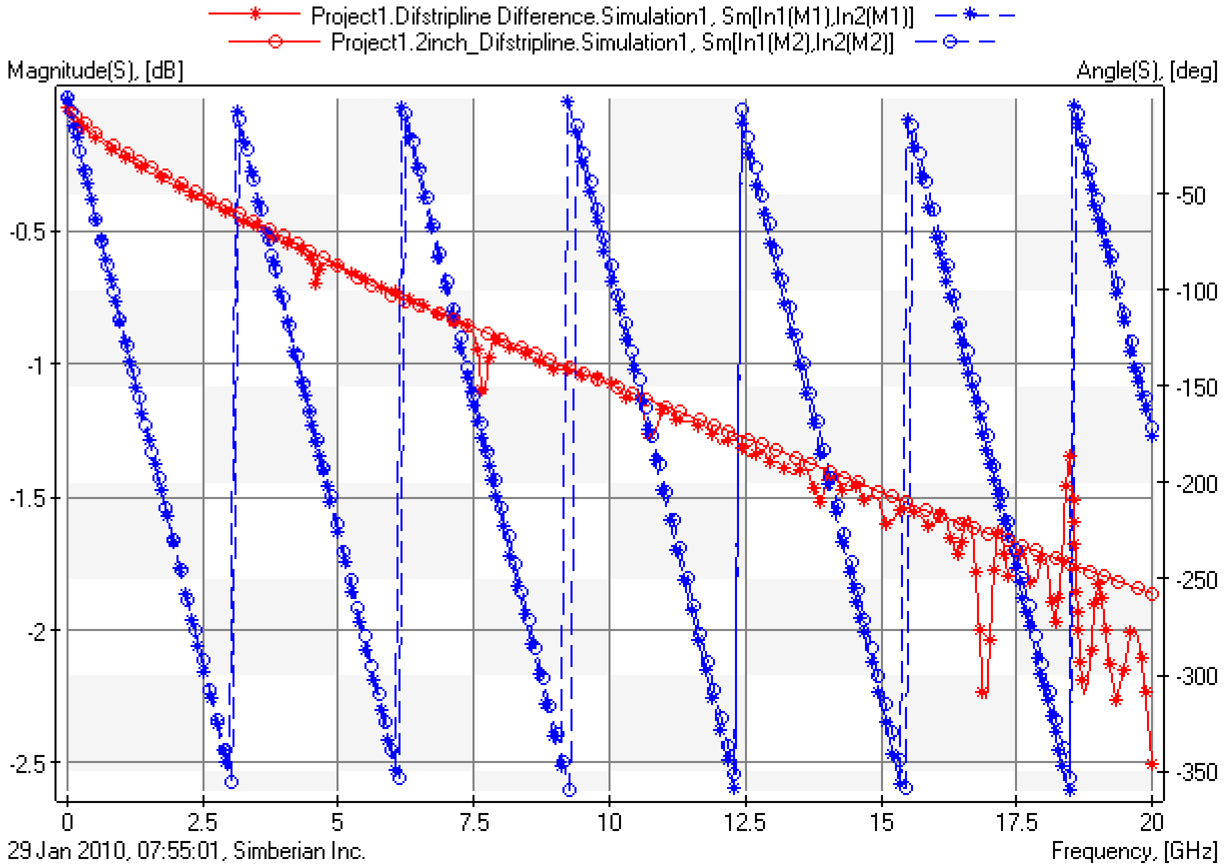



Stars – measured;
Circles – computed;

Some discrepancies at high frequencies

# Generalized even mode transmission parameter with 16-pole Debye model

- 16-pole Debye model
- RR=1.1; SR=0.25 um; RF=2

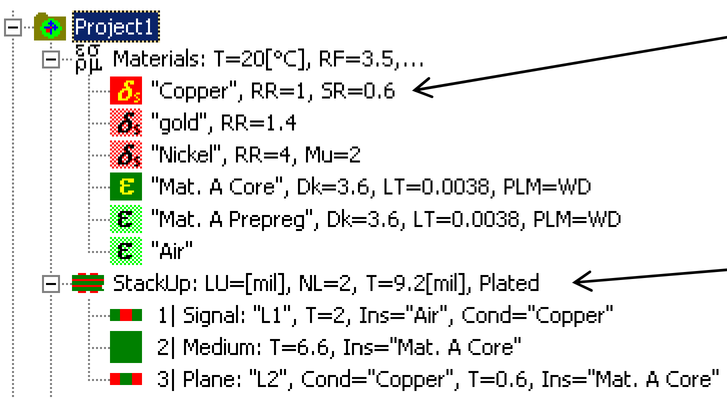



Stars – measured;
Circles – computed;

Some discrepancies at high frequencies

# Material A specifications and stackup for micro-line structures

- Core (measured with clamped strip-line, IPC TM-650, #2.5.5.5):
  - DK=3.48, LT=0.0037 @ 10 GHz, 0.0031 @ 2.5 GHz
  - DK=3.66 is recommended for analysis
- Prepreg:
  - DK=3.52, LT=0.004 @ 10 GHz

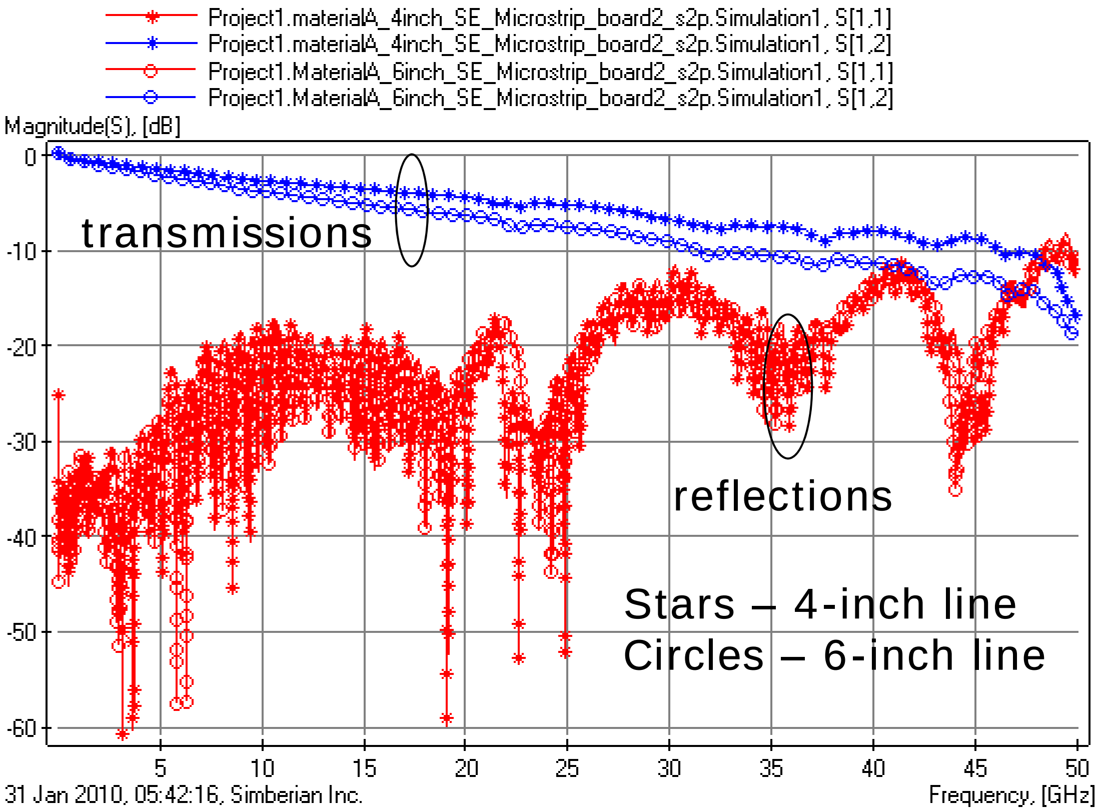


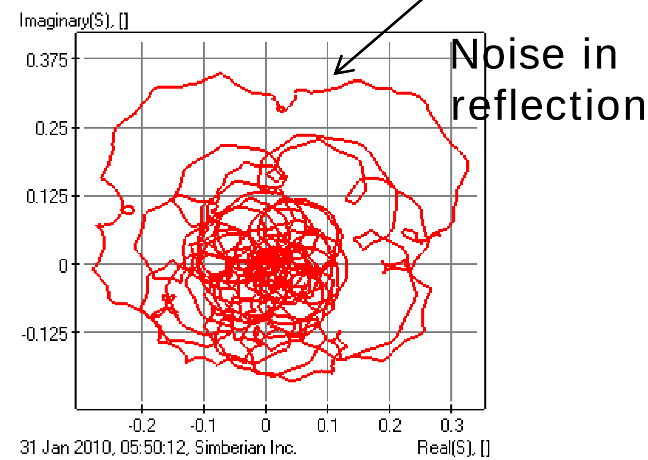

Common SR=0.6, RF=3.5

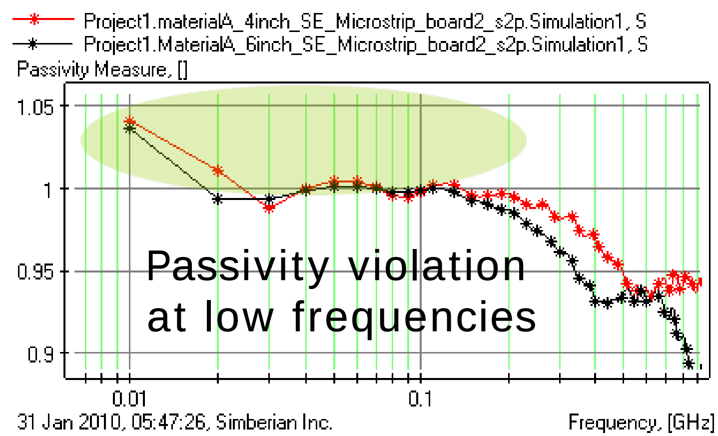
Top layer is plated with 2.5 um of Nickel and 0.05 um of Gold

# 4 and 6 inch 50-Ohm micro-strip line segments

- 4-inch segment (stars): PQM=99.98%, RQM=99.0%, SQM=41%, CQM=0%
- 6-inch segment (circles): PQM=99.99%, RQM=99.3%, SQM=45%, CQM=0%

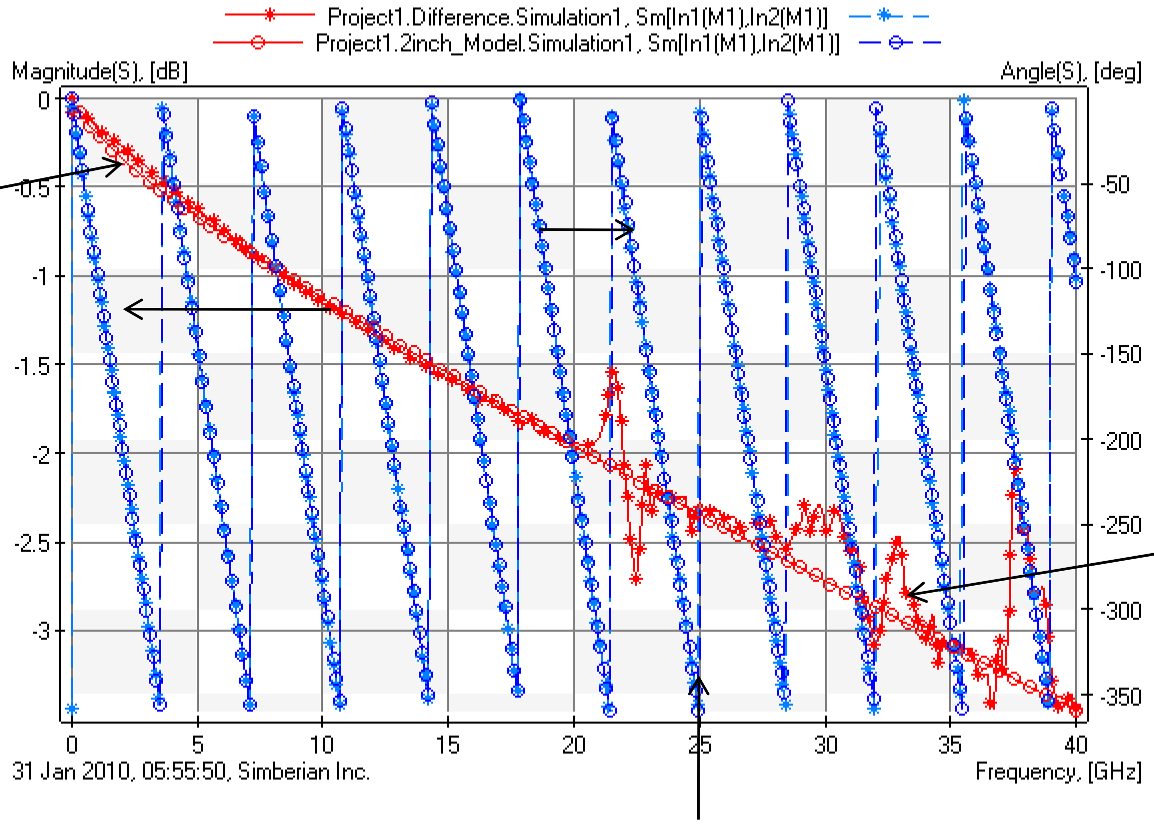


# Generalized modal transmission parameter for 50-Ohm micro-strip line

- Wideband Debye model: DK=3.6, LT=0.0038 @ 10 GHz
- Conductor: plated copper; SR=0.6 um; RF=3.5



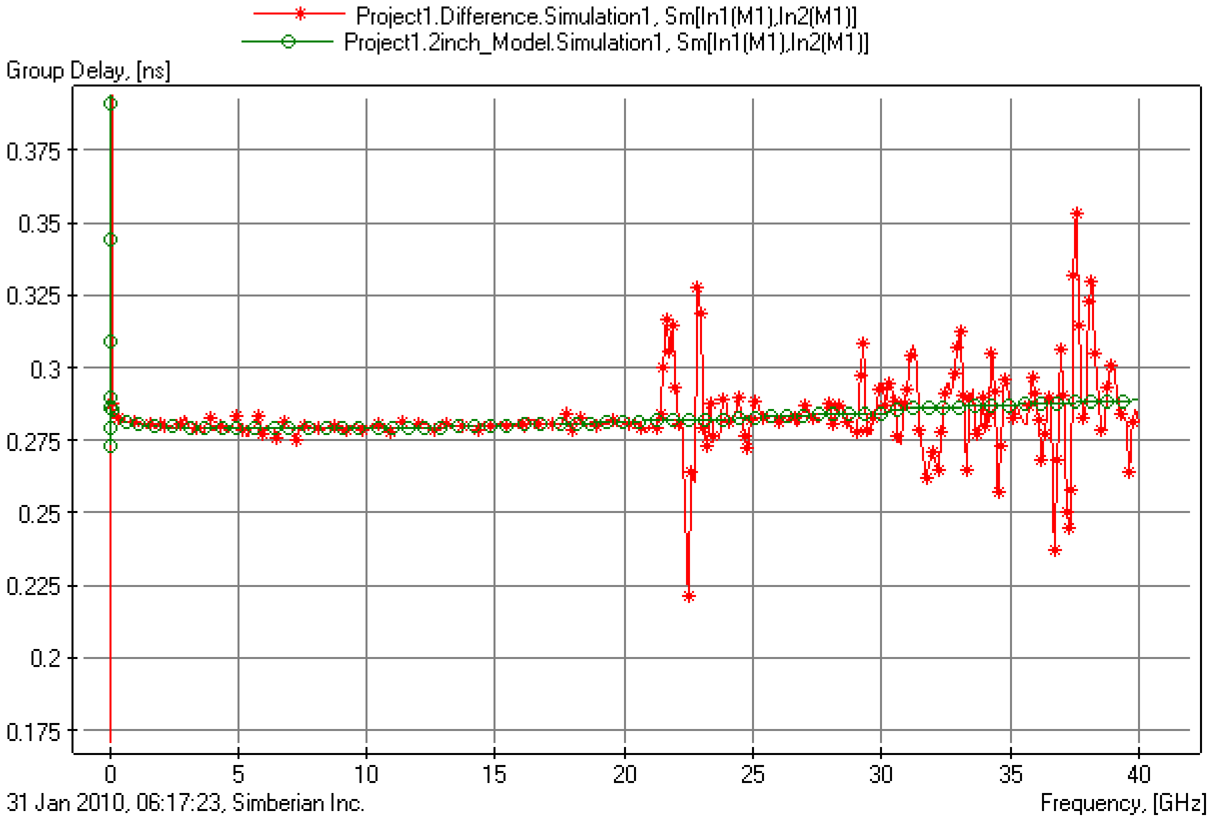

Stars – measured
Circles – computed

Larger computed attenuation

Possible effect of physical difference of line segments

# Group delay for 50-Ohm micro-strip line

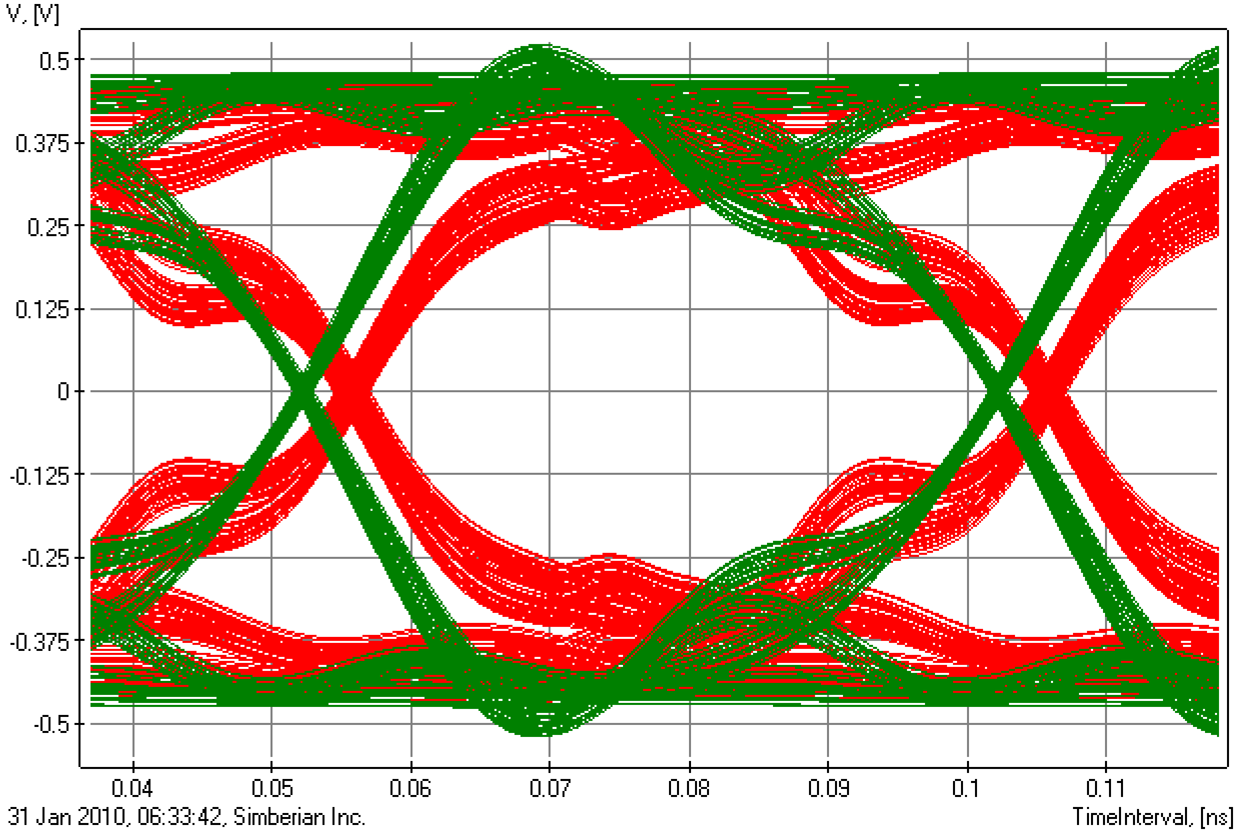
- Wideband Debye model: DK=3.6, LT=0.0038 @ 10 GHz
- Conductor: plated copper; SR=0.6 um; RF=3.5



# Importance of the roughness model

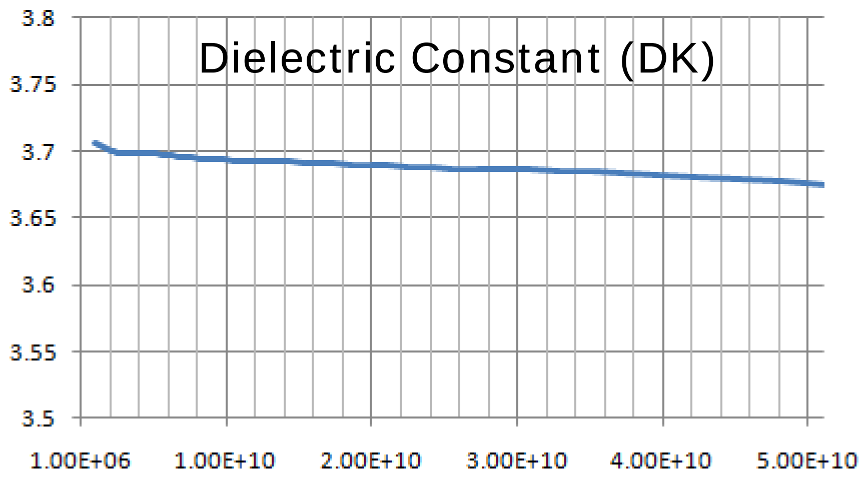
- 10-inch segment of micro-strip line
- PRBS7, 20 Gb/s, 10 ps rise time

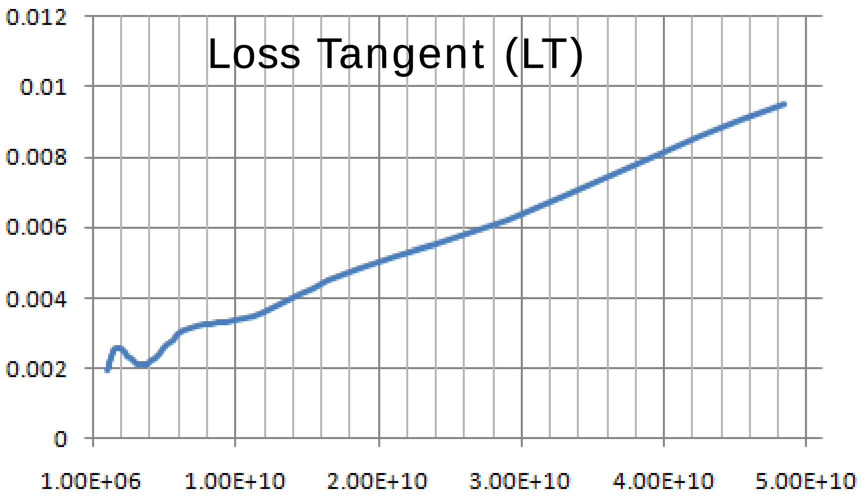



Green – no roughness
Red – with roughness

# Dielectric model for low loss material B

- Frequency-continuous 10-pole Debye model
- Very small changes in DK over the frequency range of interest
- LT is growing faster than allowed by wideband Debye model
- Roughness RMS=0.5 um, Roughness Factor=2.5
- Suitable for applications up to 100 Gb/s



# Conclusion

- The main result of this investigation is a simple and practical methodology to identify properties of dielectrics on the base of:
  - Precise measurement of generalized modal S-parameters of line segment
  - Accurate full-wave electromagnetic analysis with dispersive dielectric model and with all relevant loss and dispersion effects included
- Requires just 2 t-line segments and can be used on prototype and production boards for applications from 6-100 Gb/s
- Wideband Debye models can be effectively used for high-loss dielectrics and multi-pole Debye models for low-loss dielectrics

- Future work:
  - Automate the procedure for typical cases
  - Practical methodology to identify conductor roughness, effect of fibers,…

# Be sure to visit us:

- Simberian Inc.
  - Booth #915 – Simbeor software and PLRD-1 Physical Layer Reference Design Board
  - www.simberian.com
- Teraspeed Consulting Group
  - www.teraspeed.com

# Backup slides

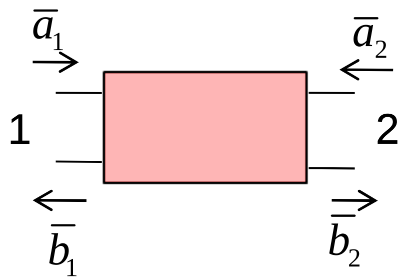
- Conversion of S-matrix to T-matrix

# S-matrices and T-matrices

Arbitrary number of ports identical on the left and right side of multiport

$$\begin{vmatrix} \overline{b}_1 \\ \overline{b}_2 \end{vmatrix} = \begin{bmatrix} S_{1,1} & S_{1,2} \\ S_{2,1} & S_{2,2} \end{bmatrix} \cdot \begin{vmatrix} \overline{a}_1 \\ \overline{a}_2 \end{vmatrix}$$

Cascading of 2 multiports described with S-parameters require solving a linear system




$$\begin{vmatrix} \overline{b}_1 \\ \overline{a}_1 \end{vmatrix} = \begin{bmatrix} T_{1,1} & T_{1,2} \\ T_{2,1} & T_{2,2} \end{bmatrix} \cdot \begin{vmatrix} \overline{a}_2 \\ \overline{b}_2 \end{vmatrix}$$

Cascading of 2 multiports described with T-parameters is simple product of two T-matrices

$$T_{1,1} = S_{2,1} - S_{1,1} \cdot S_{2,1}^{-1} \cdot S_{2,2}$$
$$T_{1,2} = S_{1,1} \cdot S_{2,1}^{-1}$$
$$T_{2,1} = -S_{2,1}^{-1} \cdot S_{2,2}$$
$$T_{2,2} = S_{2,1}^{-1}$$

$$S_{1,1} = T_{1,2} \cdot T_{2,2}^{-1}$$
$$S_{1,2} = T_{1,1} - T_{1,2} \cdot T_{2,2}^{-1} \cdot T_{2,1}$$
$$S_{2,1} = T_{2,2}^{-1}$$
$$S_{2,2} = -T_{2,2}^{-1} \cdot T_{2,1}$$

All elements are scalars in case of 2-ports (single-ended lines) or matrices in case of multi-conductor lines (differential)

*See more in Carlin, Giordano, Network Theory, An Introduction to Reciprocal and Non-Reciprocal Circuits, 1964*