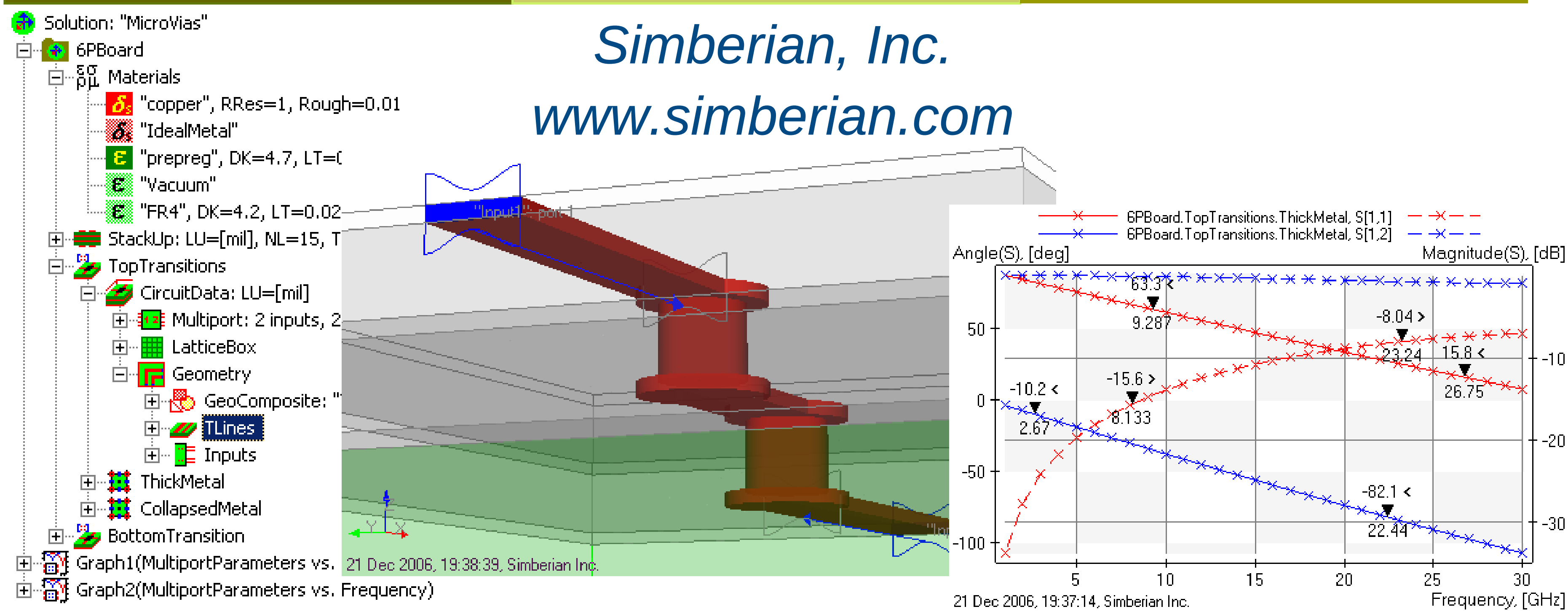
Modeling frequency-dependent dielectric loss and dispersion for multi-gigabit data channels

Simberian, Inc.
www.simberian.com



Property of Simberian Inc.

Overview

- Introduction
- Dielectric models available in Simbeor 2008
- Wideband Debye or Djordjevic-Sarkar model
- Multi-pole Debye models
- Which model to choose? – comparative study
- Experimental investigation
- Conclusion

Introduction

- Models of transmission lines accurate over 4-5 frequency decades are required to simulate multi-gigabit signals in PCB/packaging interconnects
  - 10 Gb/s channel require models from 1 MHz to 20 GHz
  - 20 Gb/s channel analysis require models from 1 MHz to 40 GHz
- Modeling of signal attenuation and dispersion due to dielectric polarization properties requires broadband causal models based on measurements of dielectric constant and loss tangent
- The most common dielectric model in electromagnetic software is model with constant dielectric constant and loss tangent – such non-causal model is not suitable for broadband analysis of interconnects
- Wideband Debye and multi-pole Debye models are becoming more popular as causal and accurate broadband alternatives
- Here we investigate and compare these models for analysis of broad-band interconnects
- Simbeor 2008 built on September 9, 2008 has been used for all computations

Dielectric models in Simbeor 2008

- Lossless
  - Specified with dielectric constant (DK) only
- Flat Non Causal
  - Specified with DK and Loss Tangent (LT)
- One Pole Debye
  - Specified with DK, LT, Measurement and Relaxation Frequencies
- Wideband Debye (Djordjevic-Sarkar)
  - Specified with DK, LT, Measurement, Low and High frequencies
- Multi-Pole Debye (uses real poles)
  - Table of DK and LT at different frequencies
- Multi-Pole Generic (uses complex poles if necessary)
  - Table of DK and LT at different frequencies

Simbeor 2008 has the most advanced set of dielectric models in the industry!

Models suitable for PCB/packaging applications

Wideband Debye dielectric model

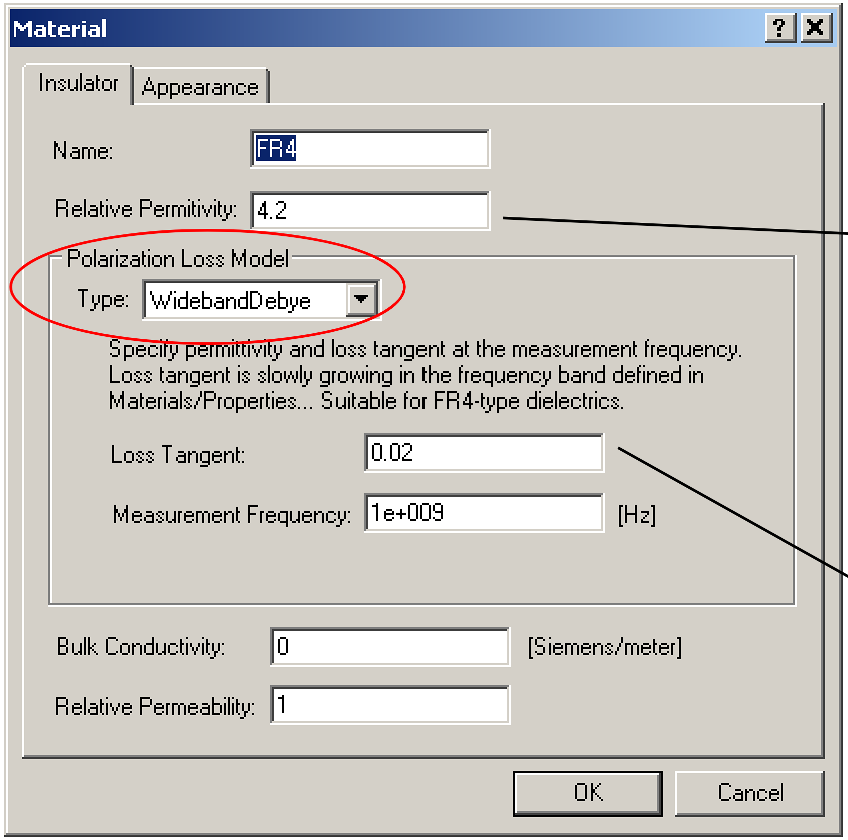
Complex dielectric constant:

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

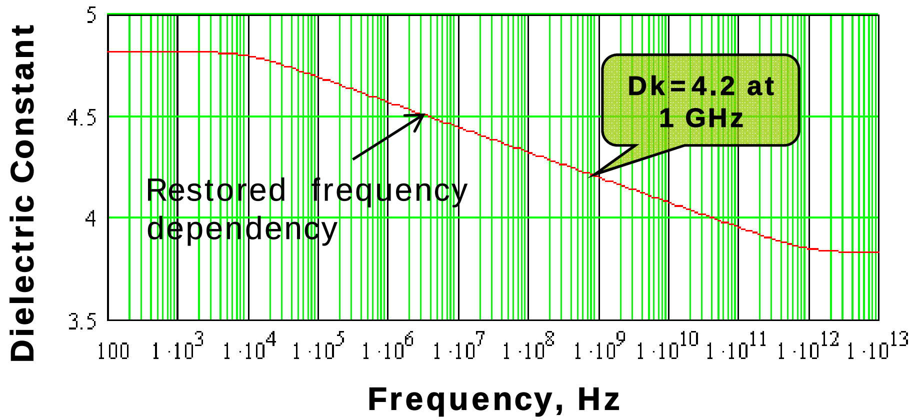
- Suggested in two papers independently
  - Djordjevic, R.M. Biljic, V.D. Likar-Smiljanic, T.K. Sarkar, Wideband frequency-domain characterization of FR-4 and time-domain causality, IEEE Trans. on EMC, vol. 43, N4, 2001, p. 662-667.
  - C. Svensson, G.E. Dermer, Time domain modeling of lossy interconnects, IEEE Trans. on Advanced Packaging, May 2001, N2, Vol. 24, pp.191-196.
- Confirmed in multiple papers (see latest DesignCon papers, and IEEE proceedings on EMC and Advanced Packaging)
- Can be specified with DK and LT at one frequency only
  - Reproduces causal frequency-dependent dielectric loss and dispersion
  - Very convenient for measurements and fitting the experimental data
- Can be easily used in any frequency-domain electromagnetic solver
- Requires approximation with the multi-pole Debye model for electromagnetic time-domain solvers
- We will use this model here as a benchmark to illustrate possible problems with the multi-pole Debye and flat non-causal models

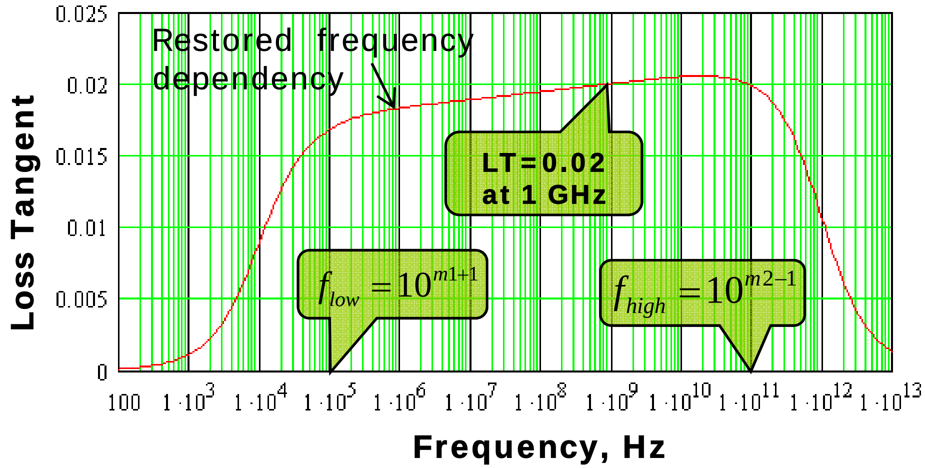
Wideband Debye dielectric model in Simbeor

Specified with just one measurement of DK and LT



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





flow and fhigh are specified in common properties of materials

Multi-pole Debye dielectric model

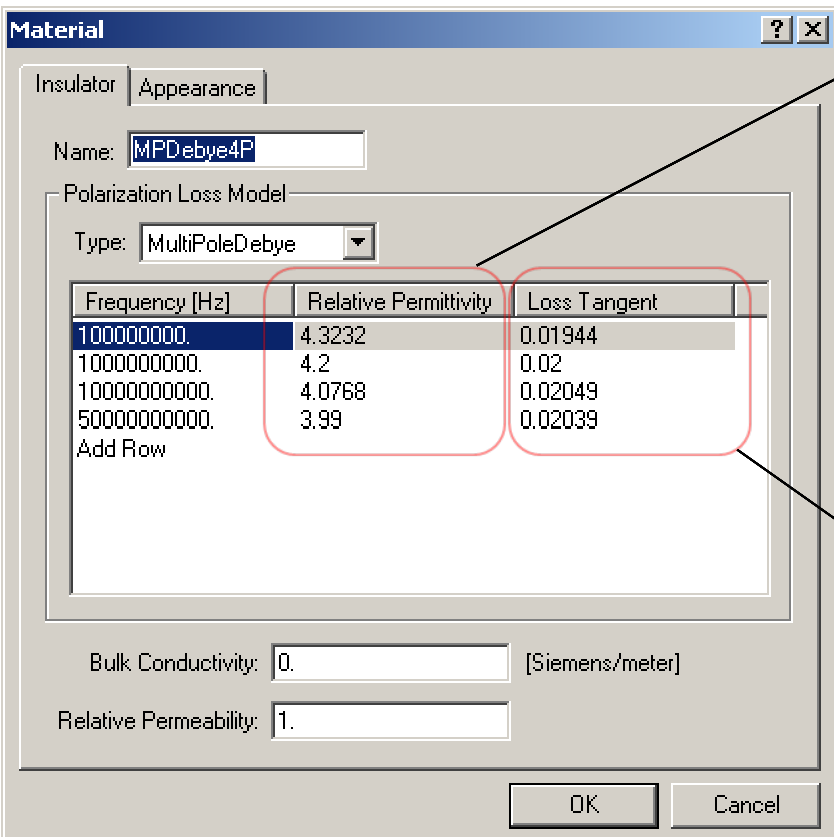
Complex dielectric constant for Debye model with K poles

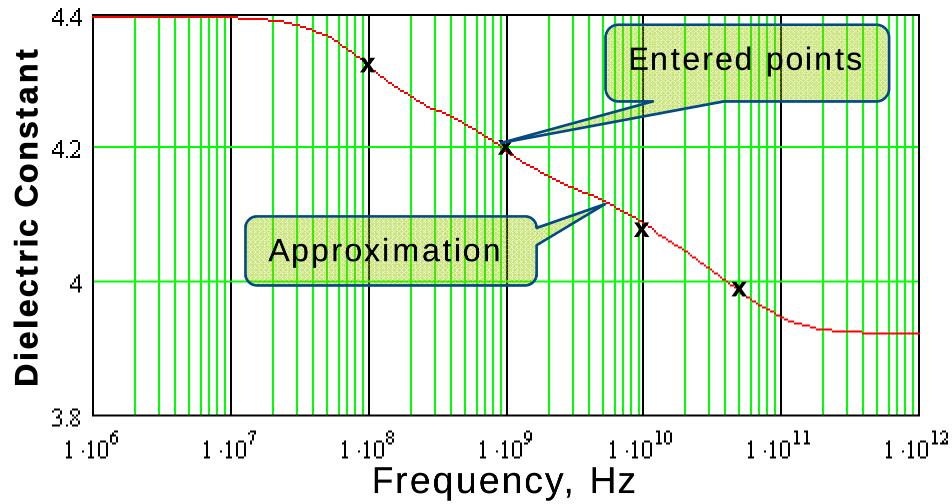
$$\varepsilon(f) = \varepsilon_r(\infty) + \sum_{k=1}^{K} \frac{\Delta\varepsilon_k}{1 + i\frac{f}{f_{rk}}}$$

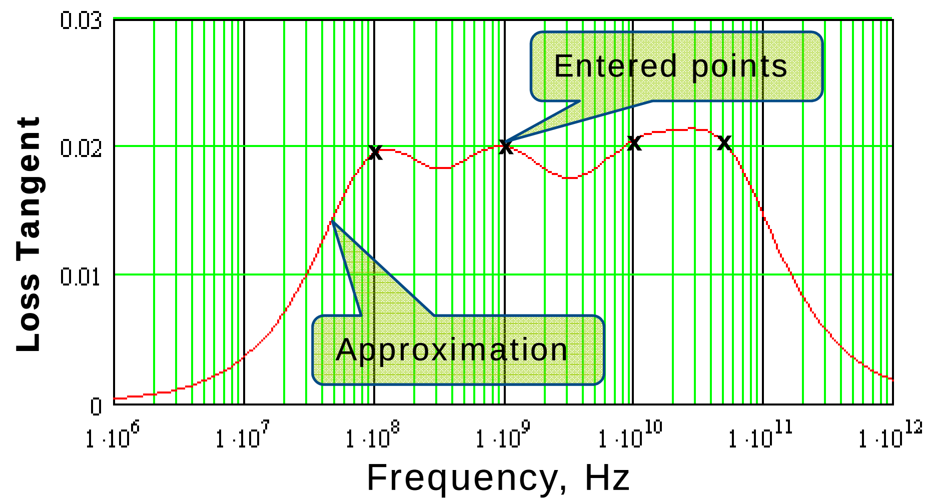
- Suggested by P. Debye in
  - P. Debye, Polar molecules, Dover, 1929
- Typically used in time-domain solvers because of convolution integrals in time-domain can be approximated with the fast recursive convolution
- Can be used to approximate set of measured dielectric constant and loss tangent if wideband Debye model does not provide good accuracy
- Model with K poles can be built with K measurements of DK and LT
- At least 4 measurement points are required for good approximation of broadband PCB/packaging interconnects (the proof follows)

Example of 4-pole Debye model specified with 4 measurements in Simbeor

DK and LT is specified at 4 frequency points – DK&LT are approximated with 4-pole Debye model as shown on the right

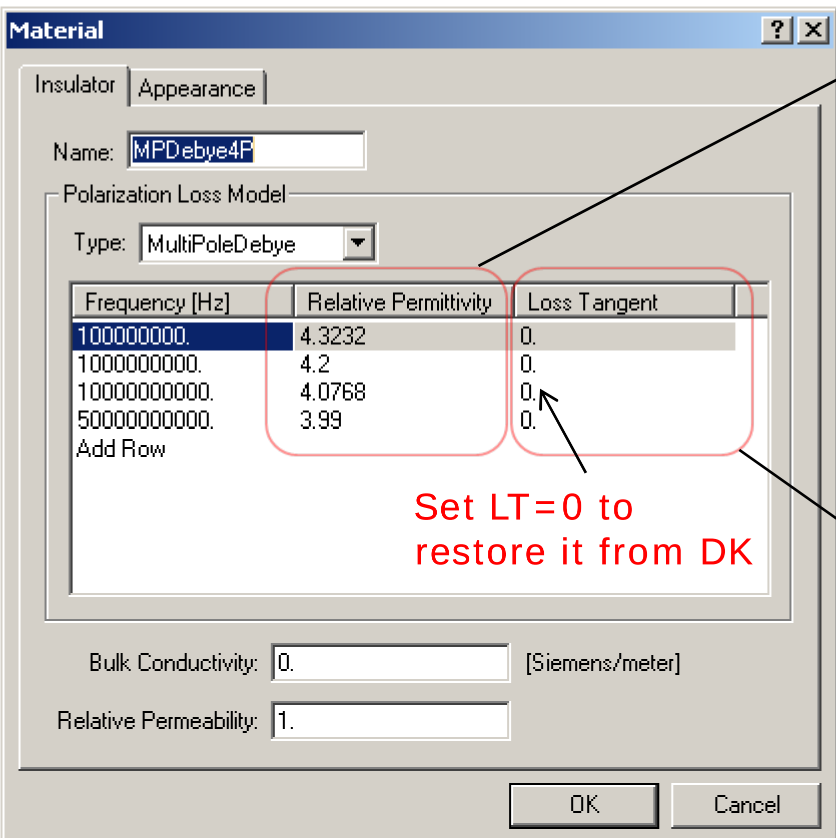


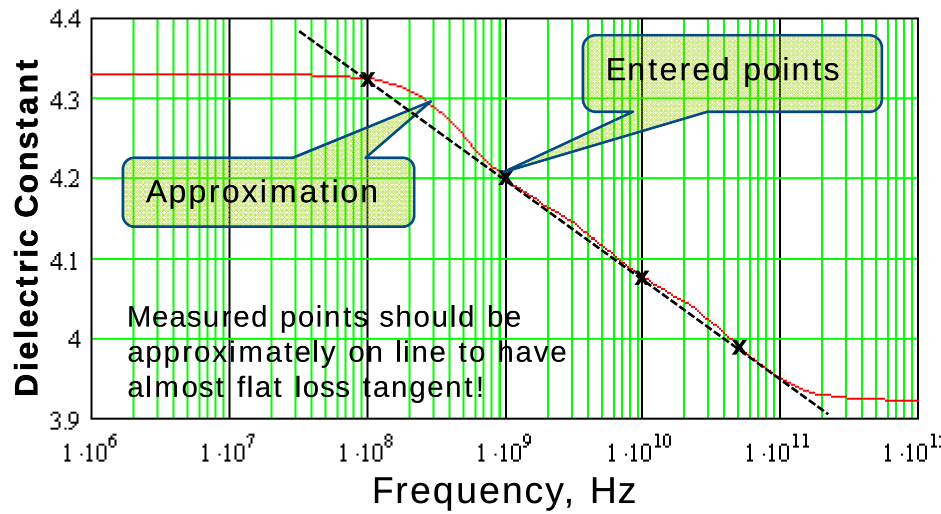


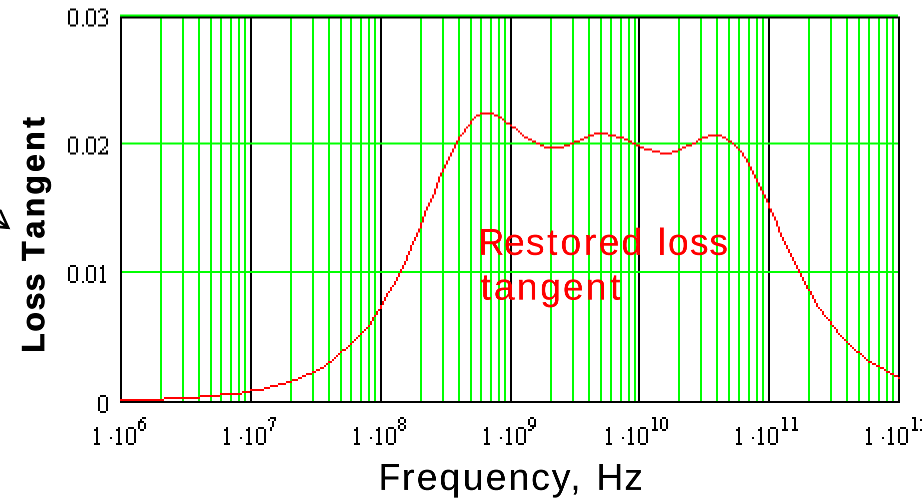


Example of 4-pole Debye model specified with 4 measurements of DK only in Simbeor

DK is specified at 4 frequency points – DK&LT are approximated with 3-pole Debye model as shown on the right (loss tangent is restored)







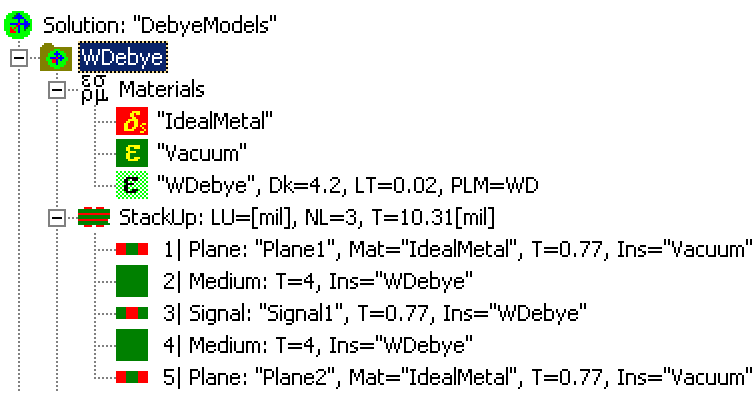
Which dielectric model to choose?

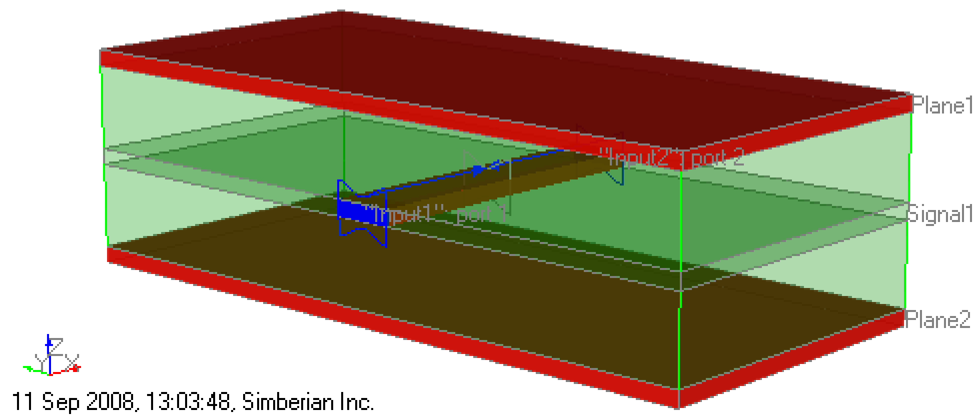
- Wideband Debye model is probably the best choice for composite dielectrics in frequency domain
- If measured data can not be approximated with the wideband Debye model, then multi-pole model is the next best choice
- Multi-pole Debye models is the only choice for time-domain electromagnetic solvers – it can be as accurate as the wideband Debye with sufficient number of poles
- How many poles to use for broad-band analysis of interconnects?
- Let's investigate a simple strip line in homogeneous dielectric

Strip line configuration

- 2.9 mil strip line in homogeneous dielectric (about 50 Ohm)
- Metal is simulated as lossless to see just the dielectric effects
- Compute and compare t-line parameters and 2-inch line segment S-parameters with 1, 2, 3 and 4 pole Debye models

Stackup for “benchmark” strip lines
with wideband Debye dielectric model

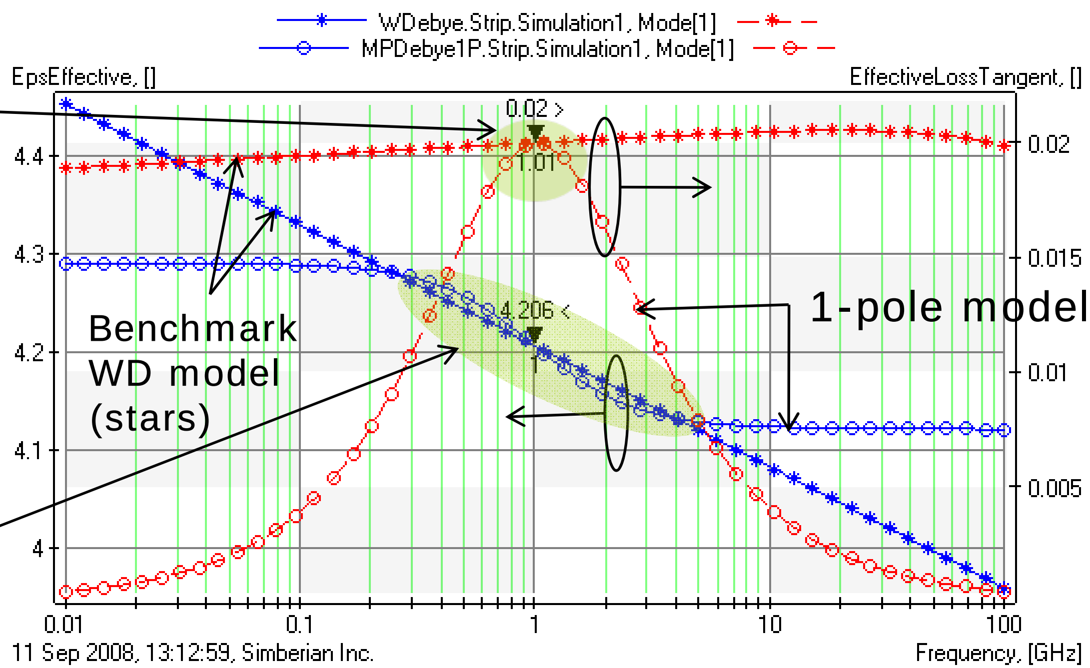




Strip line with 1-pole Debye model

- Attempt to approximate benchmark wideband Debye (WD) model with 1-pole Debye model (assuming that real dielectric behaves as WD model)
- Effective dielectric constant and effective loss tangent correspond to actual dielectric DK and LT

Loss tangent approximation is good only over very narrow frequency band – 0.5 GHz to 1.5 GHz in this case

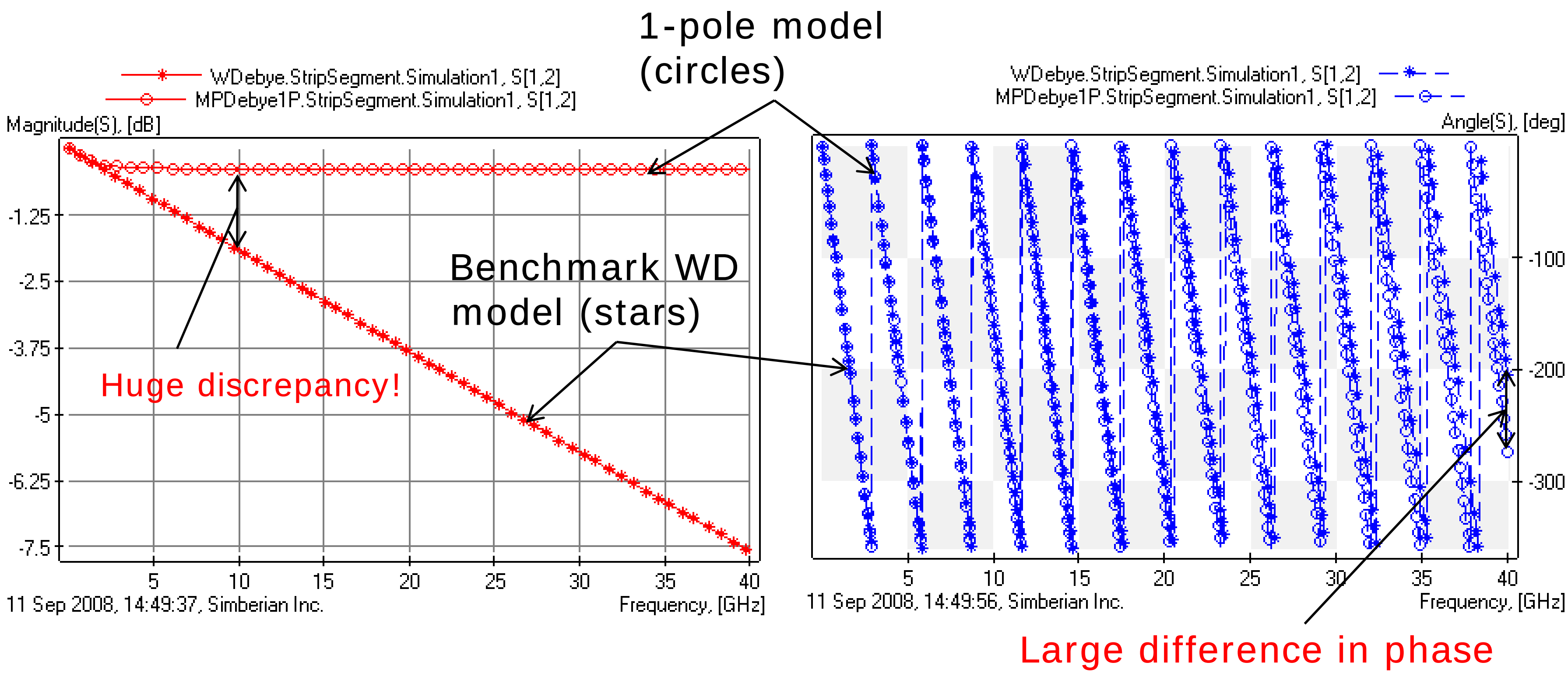


Dielectric constant is approximated well over 1 frequency decade

1 frequency point with DK=4.2, and LT=0.02 @ 1GHz is specified for both models

2-inch segment of strip line with 1-pole Debye model

- Magnitude and phase of transmission coefficient S[1,2]
- Such approximation is not acceptable even for 5 Gb/s channel analysis (huge discrepancy starting from about 1.5 GHz)



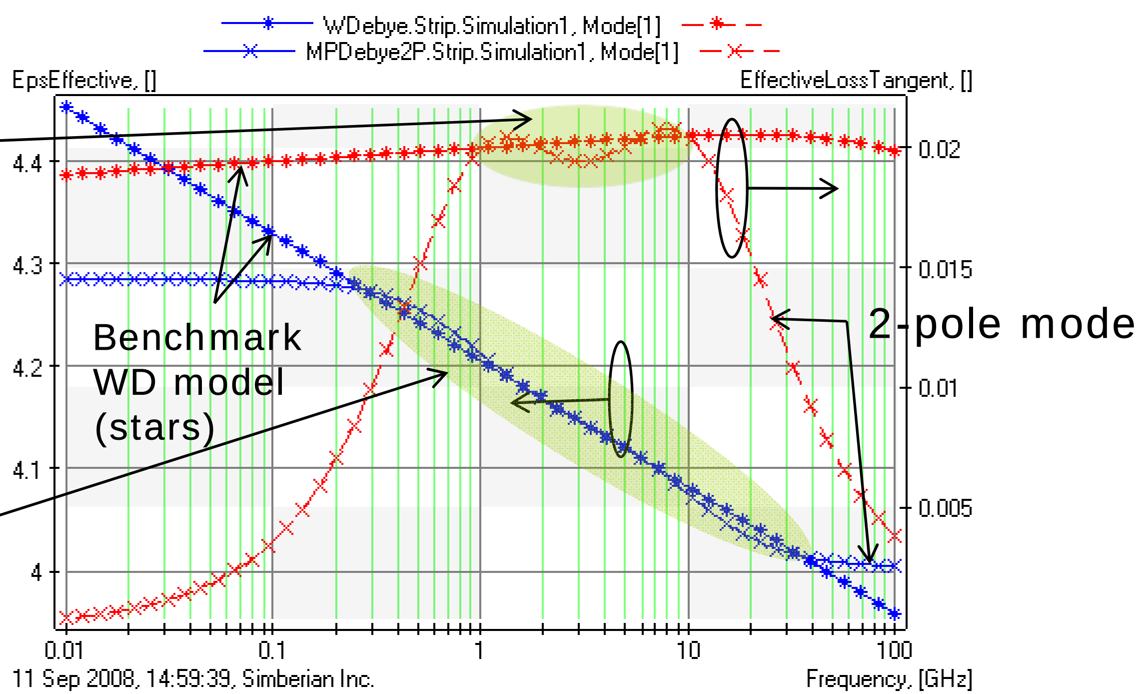
Strip line with 2-pole Debye model

- Attempt to approximate benchmark wideband Debye (WD) model with 2-pole Debye model (points specified at 1 GHz and 10 GHz)
- Effective dielectric constant and effective loss tangent correspond to actual dielectric DK and LT

This model is often used in time-domain and in some frequency-domain solvers

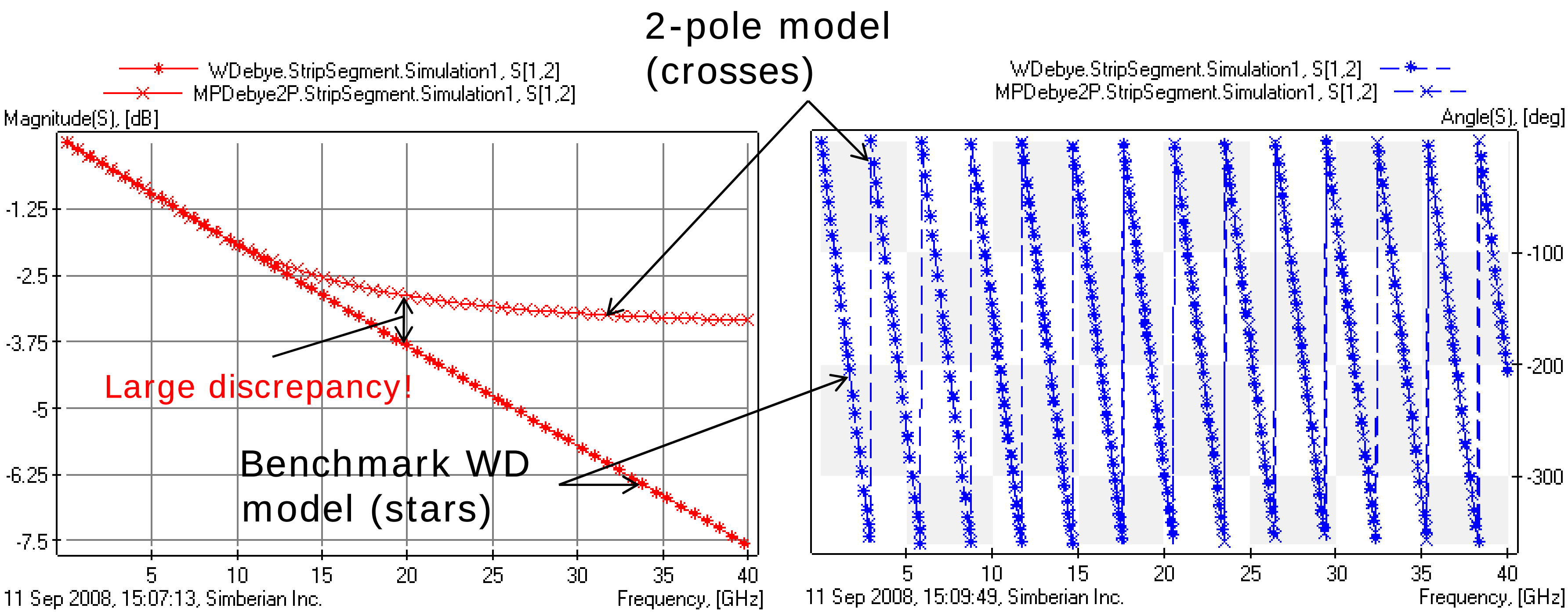
Loss tangent approximation is good only over 1 frequency decade

Dielectric constant is approximated well over 2 frequency decades



2-inch segment of strip line with 2-pole Debye model

- Magnitude and phase of transmission coefficient S[1,2]
- Such approximation may be acceptable for 5 Gb/s but is not acceptable for 10 Gb/s channel analysis (large discrepancy starting from 12 GHz)



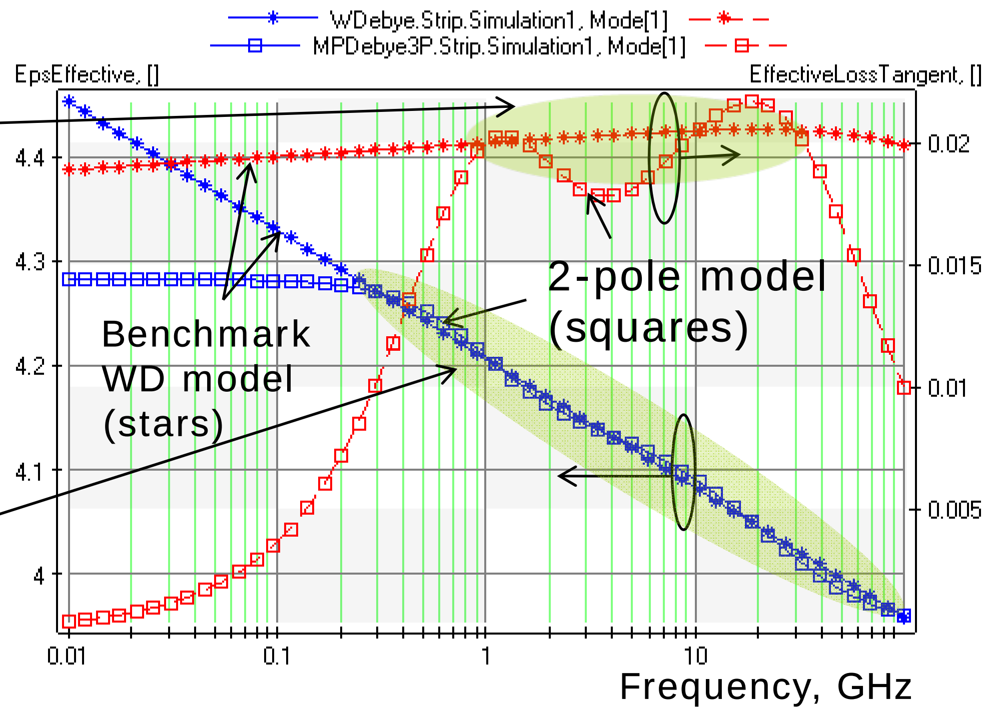
Phases are very close

Strip line with 3-pole Debye model

- Attempt to approximate benchmark wideband Debye (WD) model with 3-pole Debye model (points specified a 1, 10 and 30 GHz)
- Effective dielectric constant and effective loss tangent correspond to actual dielectric DK and LT

Loss tangent approximation is relatively good over 1.5 frequency decades

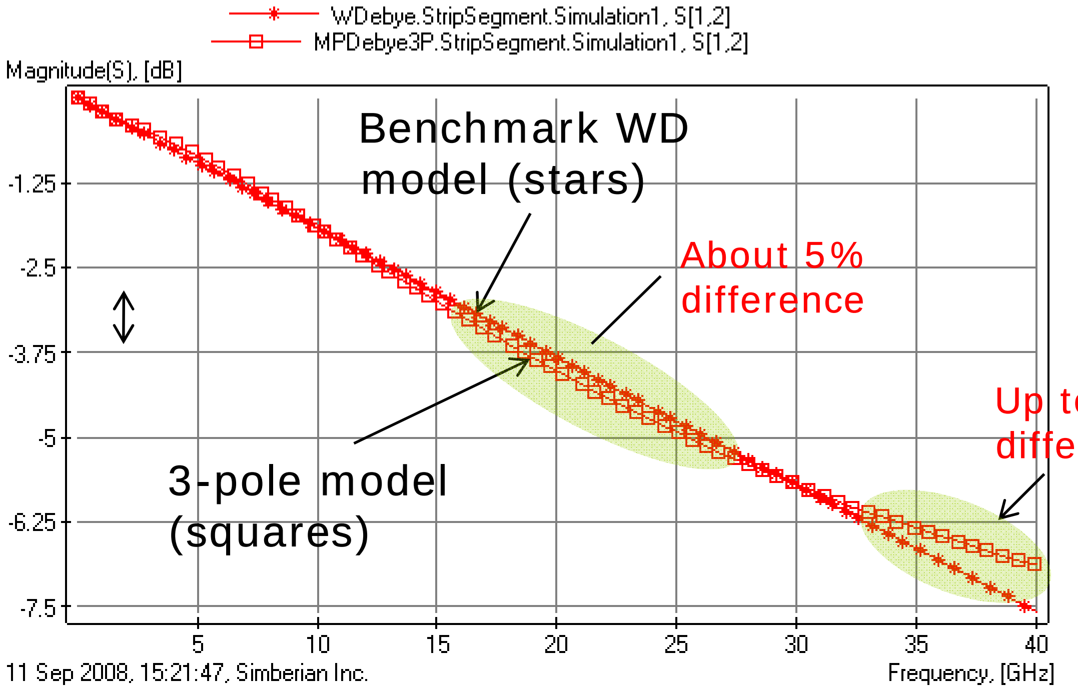
Dielectric constant is approximated well over 2.5 frequency decades



2-inch segment of strip line with 3-pole Debye model

- Magnitude and phase of transmission coefficient S[1,2]
- Such approximation may be acceptable for 10 Gb/s and even 20 Gb/s channel analysis with appropriate arrangement of the measurement points

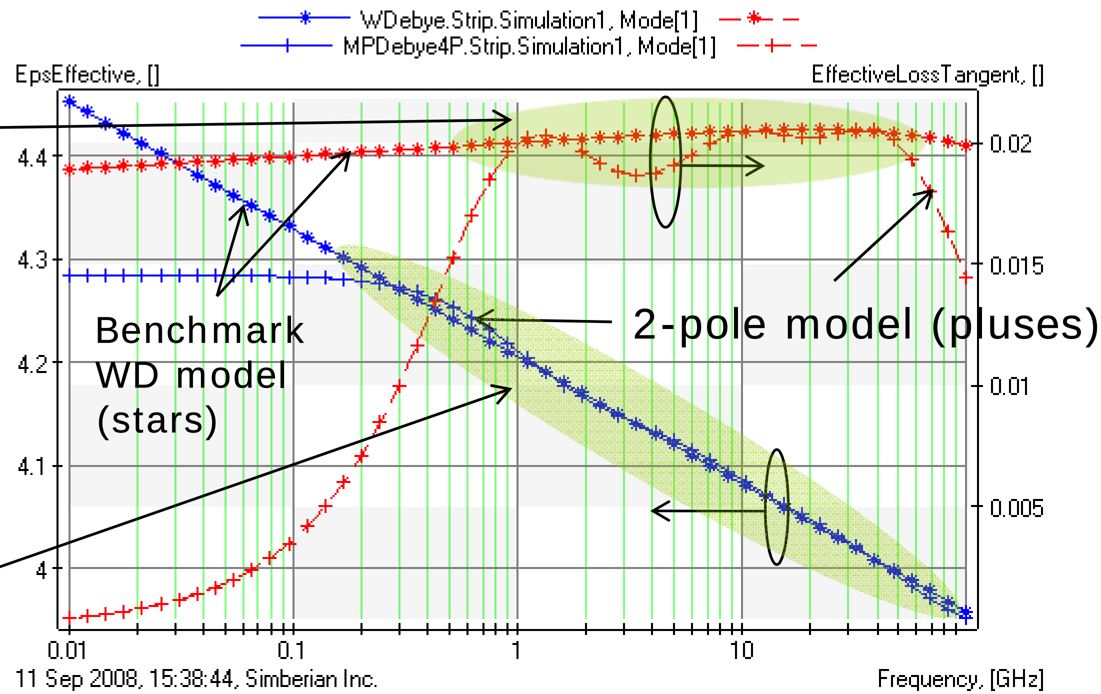
The phases and group delays for two models are almost identical



Strip line with 4-pole Debye model

- Attempt to approximate benchmark wideband Debye (WD) model with 4-pole Debye model (points specified at 1, 10, 30 and 40 GHz)
- Effective dielectric constant and effective loss tangent correspond to actual dielectric DK and LT

Loss tangent approximation is good almost over 2 frequency decade
It is sufficient because of dielectric losses are much smaller than conductor losss below 500 MHz

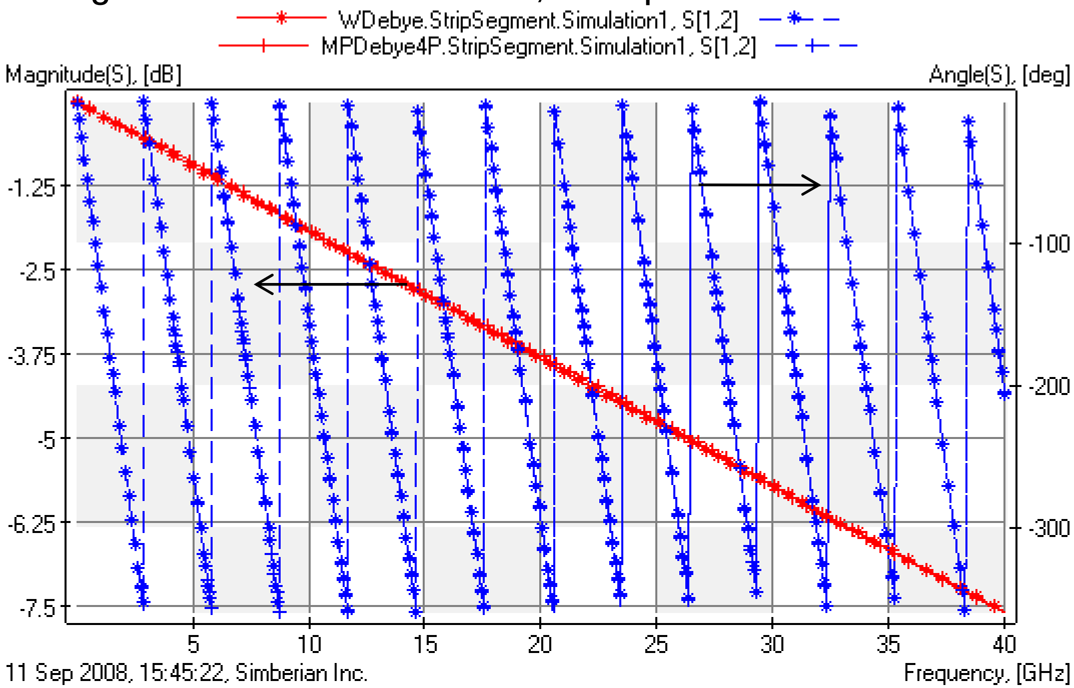


Dielectric constant is approximated well almost over 3 frequency decades

2-inch segment of strip line with 4-pole Debye model

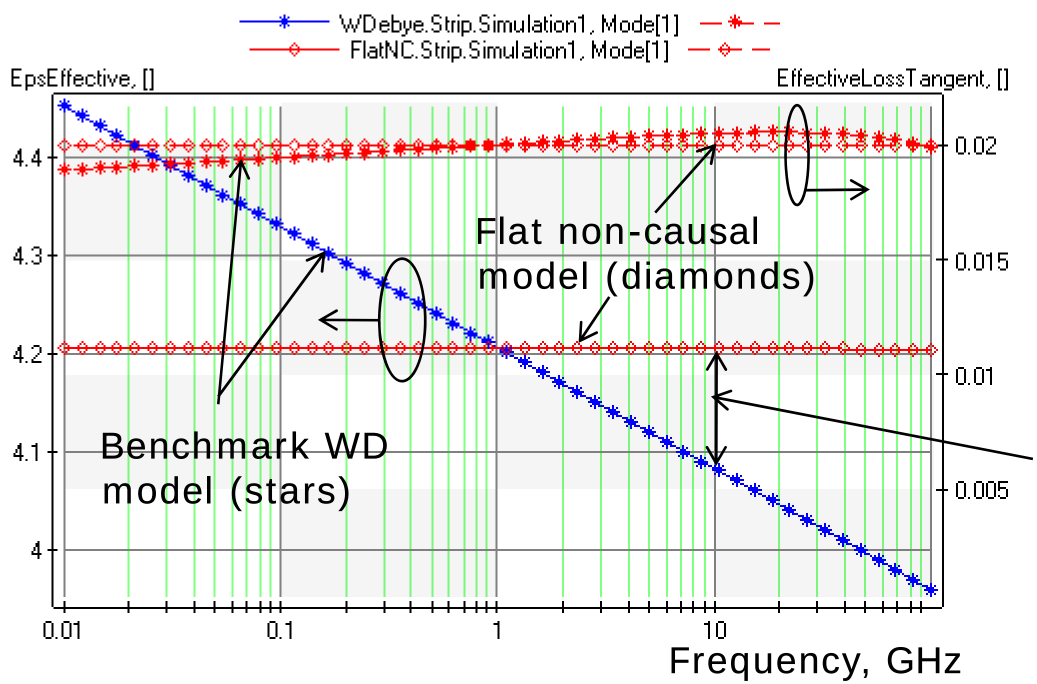
- Magnitude and phase of transmission coefficient S[1,2]
- Such approximation is good for 20 Gb/s channel analysis and even beyond!

Magnitude, phases and group delay are almost identical
Benchmark WD model – stars, 4-pole model - pluses
Magnitudes are red curves, and phases are blue curves



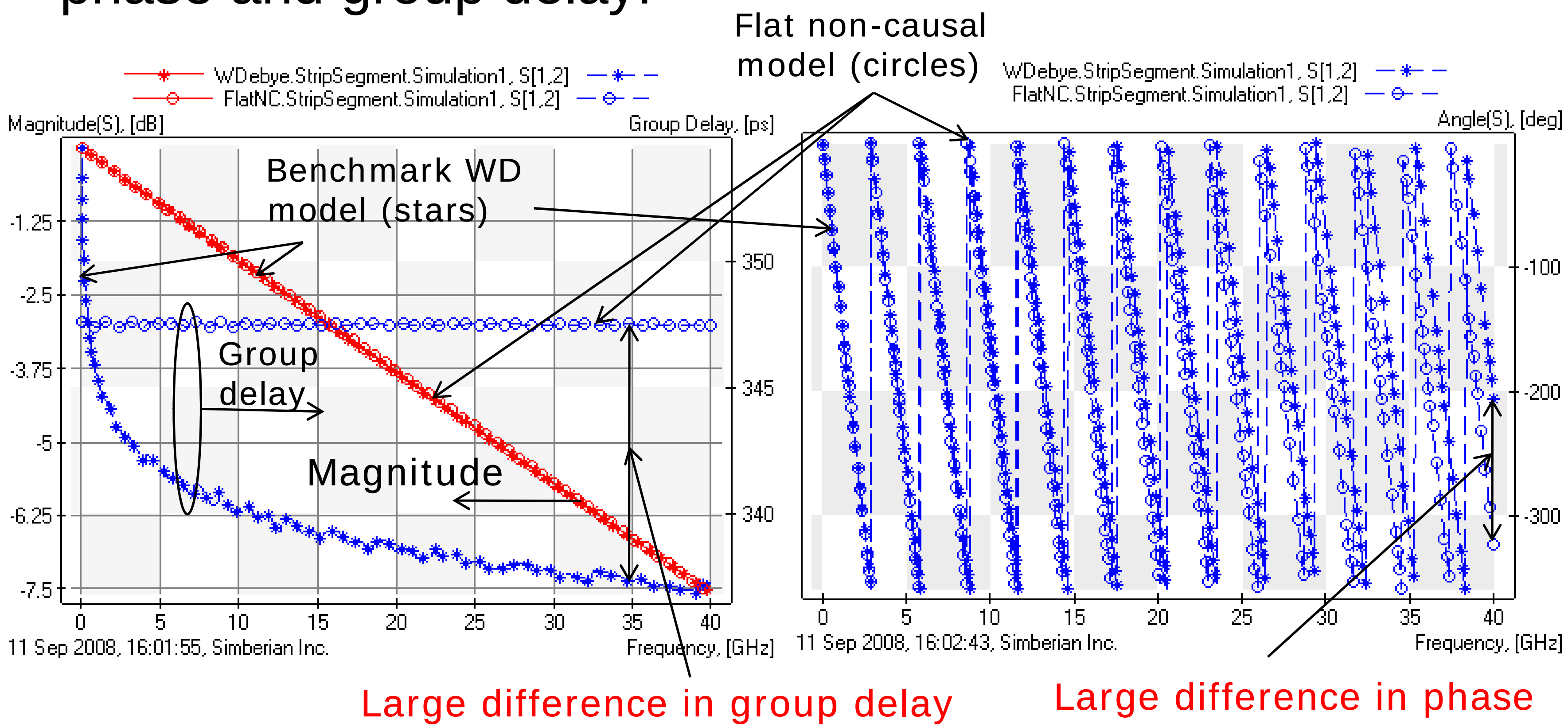
What about the most common flat non-causal dielectric model?

- Assumes that DK and LT do not change with the frequency – it leads to non-causality of the model with all consequences
- Cannot be used directly in time-domain solvers
- May provide good approximation for loss tangent but very bad approximation of the real part of dielectric constant (as shown below)



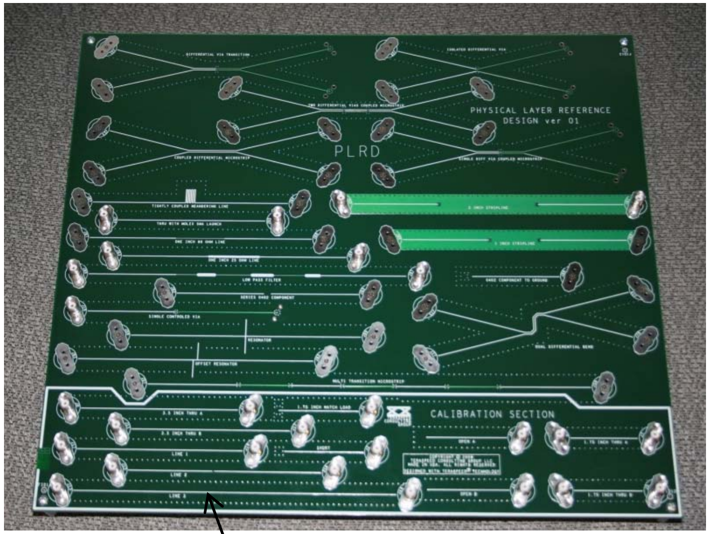
2-inch strip line segment with flat non-causal model

- Good approximation of the transmission coefficient magnitude |S[1,2]|, but extremely bad approximation of phase and group delay!



Experimental investigation

- PLRD-1 board created and independently investigated by Teraspeed Consulting Group www.teraspeed.com
- Precise measurement, de-embedding and material properties identification methodologies with the board are available from Teraspeed
  - For more information contact to Alfred Neves at al@teraspeed.com or Yuriy Shlepnev at shlepnev@simberian.com

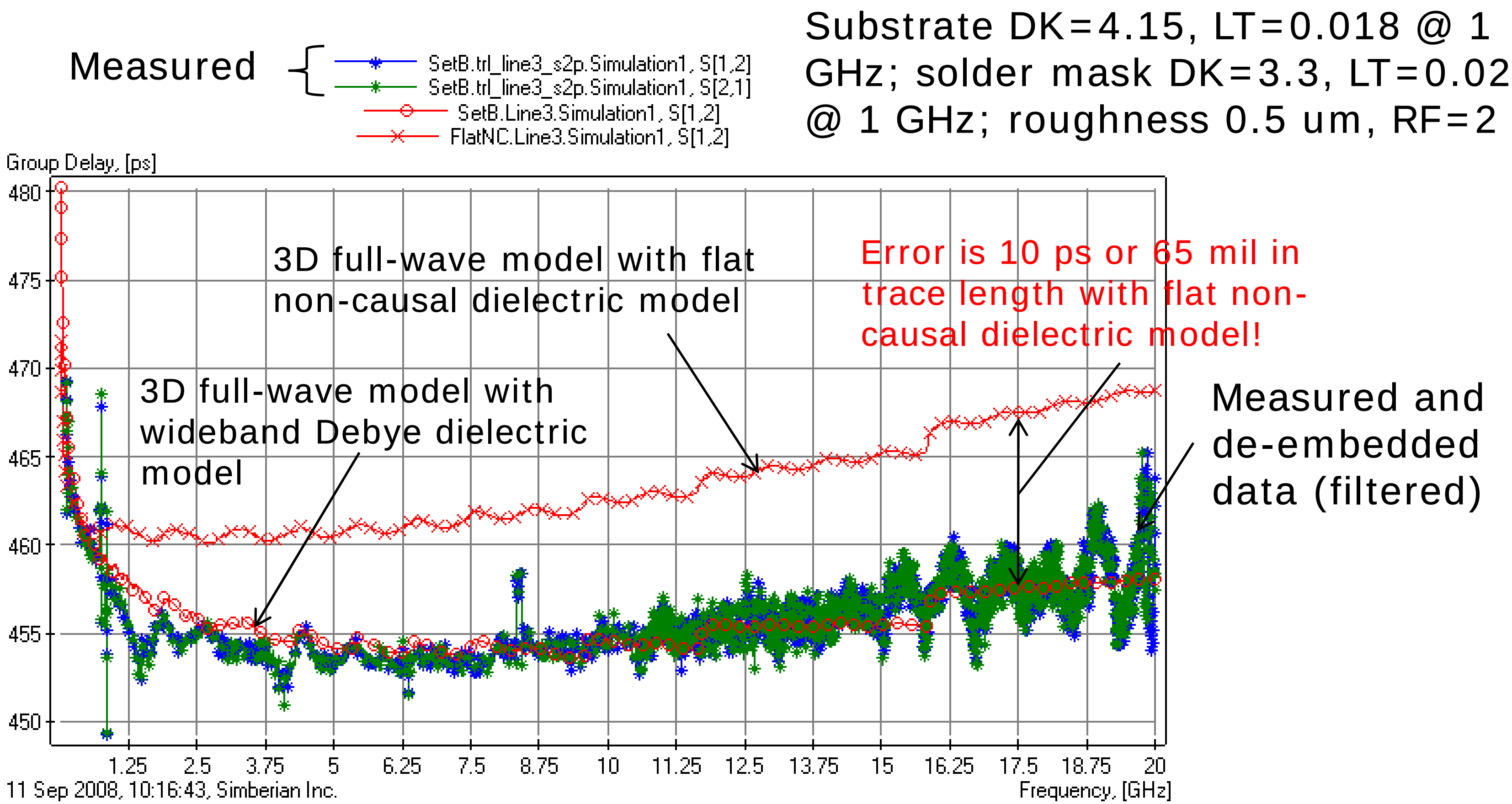


Line3 – 17 mil wide micro-strip line, 3-inch long after TRL de-embedding, substrate 8.9 mil, solder mask 1.4 mil

All measurements and corresponding Simbeor solutions for PLRD-1 are available on request

Experimental investigation

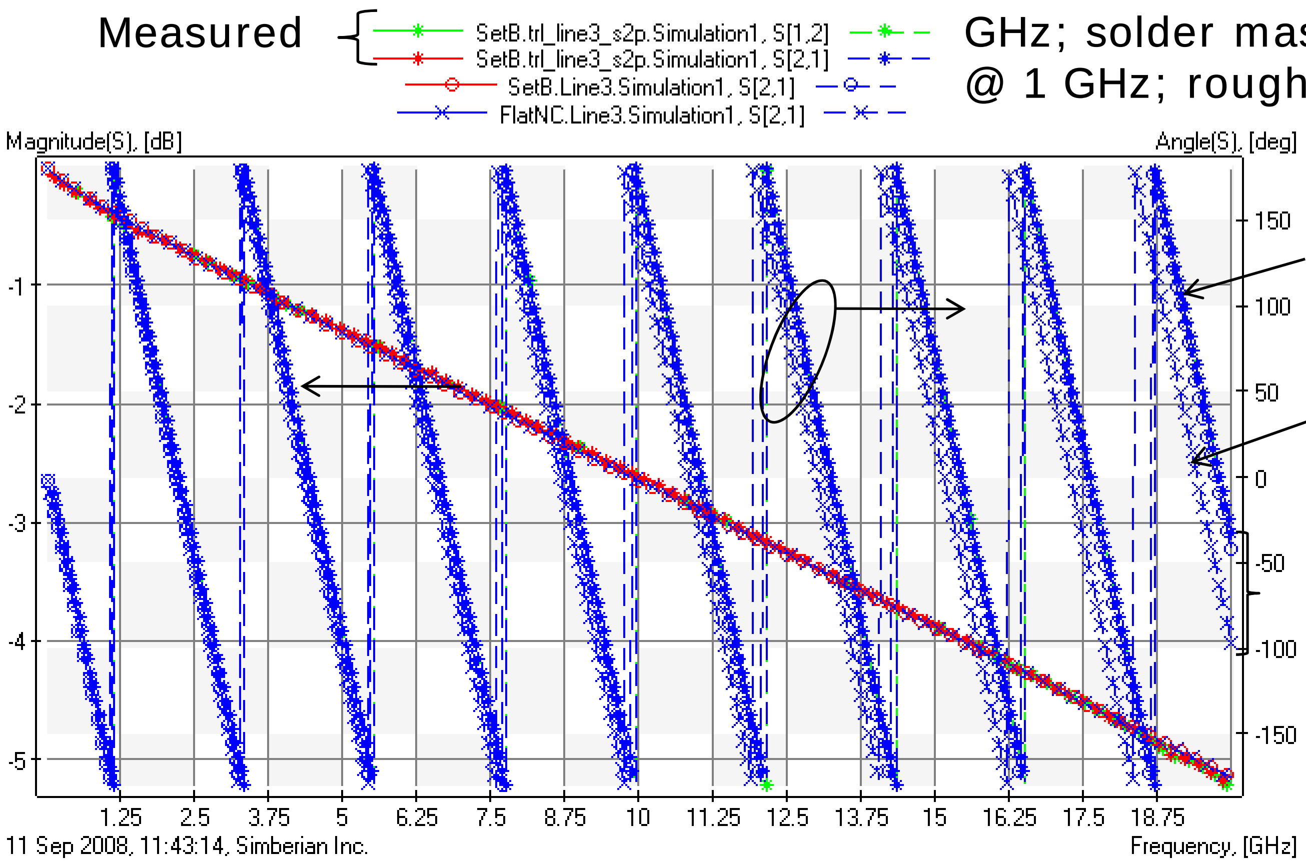
- Group delay in 3-inch micro-strip Line 3



Experimental investigation

- Magnitude and angle of the transmission coefficient S[2,1]

Substrate DK=4.15, LT=0.018 @ 1 GHz; solder mask DK=3.3, LT=0.02 @ 1 GHz; roughness 0.5 um, RF=2



Conclusion

- Wideband Debye model is probably the best for FR-4 type composite dielectric – simple, causal and easy to fit to experimental data
- Multi-pole Debye models may be completely equivalent to wideband Debye model with sufficient number of poles
  - It can be used if measured data can not be fitted with the wideband Debye model
- Flat non-causal models approximate attenuation well, but introduce large errors into phase and group delay (dispersion) and causes non-causality of extracted S-parameters
- To investigate "What dielectric model is in your solver?", extract parameters of a line segment in frequency domain and compare with precisely de-embedded measurements
- Setting up all simulations and model building with Simbeor for this notes took approximately 30 min

Solutions and contact

- Simbeor solution files used to illustrate these notes are available for download from simberian web site
  - http://www.simberian.com/AppNotes/Solutions/ModelingDielectrics_2008_06.zip
- Send questions and comments to
  - General: info@simberian.com
  - Sales: sales@simberian.com
  - Support: support@simberian.com
- Web site www.simberian.com