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Laminate Materials Characterization for High Speed Applications

Alfred Neves – Wild River Technology

Yuriy Shlepnev – Simberian Inc.

Alfred P. Neves

Wild River Technology

Al has 30 years of experience in the design and application development of semiconductor products, capital equipment design focused on jitter and signal integrity analysis, and has successfully been involved with numerous business developments and startup activity for the last 13 years. Al focuses on measure based model development, package characterization, high-speed board design, low jitter design, analysis, and training.

Dr. Yuriy Shlepnev

Simberian Inc.

Yuriy Shlepnev is President and Founder of Simberian Inc., where he develops Simbeor electromagnetic signal integrity software. He received M.S. degree in radio engineering from Novosibirsk State Technical University in 1983, and the Ph.D. degree in computational electromagnetics from Siberian State University of Telecommunications and Informatics in 1990. He was principal developer of electromagnetic simulator for Eagleware Corporation and leading developer of electromagnetic software for simulation of signal and power distribution networks at Mentor Graphics. The results of his research are published in multiple papers and conference proceedings.

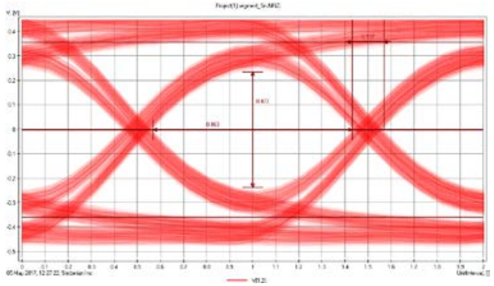
Outline

- What is laminate and why should we care
- Electrical properties of dielectrics in laminates
- Electrical properties of copper in laminates
- Broadband material model identification
- Conclusion

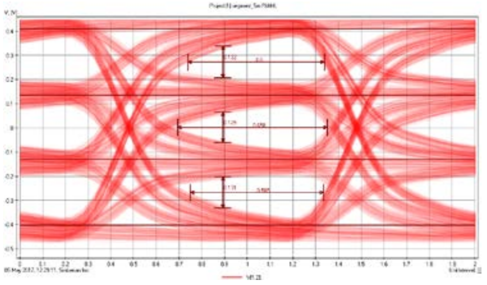
PCBs will never die!

- Copper interconnects in layered dielectrics
- System-level integration/packaging at relatively short distances (up to ~ 0.5 m)
  - Best bps/volume
  - Good bps/Watt – beats optical
  - Best bps/$ - beats optical & cables + conn.
- Data rate can be extended up to 100 Gbps (NRZ) or 200 Gbps (PAM4)
  - **Requires understanding and proper selection of laminate dielectrics, copper foil and fabrication process**

100 Gbps – 6 mil, 5 inch strip

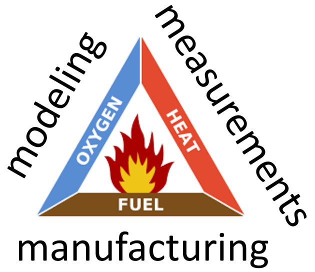


200 Gbps – 6 mil, 5 inch strip



Challenges for 100 Gbps PCBs

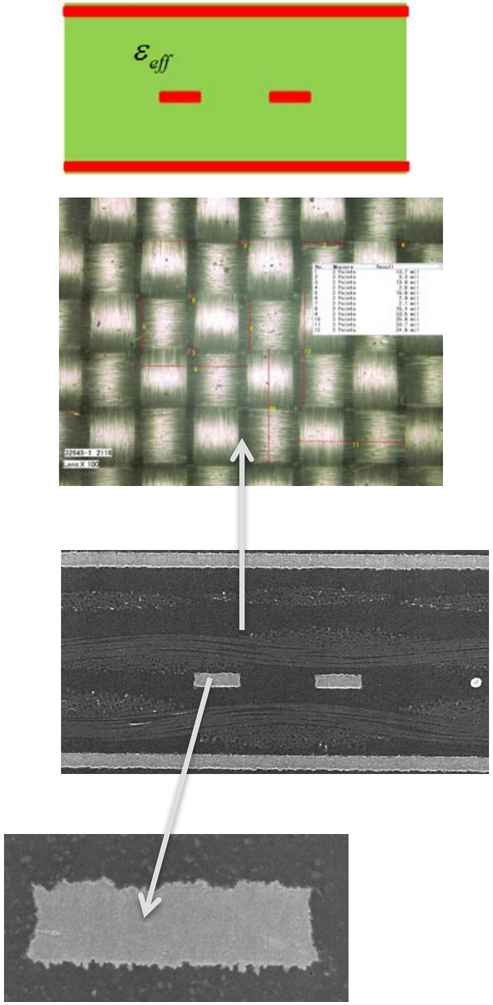
- Loss and Dispersion Model Development
  - Measurement correspondence
  - Suited for EDA (not just unclad dielectric!)
  - Meets BW requirements
  - Surface Roughness models
- Marry EDA tools and knowledge with actual fabrication
- Make pristine measurements



Design success “fire triangle”

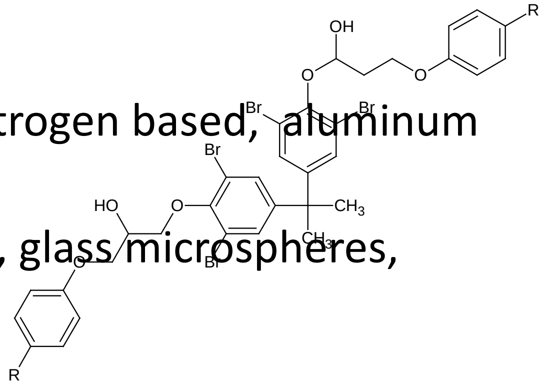
PCB manufacturing process

- Copper foil (3M, Oak Mitsui, Circuit Foil,…) – rough on one side, **no electrical models at all**
- Unclad/prepreg and copper-clad/core laminates (Taconic, Rogers, Arlon, Isola, Nelco, Panasonic, ITEQ, Nan Ya, Shengyi,…)
  - Most laminates use resin on woven glass fabric – inhomogeneous!
  - Unclad dielectric properties (Dk, Df), in plane at a few frequency points are usually available, **no broadband models**
- PCBs are fabricated with copper foils and laminates (TTM Technology, Sanmina-SCI,…)
  - Complicated fabrication process: **oxide treatment**, etching, bonding, drilling, plating, solder mask application, surface finish processes, …
  - The final geometry is not exactly what you designed in a layout tool
- To predict interconnect behavior, all components should be understood and taken into account in the modeling
  - Dielectric and conductor roughness models in particular…

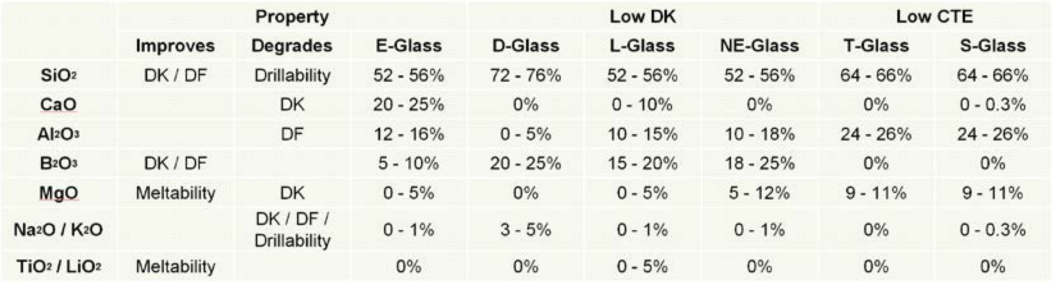


Laminate chemistry

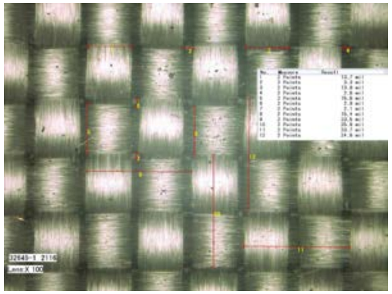
- Resin
  - Brominated – Tetrabromobisphenol A (TBBA)
  - Low halogen / halogen free: phosphorous and nitrogen based, aluminum and magnesium hydroxide,…
  - Filler components: aluminum silicate, talc, rubber, glass microspheres, boron nitride,…



- Fabric – not just glass



	Property			Low DK			Low CTE	
	Improves	Degrades	E-Glass	D-Glass	L-Glass	NE-Glass	T-Glass	S-Glass
SiO_2	DK / DF	Drillability	52 - 56%	72 - 76%	52 - 56%	52 - 56%	64 - 66%	64 - 66%
CaO		DK	20 - 25%	0%	0 - 10%	0%	0%	0 - 0.3%
Al_2O_3		DF	12 - 16%	0 - 5%	10 - 15%	10 - 18%	24 - 26%	24 - 26%
B_2O_3	DK / DF		5 - 10%	20 - 25%	15 - 20%	18 - 25%	0%	0%
MgO	Meltability	DK	0 - 5%	0%	0 - 5%	5 - 12%	9 - 11%	9 - 11%
Na_2O / K_2O		DK / DF / Drillability	0 - 1%	3 - 5%	0 - 1%	0 - 1%	0%	0 - 0.3%
TiO_2 / LiO_2	Meltability		0%	0%	0 - 5%	0%	0%	0%



- Cladded with copper foil roughened and oxide treated to make PCBs

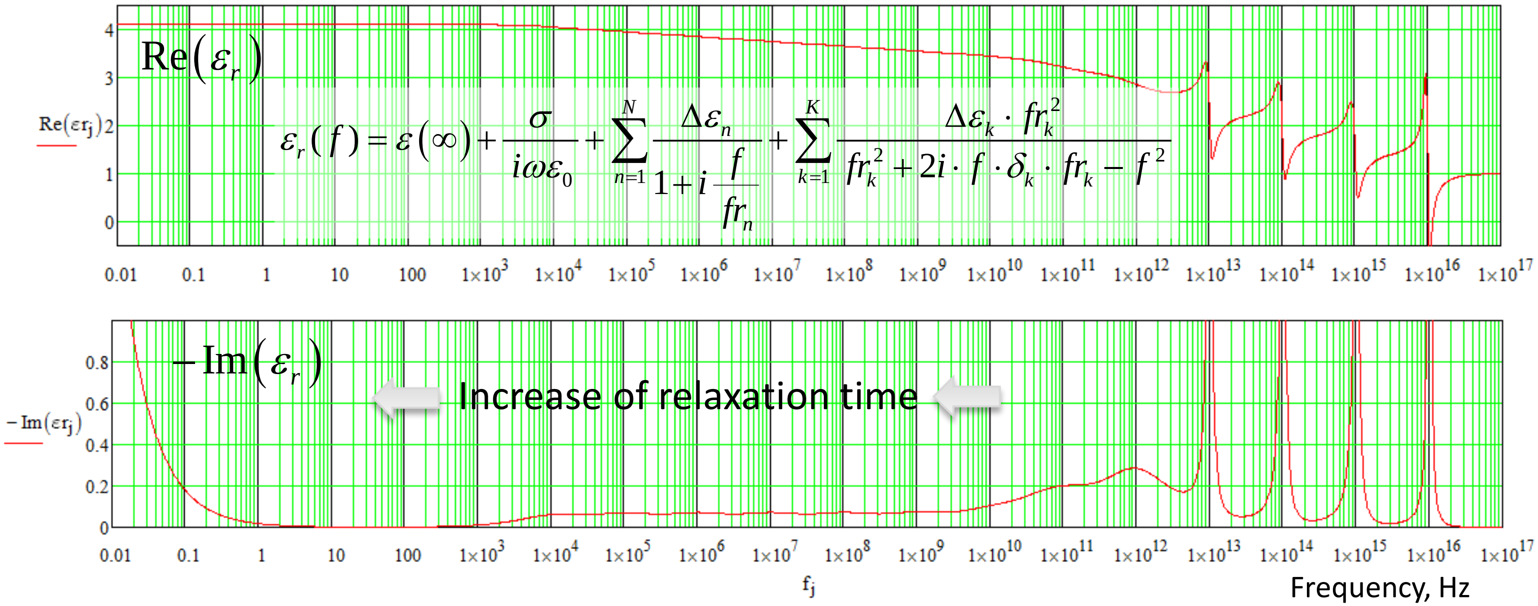
See more at "Material World…", DesignCon2016

Permittivity of composite materials

…if one asks a fellow scientist [physicist] “what happens when EM radiation in the range from 10^-6 to 10^12 Hz is applied to those systems [solids]” the answer is usually tentative or incomplete… - G. Williams in F. Kremer, A. Schonhals, Broadband Dielectric Spectroscopy, 2003

$$\langle\bar{D}\rangle = \varepsilon_0\varepsilon_r(f)\langle\bar{E}\rangle$$

conduction **relaxation** resonances

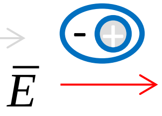


$$\varepsilon_r(f) = \varepsilon(\infty) + \frac{\sigma}{i\omega\varepsilon_0} + \sum_{n=1}^{N} \frac{\Delta\varepsilon_n}{1 + i\,\frac{f}{fr_n}} + \sum_{k=1}^{K} \frac{\Delta\varepsilon_k \cdot fr_k^2}{fr_k^2 + 2i \cdot f \cdot \delta_k \cdot fr_k - f^2}$$

Increase of relaxation time

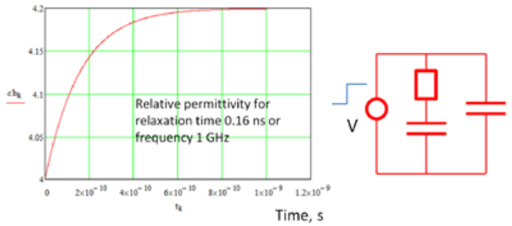
Frequency, Hz

Electronic polarization of atoms (induced dipoles)



D.D. Pollock, Physical properties of materials for engineers, 1982, v III

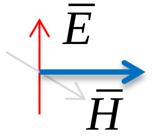
One-pole Debye model



$$\varepsilon_r(f) = \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + i\, f / f_r}$$

$$\Gamma(f) = i2\pi f \sqrt{\varepsilon_r(f)\cdot\varepsilon_0\cdot\mu_0}$$

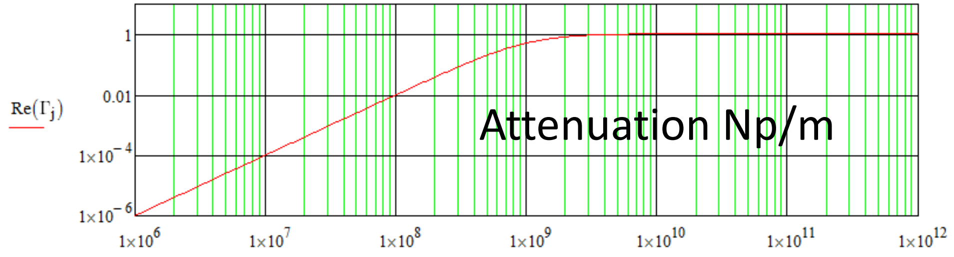
- plane wave propagation constant

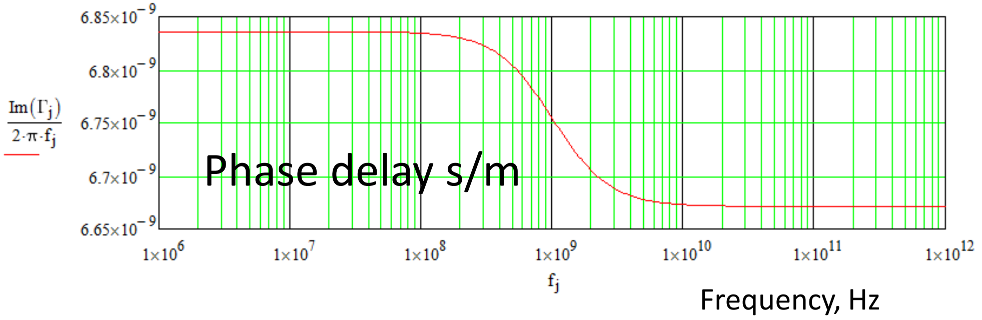


Pole:

Example:

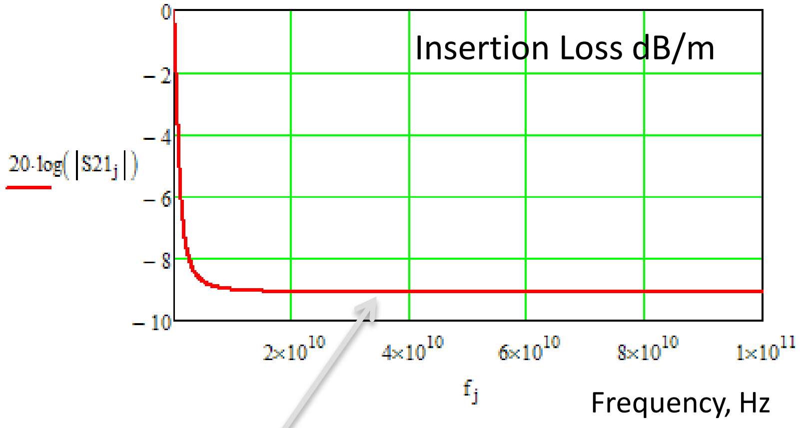
$\varepsilon_\infty = 4.0;\ \Delta\varepsilon = 0.2;\ f_r = 1GHz$





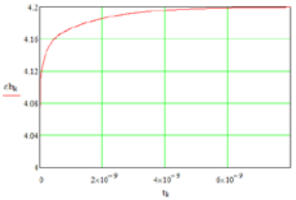
Generalized transmission parameter for distance *l:*

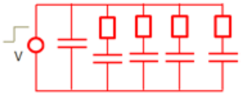
$$S21(\omega) = e^{-\Gamma\cdot l}$$



It works well for quartz for instance, but will it work for PCB laminates?

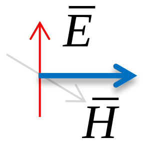
Multi-pole Debye model



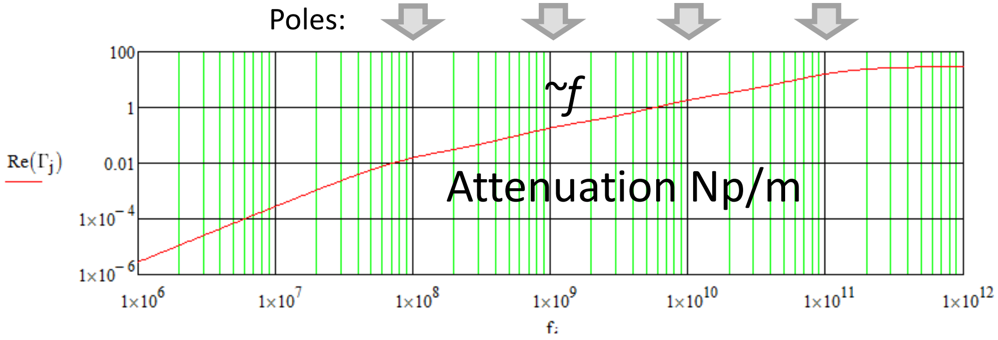


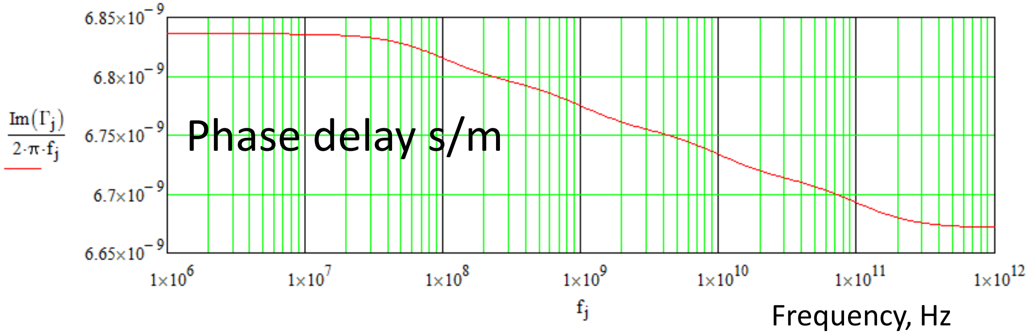
$$\varepsilon_r(f)=\varepsilon_\infty+\sum_{k=1}^{K}\frac{\Delta\varepsilon_k}{1+i\,f/f_{rk}} \Rightarrow \Gamma(f)=i2\pi f\sqrt{\varepsilon_r(f)\cdot\varepsilon_0\cdot\mu_0}$$

- plane wave propagation constant



Poles:





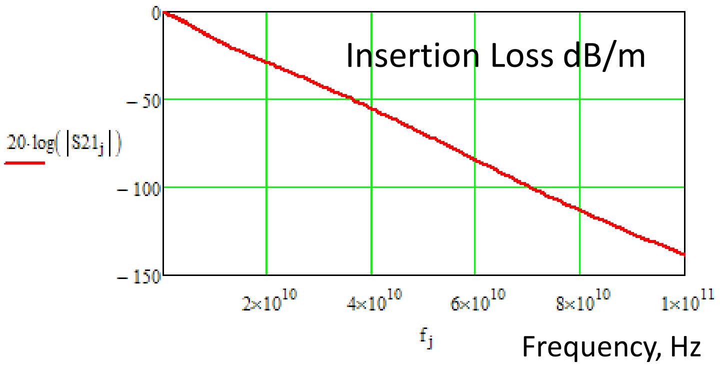
Frequency, Hz

4-pole example:

$$\varepsilon_\infty=4.0;\Delta\varepsilon_k=0.05;$$
$$f_{r1}=0.1;\ f_{r2}=1;\ f_{r3}=10;\ f_{r4}=100;\ [\mathrm{GHz}]$$

Generalized transmission parameter for distance *l*:

$$S21(\omega)=e^{-\Gamma\cdot l}$$



Frequency, Hz

Will it work for any PCB dielectric?

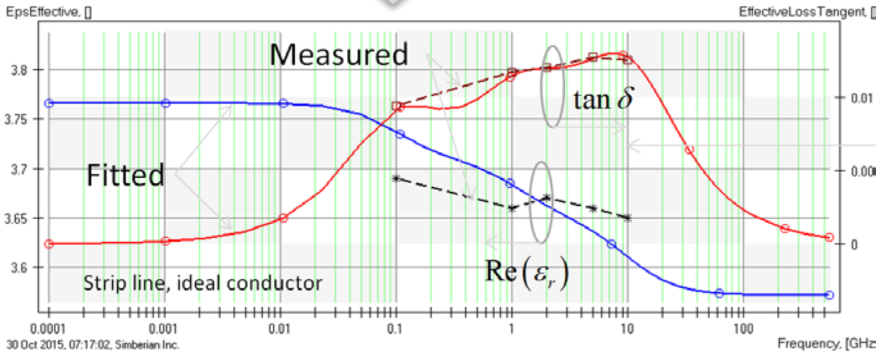
Fitting Dk and LT points from laminate spreadsheet

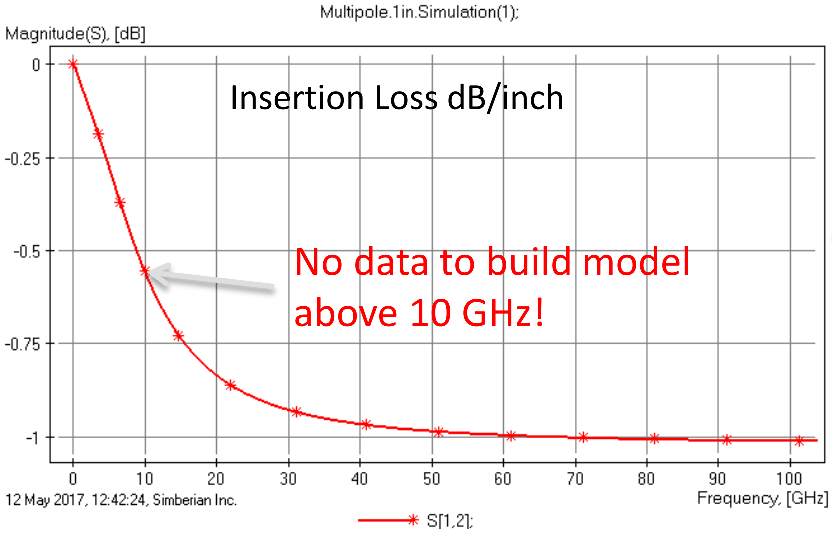
$$\varepsilon_r(f) = \varepsilon_\infty + \sum_{k=1}^{K} \frac{\Delta\varepsilon_k}{1 + i\, f / f_{rk}}$$

- **3 problems**
- The result is very sensitive to measurement errors (requires data points consistent with the model)
- Bandwidth is restricted by the first and the last frequency point
- **Out of plane values in unclad laminate =>**

From Isola's FR408HR specifications

Dk, Permittivity (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A) B. @ 1 GHz (HP4291A) C. @ 2 GHz (Bereskin Stripline) D. @ 5 GHz (Bereskin Stripline) E. @ 10 GHz (Bereskin Stripline)	3.69 3.66 3.67 3.66 3.65
Df, Loss Tangent (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A) B. @ 1 GHz (HP4291A) C. @ 2 GHz (Bereskin Stripline) D. @ 5 GHz (Bereskin Stripline) E. @ 10 GHz (Bereskin Stripline)	0.0094 0.0117 0.0120 0.0127 0.0125



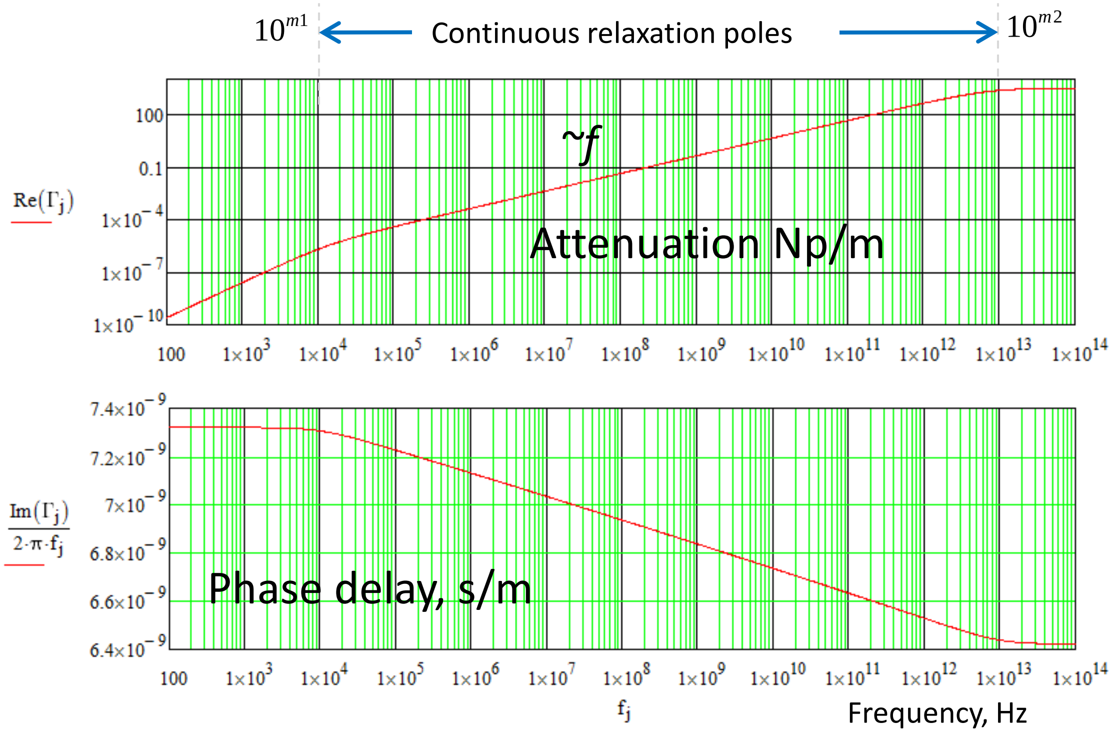


No data to build model above 10 GHz!

Wideband Debye model

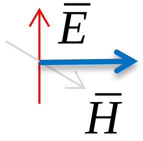
Aka Djordjevic-Sarkar or Swensson-Dermer

$$\varepsilon_r(f) = \varepsilon_\infty + \sum_{k=1}^{K} \frac{\Delta\varepsilon_k}{1 + i\, f / f_{rk}} \Rightarrow \varepsilon_r(f) = \varepsilon_\infty + \frac{\Delta\varepsilon}{(m_2 - m_1)\cdot \ln(10)} \cdot \ln\left[\frac{10^{m2} + if}{10^{m1} + if}\right]$$



Plane wave propagation constant

$$\Gamma(f) = i2\pi f \sqrt{\varepsilon_r(f)\cdot\varepsilon_0\cdot\mu_0}$$



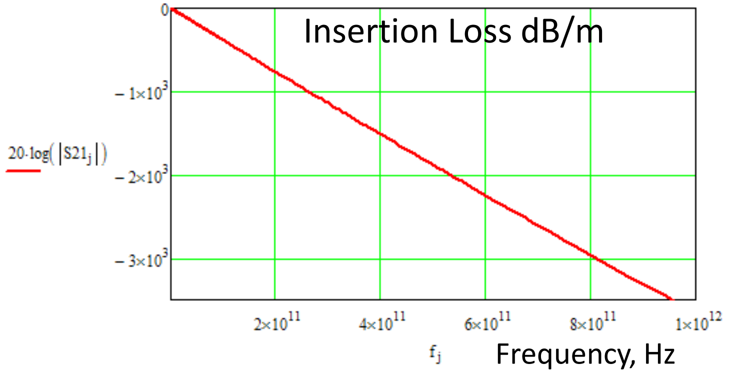
Example:

$$\varepsilon_\infty = 3.707;\ \Delta\varepsilon = 1.108;\ m1 = 4;\ m2 = 13;$$

$$\mathrm{Re}\left(\varepsilon(10^9)\right) = 4.2;\ \tan\delta\left(10^9\right) = 0.02$$

Generalized transmission parameter for distance *l:*

$$S21(\omega) = e^{-\Gamma\cdot l}$$



This model can be defined with Dk and LT measured at 1 frequency point!

Other wideband model options: Havriliak-Negami

Which point to use?

Ambiguous, but model is usable!

$$\varepsilon_r(f) = \varepsilon_\infty + \frac{\Delta\varepsilon}{(m_2 - m_1)\cdot\ln(10)}\cdot\ln\left[\frac{10^{m2}+if}{10^{m1}+if}\right]$$

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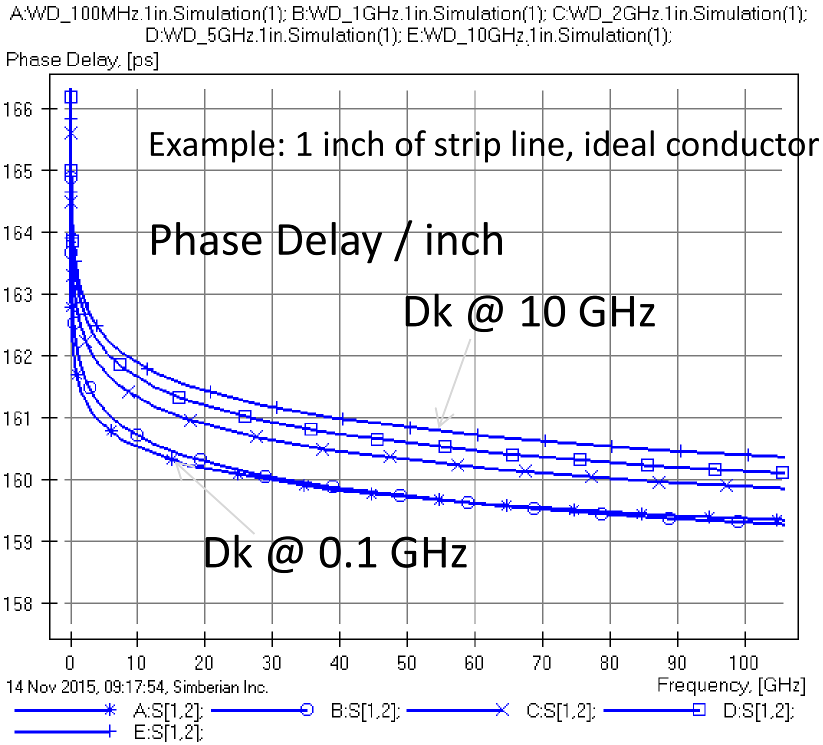
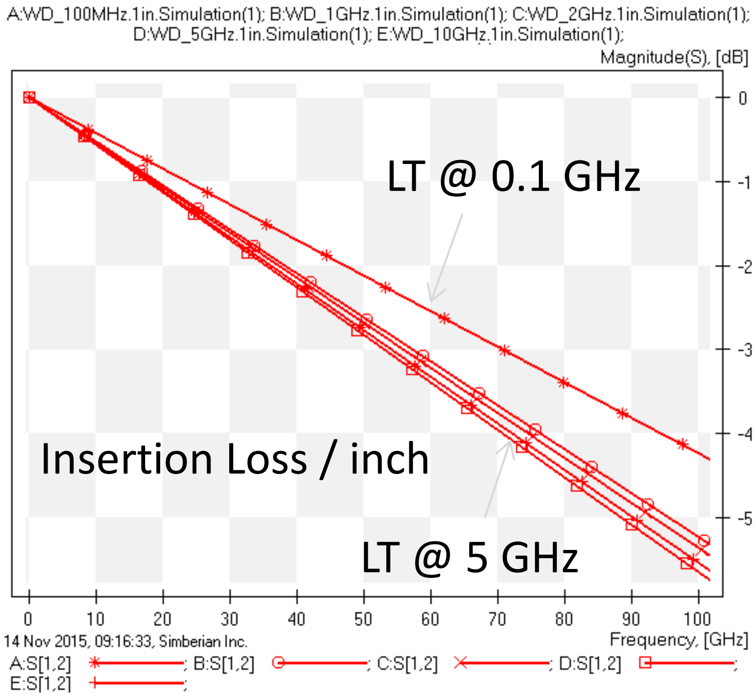


Example: 1 inch of strip line, ideal conductor

Phase Delay / inch

Dk @ 10 GHz

Dk @ 0.1 GHz



LT @ 0.1 GHz

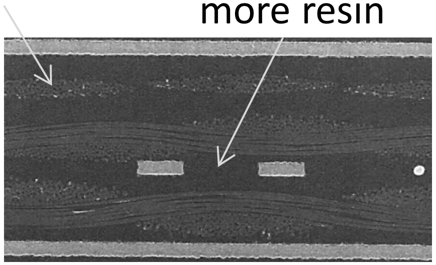
Insertion Loss / inch

LT @ 5 GHz

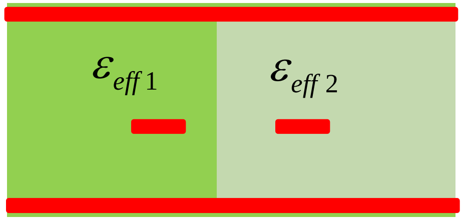
Computed with Simbeor THz

Laminate spatial inhomogeneity and feature size

- Dielectric inhomogeneity may cause signal degradation at higher data rates or frequencies – skew, mode conversion, anisotropic behavior,…
- Use or smaller and smaller homogenization area to define dielectric properties



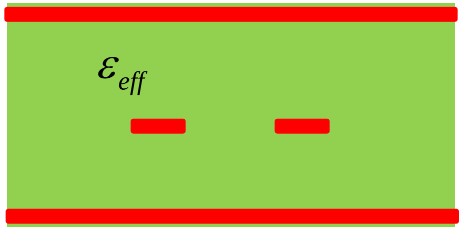
Imbalanced effective dielectrics



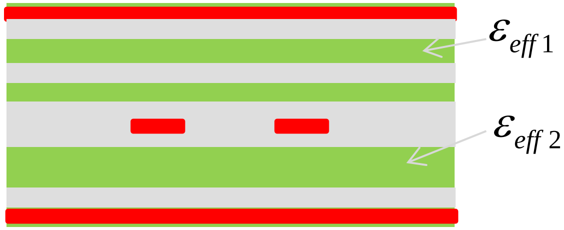
$$\langle \bar{D} \rangle = \varepsilon_{eff} \langle \bar{E} \rangle \qquad \langle \bar{F} \rangle = \frac{1}{V} \int_V \bar{F} \cdot dv$$

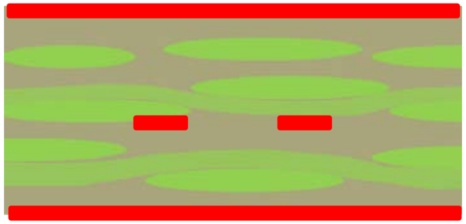
More and more details is required to extend model frequency range – too complicated…

Homogeneous effective dielectric



Layered effective dielectrics





Almost random – statistical models

Alternatively, use of more homogeneous dielectric (same Dk for resin and fabric) can extend the predictable frequency range of simple homogeneous laminate models

Laminate spatial inhomogeneity and wavelength

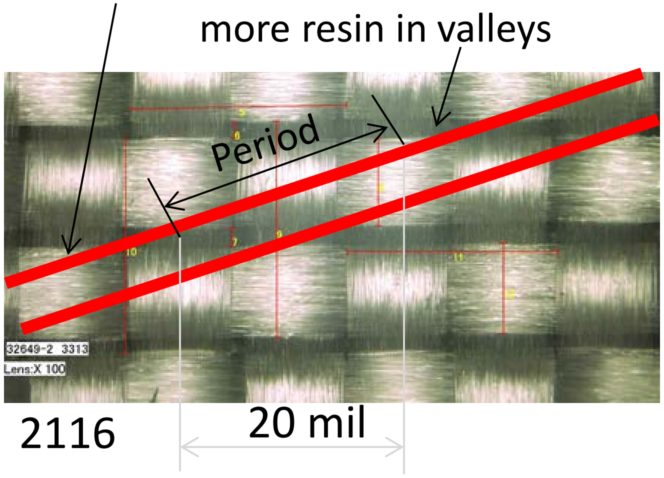
- **Homogenization area must be much smaller than the wavelength**
- Effect of inhomogeneity along traces grow with frequency – skew, resonances…

$$\langle \bar{D} \rangle = \varepsilon_{eff} \langle \bar{E} \rangle$$

$$\langle \bar{F} \rangle = \frac{1}{V} \int_{V} \bar{F} \cdot dv$$

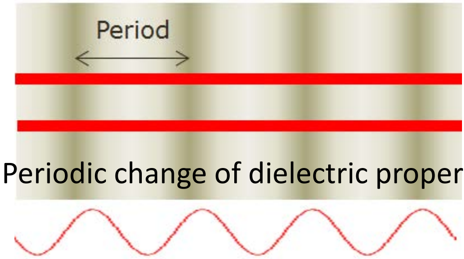
more glass fiber at humps

more resin in valleys



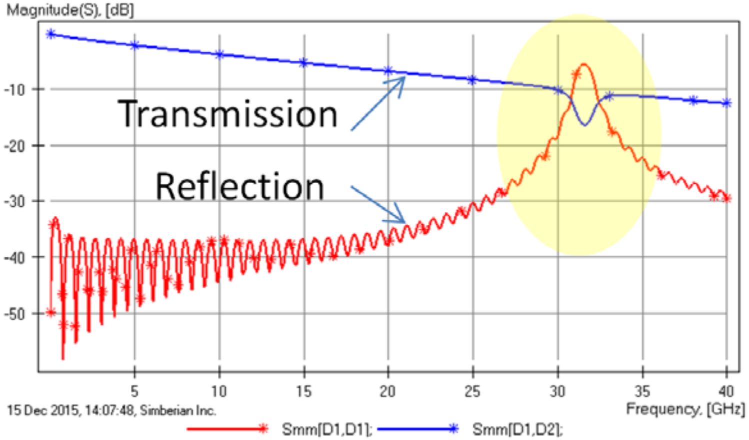
Wavelength in dielectric:
1 GHz – 6 in; 10 GHz – 600 mil;
50 GHz – 120 mil; 100 GHz – 60 mil;

1D or 2D non-uniform t-line models



Resonance at
Period = Wavelength/2

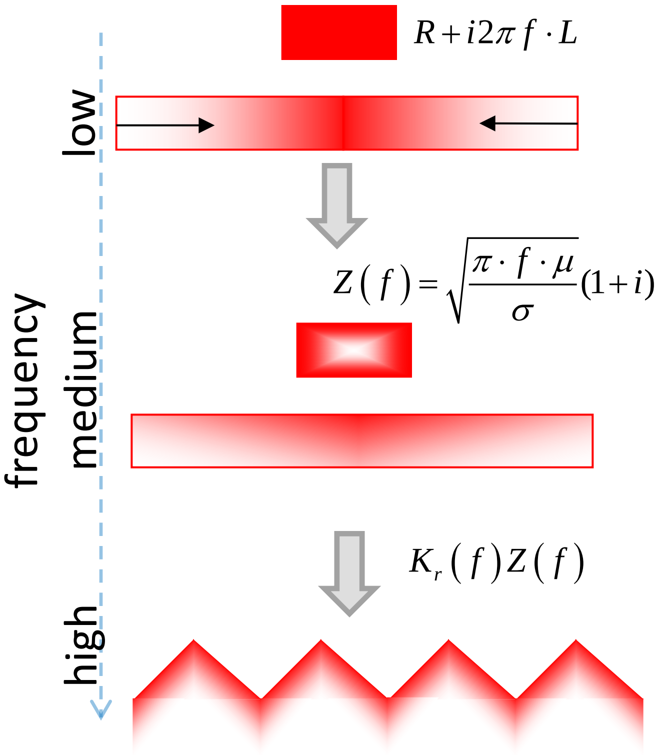
Periodic change of dielectric properties



Alternative to complicated statistical modeling – use more homogeneous laminates!

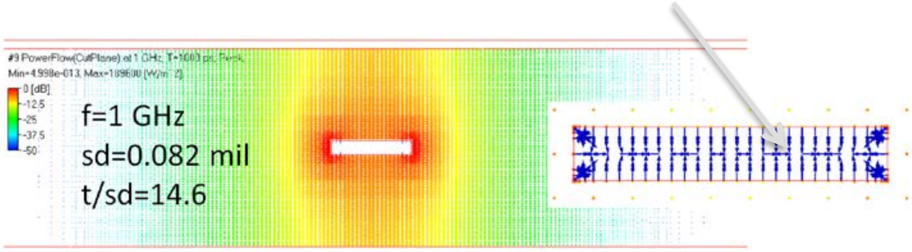
Conductor loss and dispersion

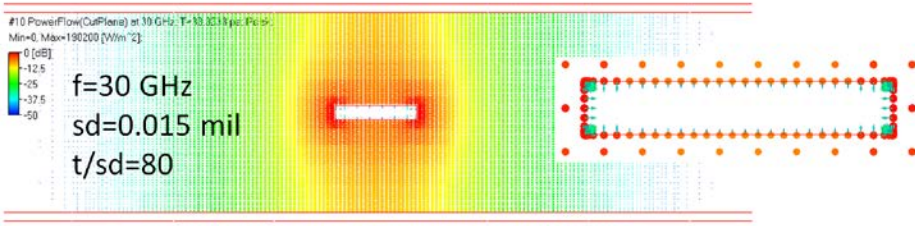
- Current crowding below strips
  - Around 10-100 KHz
  - Increases R and decreases L at very low frequencies
- Skin-effect
  - Transition frequencies from 1 MHz to 100 GHz (see chart)
  - Surface impedance boundary conditions (SIBC) for well-developed skin-effect – R and L ~ sqrt(frequency)
- Skin-effect on rough surface
  - May be comparable with skin depth starting from 10 MHz
  - Increases both R and L (and possibly C)
- Ferromagnetic resonances from 2 to 3 GHz (Nickel)
- Plasmonic effects above 1 THz – (Drude model)

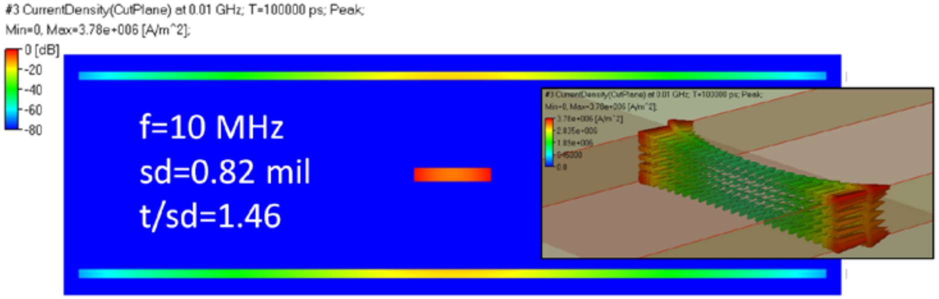


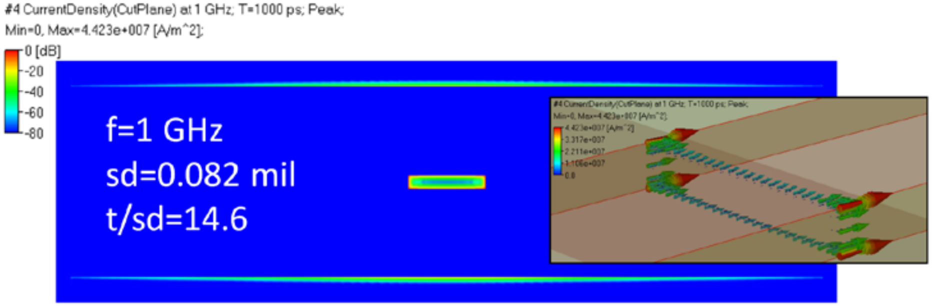
Currents and power flow in strip line

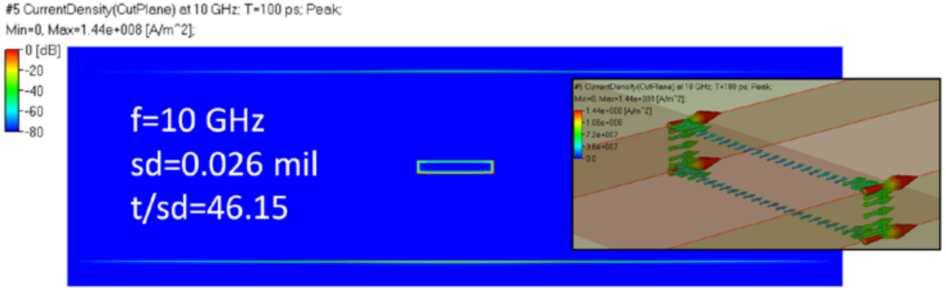
Conductor absorbs energy

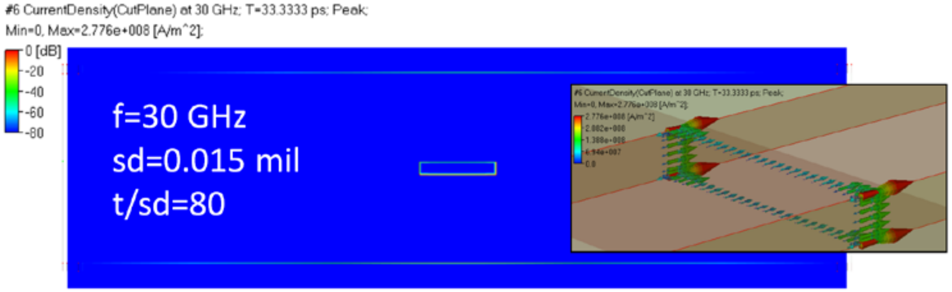












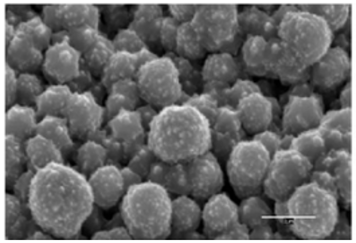
See more in “How Interconnects Work”
Does roughness change the conductor behavior?

Rough copper absorbs more energy

Losses estimation for conductive sphere are used to derive equation for multiple spheres:

$$\frac{P_{rough}}{P_{smooth}} \approx \frac{A_{Matte}}{A_{hex}} + \frac{3}{2}\sum_{i=1}^{j}\left(\frac{N_i 4\pi a_i^2}{A_{hex}}\right)\Big/\left[1+\frac{\delta}{a_i}+\frac{\delta^2}{2a_i^2}\right]$$

P.G. Huray, The foundation of signal integrity, 2010



Amatte/Ahex can be accounted for by resistivity;
Can be simplified to model with 2 parameters per ball (*RFi* and *Di*):

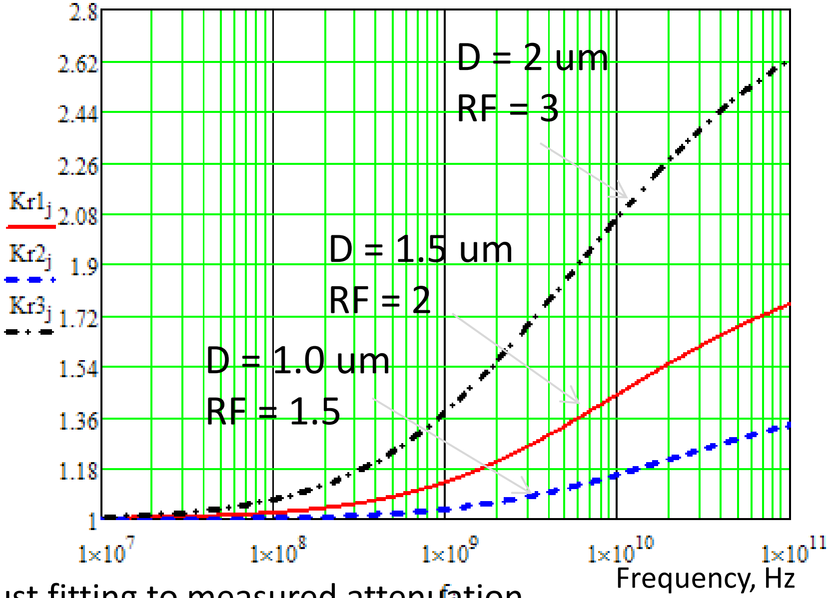
$$K_{sr} = 1 + \sum_i (RF_i - 1)\cdot\left(1+\frac{2\delta_s}{D_i}+\frac{2\delta_s^2}{D_i^2}\right)^{-1}$$

Roughness Factor (unit less):

$$\delta_s = \sqrt{\frac{1}{\pi\cdot f\cdot\mu\cdot\sigma}}$$

$$RF_i = 1 + \frac{3\pi\cdot N_i\cdot D_i^2}{2\cdot A_{hex}}$$

Di – ball *i* diameter;
Ni – number of balls with diameter *Di*;



Can be applied similar to multipole Debye model with just fitting to measured attenuation

Modified Hammerstad model

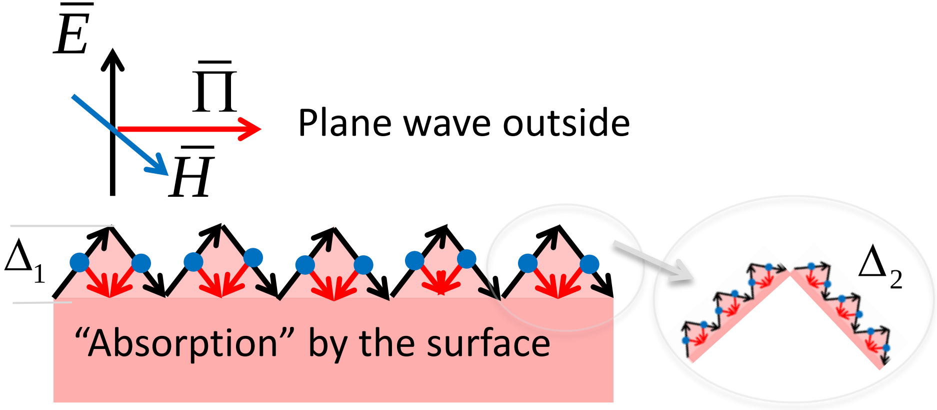
Roughness correction coefficient – increase of absorption by *Ksr*:

$$K_{sr} = \prod_i \left[1 + \left(RF_i - 1\right)\cdot\left(\frac{2}{\pi}\cdot\arctan\left[1.4\frac{\Delta_i}{\delta_s}\right]\right)\right]$$

Conductor skin-depth $\delta_s = \sqrt{\frac{1}{\pi\cdot f\cdot\mu\cdot\sigma}}$

Δ ~ root mean square peak-to-valley distance (level i)

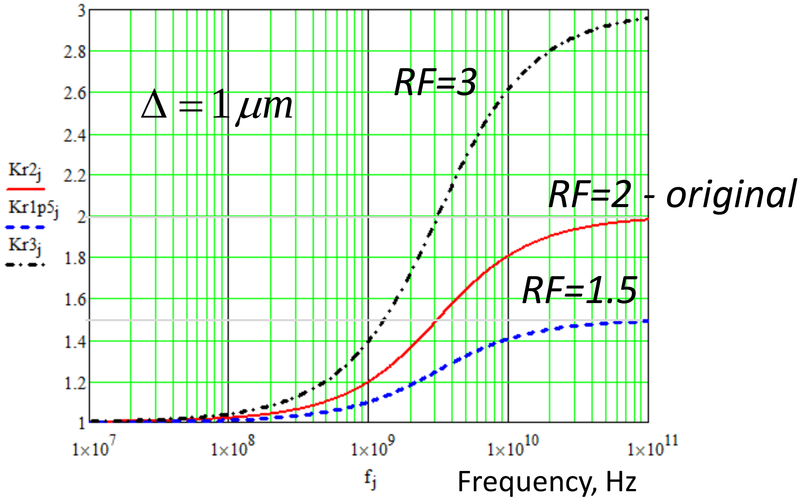
RF - roughness factor, defines maximal growth of losses due to metal roughness (increase of surface at level i)



Plane wave outside

“Absorption” by the surface

Bumps are much smaller than wavelength!



Frequency, Hz

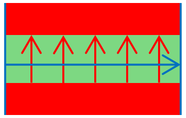
Modified model suggested in Y. Shlepnev, C. Nwachukwu, Roughness characterization for interconnect analysis. - Proc. of the 2011 IEEE Int. Symp. on EMC, Long Beach, CA, USA, August, 2011, p. 518-523

Other options: Hemispherical model, Effective Roughness Dielectric,…

Loss and dispersion with rough conductors

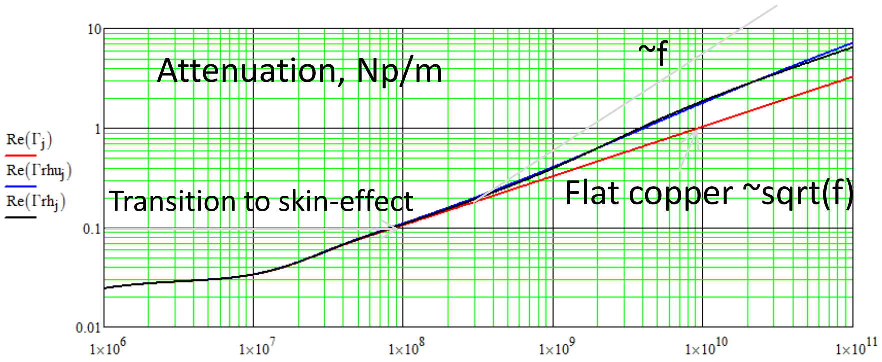
Parallel-plate waveguide – ideal to investigate RCCs

PMC



PMC

Copper: w=20 mil; t=1 mil; Rough;
Ideal dielectric: Dk=4; h=5.3 mil;

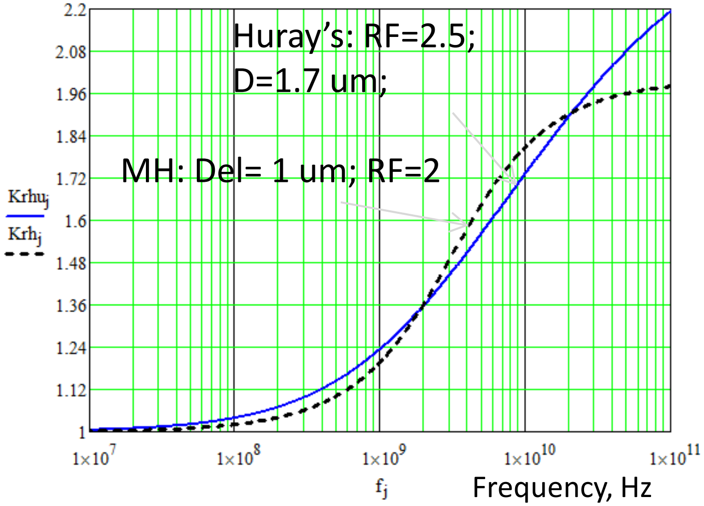


Attenuation, Np/m

~f

Transition to skin-effect

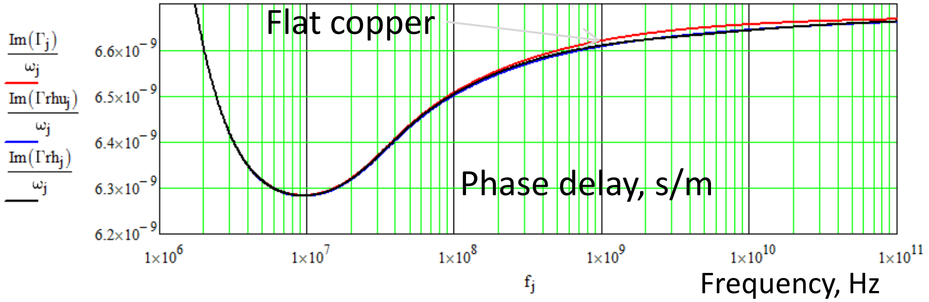
Flat copper ~sqrt(f)



Huray's: RF=2.5;
D=1.7 um;

MH: Del= 1 um; RF=2

Frequency, Hz



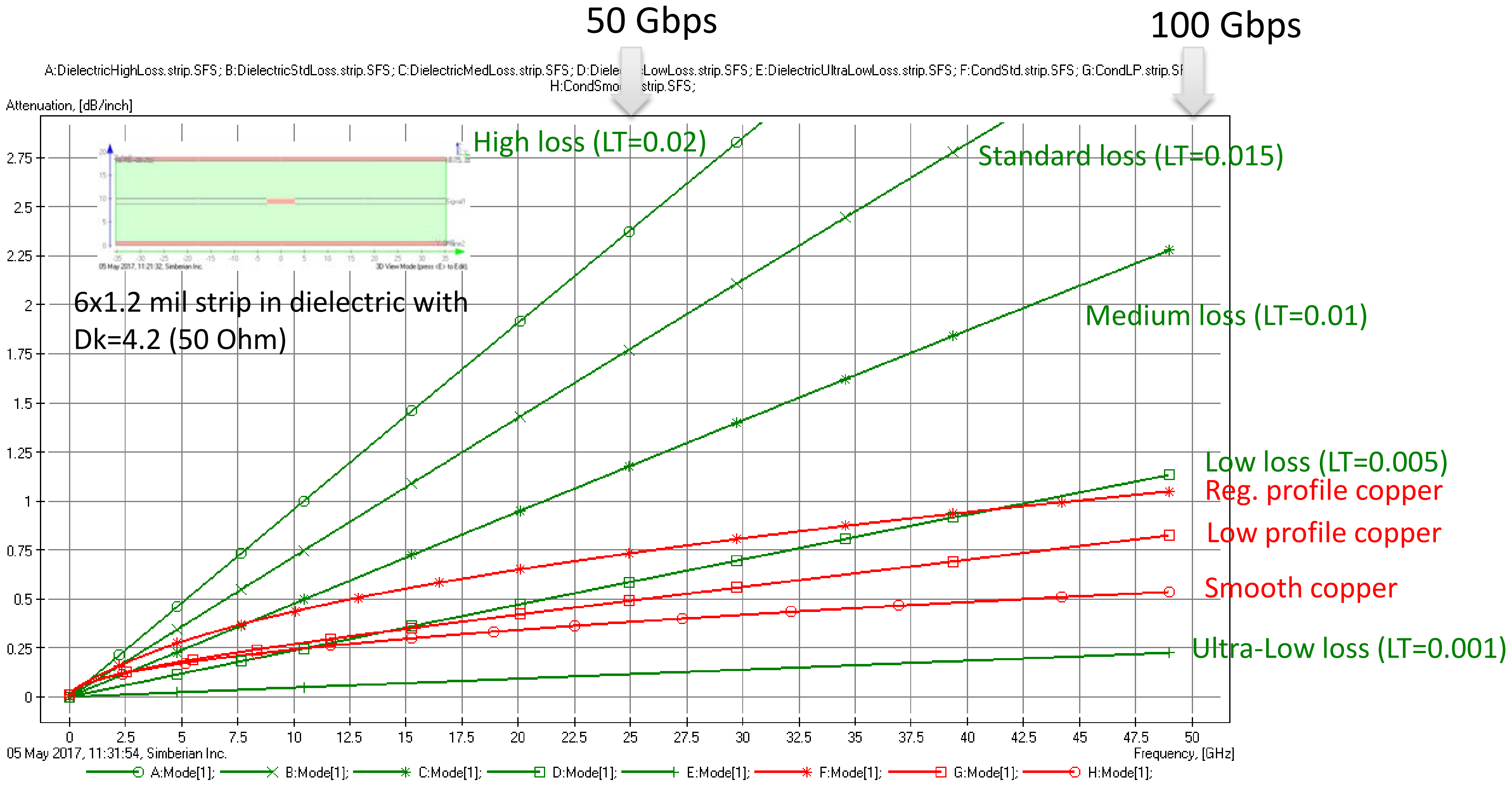
Flat copper

Phase delay, s/m

Frequency, Hz

Flat copper: Red lines;
Huray's one-ball: blue lines;
Modified Hammerstad (MH): black lines;

Comparison of dielectric and copper losses



6x1.2 mil strip in dielectric with Dk=4.2 (50 Ohm)

Minimal possible losses on PCB are limited mostly by copper and copper roughness!
Larger smooth strips in dielectric with lower Dk and ultra-lower losses -> closer to cables;

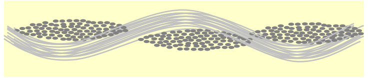
Material model identification

IN GENERAL

- For test structures …
  - Sample in transmission or resonant structure
  - Transmission line segment or resonator made with the material
- Make measurements …
  - Capacitance
  - S-parameters measured with VNA
  - TDR/TDT measurements
  - Combination of measurements
- Correlated with a numerical model
  - Analytical or closed-form
  - Static or quasi-static field solvers
  - 3D full-wave solvers

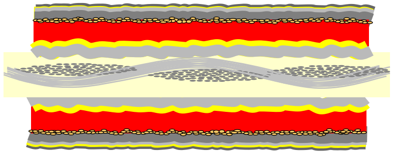
FOR PCBs

- Unclad laminate (IPC):



- Capacitance Test Method
- Stripline resonator or “Berezkin”
- Resonant Cavity Structures
- Free-space Transmission

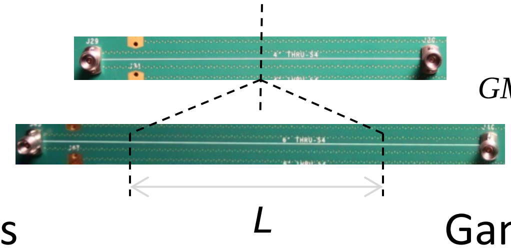
- **Copper-clad laminate:**



- **Generalized Modal S-Parameters (GMS)**
- **Gamma extraction: Short Pulse Propagation (SPP) with TDT or S-par.**
- Techniques with de-embedding,…

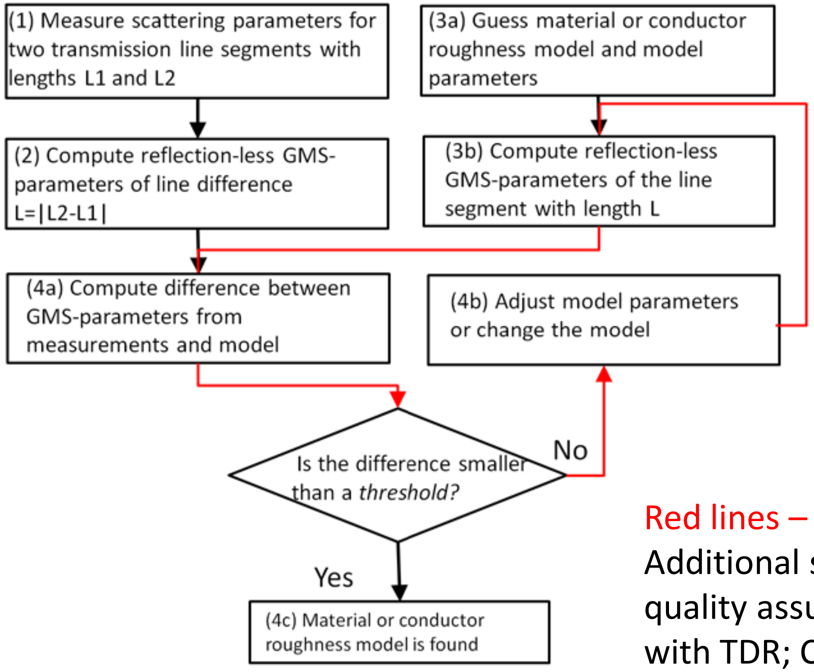
Identification with S-parameters of two line segments

$$GMS = \begin{pmatrix} 0 & \exp(-\Gamma \cdot L) \\ \exp(-\Gamma \cdot L) & 0 \end{pmatrix}$$



$$GMT = eigenvals\left(T2 \cdot T1^{-1}\right) = \begin{pmatrix} \exp(-\Gamma \cdot L) & 0 \\ 0 & \exp(\Gamma \cdot L) \end{pmatrix}$$

Use of raw GMS-parameters



(1) Measure scattering parameters for two transmission line segments with lengths L1 and L2

(2) Compute reflection-less GMS-parameters of line difference L=|L2-L1|

(3a) Guess material or conductor roughness model and model parameters

(3b) Compute reflection-less GMS-parameters of the line segment with length L

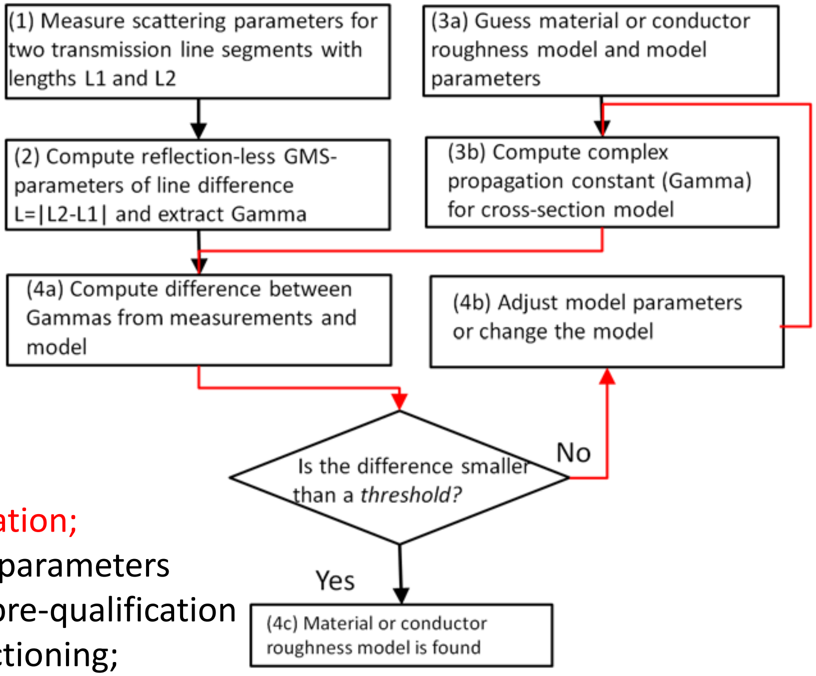
(4a) Compute difference between GMS-parameters from measurements and model

Is the difference smaller than a *threshold?*

No → (4b) Adjust model parameters or change the model

Yes → (4c) Material or conductor roughness model is found

Gamma extraction – "SPP Light"



(1) Measure scattering parameters for two transmission line segments with lengths L1 and L2

(2) Compute reflection-less GMS-parameters of line difference L=|L2-L1| and extract Gamma

(3a) Guess material or conductor roughness model and model parameters

(3b) Compute complex propagation constant (Gamma) for cross-section model

(4a) Compute difference between Gammas from measurements and model

Is the difference smaller than a *threshold?*

No → (4b) Adjust model parameters or change the model

Yes → (4c) Material or conductor roughness model is found

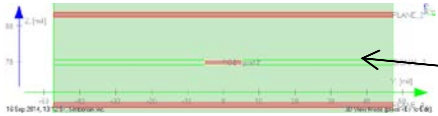
Red lines – optimization;
Additional steps: S-parameters quality assurance; pre-qualification with TDR; Cross-sectioning;

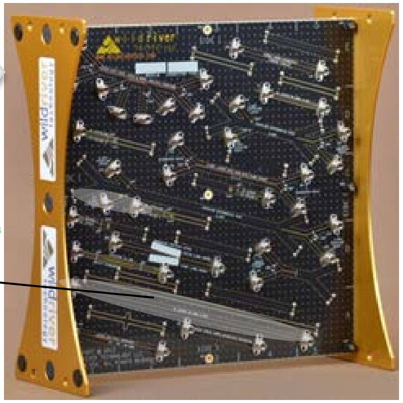
Y. Shlepnev, Broadband material model identification with GMS-parameters, EPEPS 2015.
Y. Shlepnev, Y. Choi, C. Cheng, Y. Damgaci, Drawbacks and Possible Improvements of Short Pulse Propagation Technique, EPEPS 2016.

Example of identification

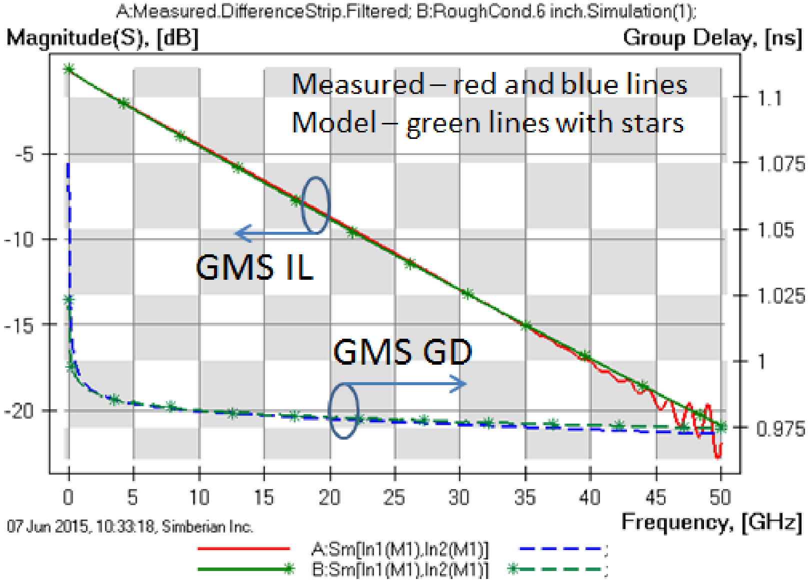
CMP-28 channel modelling platform from Wild River Technology http://www.wildrivertech.com/

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

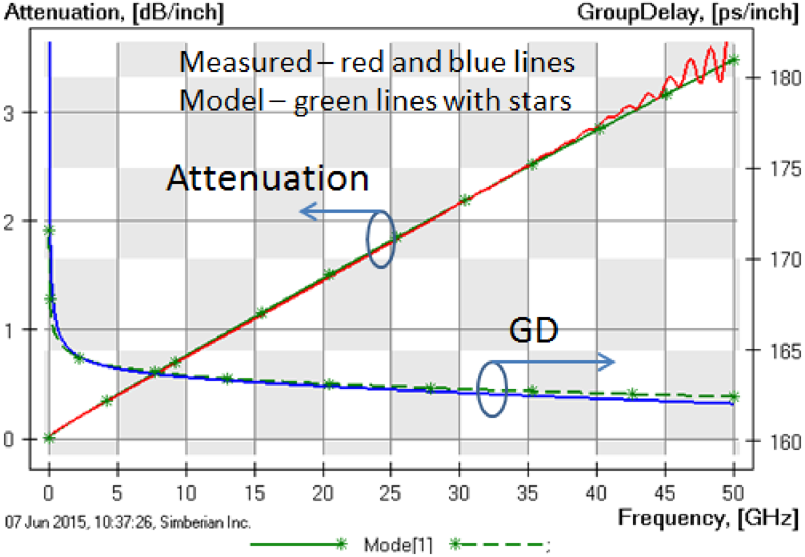




GMS-parameters



Gamma (SPP Light)

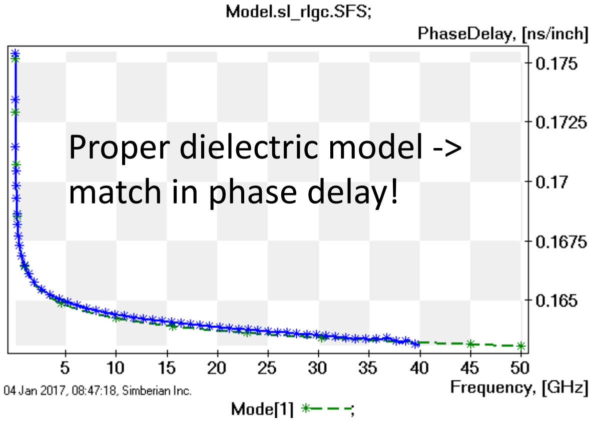


Models are usable above 50 GHz!

Signal Integrity Journal
Signal Integrity · Power Integrity · EMC/EMI

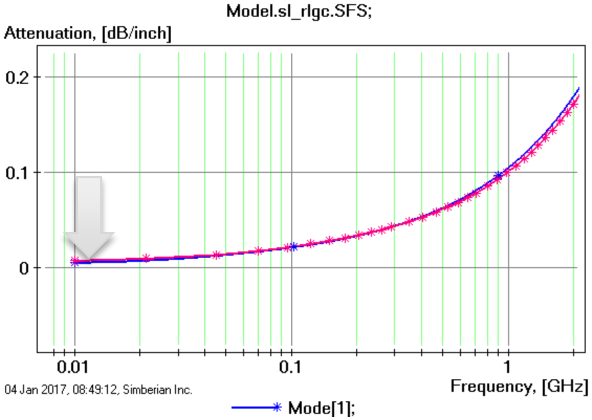
Separation of dielectric and conductor losses

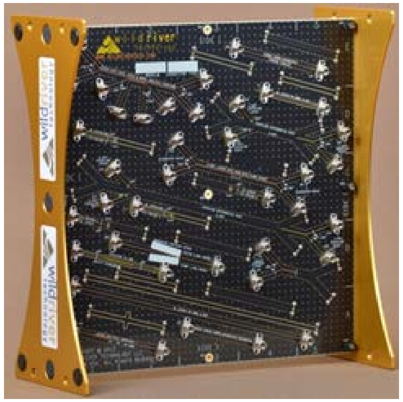
1. Adjust Dk to match phase delays



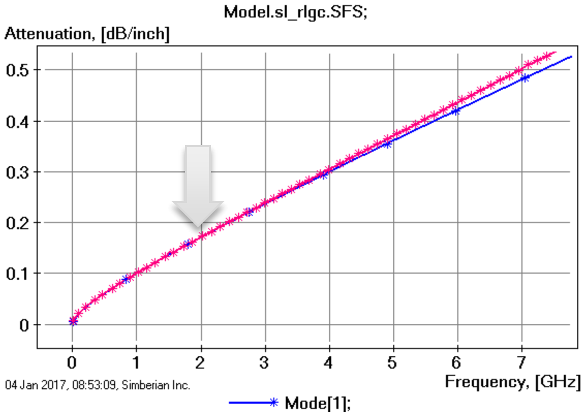
Proper dielectric model -> match in phase delay!

2. Adjust coper resistivity to match attenuation below 10-30 MHz

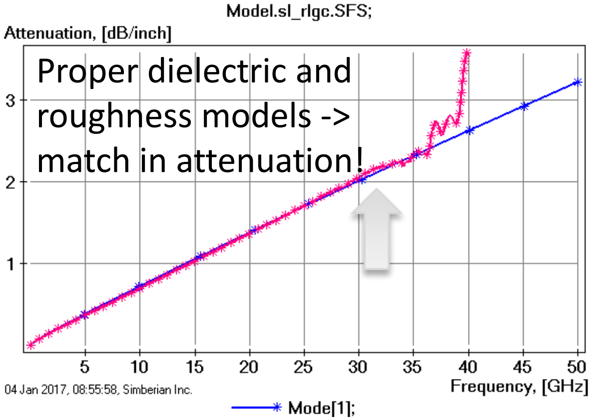




3. Adjust LT to match attenuation below 1-2 GHz



4. Adjust roughness parameters match attenuation above 2 GHz



Proper dielectric and roughness models -> match in attenuation!

5. Correct Dk to match phase delay, if necessary;

Models are usable up to 50 GHz and for a range of strip widths!

Conclusion

- Electrical properties of laminate dielectrics are defined mostly by atomic relaxation in composite materials
  - Permittivity can be approximated with Debye-type models up to 100 GHz
  - Moisture and temperature change dielectric properties – must be accounted
  - Dielectric inhomogeneity should be either modeled or eliminated – statistical models may be needed
- Roughness increases absorption by conductor surface
  - Model with roughness correction coefficients
- Dielectric models provided by laminate manufacturers can be used only for preliminary analysis
- Final dielectric and conductor roughness models must be validated or identified for analysis at 6 Gbps and higher
  - GMS-parameters or SPP Light are the simplest and the most accurate techniques

See more at “Material World” at http://www.simberian.com/TechnicalPresentations.php
App notes and “How Interconnects Work” at http://www.simberian.com