UBM

A MATERIAL WORLD

Modeling dielectrics and conductors for interconnects operating at 10-50 Gbps

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Outline

- Broadband dielectric and conductor models

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- PCB materials and model identification techniques

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- Practical examples of material model identification

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“Material world” terminology

- ***Materials:***
  - ***Dielectrics***… are the broad expanse of nonmetals considered from the standpoint of their interactions with electric, magnetic or electromagnetic fields. - A. R. von Hippel, “Dielectric materials and applications”
  - ***Conductors*** are materials that allow the flow of electrical current
- ***Linear*** material satisfy superposition property: $\bar{x}_1 \to \bar{w}_1;\ \bar{x}_2 \to \bar{w}_2 \ \Rightarrow\ \alpha\cdot\bar{x}_1 + \beta\cdot\bar{x}_2 \to \alpha\cdot\bar{w}_1 + \beta\cdot\bar{w}_2$
- ***Time Invariant*** material does not change behavior with time: $\bar{x}(t) \to \bar{w}(t) \Rightarrow\ \bar{x}(t-\tau) \to \bar{w}(t-\tau)$
- Material is ***passive*** if energy is absorbed for all possible values of fields for all time

$$P(t) = \int_{-\infty}^{t} \left[\int_S \bar{E}(\tau) \times \bar{H}(\tau) \cdot d\bar{s} \right] d\tau \geq 0,\ \forall t$$

- Material is ***homogeneous*** if properties do not change through some area/volume
- Material is ***isotropic*** if properties do not change with direction
- Material is ***anisotropic*** if properties change with direction
- ***Temporal dispersion*** is momentary delay or lag in properties of a material usually observed as frequency dependency of the material properties

Maxwell's equations in macroscopic form

$$\nabla \cdot \bar{D} = \rho_{free}$$
$$\nabla \cdot \bar{B} = 0$$

Gauss's laws

$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t}$$

Faraday's law

$$\nabla \times \bar{H} = \frac{\partial \bar{D}}{\partial t} + \bar{J}_{free}$$

Ampere's law

$$\bar{D} = \varepsilon_0 \bar{E} + \bar{P}$$
$$\bar{B} = \mu_0 \left(\bar{H} + \bar{M} \right)$$

Fields in materials

$\bar{E}$ - Electric Field (V/m)

$\bar{H}$ - Magnetic Field (A/m)

$\bar{D}$ - Electric Flux (Coulomb/m^2)

$\bar{B}$ - Magnetic Flux (Tesla or Weber/m^2)

ρ_{free} - Free Charge (Coulomb/m^3)

$\bar{J}_{free}$ - Free Current (A/m^2)

$\bar{P}$ - Polarization (Coulomb/m^2)

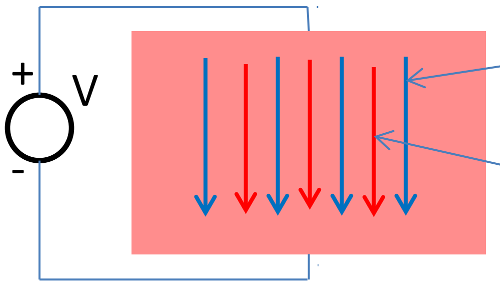
$\bar{M}$ - Magnetization (A/m)

No material equations here…

Currents in Ampere's law: $\nabla \times \bar{H} = \frac{\partial \bar{D}}{\partial t} + \bar{J}_{free}$

Conductivity current [A/m^2]

Translational motion of free charges in electric field: $J_{free} = f\left(\bar{E}, \mathrm{T}, \ldots\right)$



Ohm's Law for LTI, isotropic:

$$J_{free} = \sigma \bar{E}$$

σ - bulk conductivity, Siemens/m

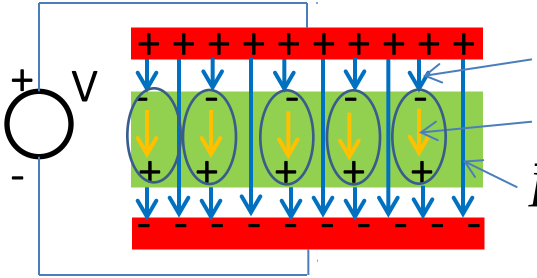
dispersive in general;
almost constant up to THz;

$$\nabla \times \bar{H} = \frac{\partial \bar{D}}{\partial t} + \sigma \bar{E}$$

$\rho = 1/\sigma$ - bulk resistivity, Ohm*m

Currents in Ampere's law: $\nabla \times \bar{H} = \frac{\partial \bar{D}}{\partial t} + \sigma \bar{E}$

$\bar{D} = \varepsilon_0 \bar{E} + \bar{P}$ **Polarization [Coulomb/m^2]** is displacement of charges bound to atoms, molecules, lattices, boundaries,… - creates electric field



$\bar{E}$ electric field in vacuum

$\bar{P}$ **polarization**

$\bar{E}_{dia}$ **smaller** electric field in dielectric

$$\bar{P} = \lim_{V \to 0} \frac{\sum q\bar{d}}{V}$$

average of dipole moments [Coulomb/m^2]

A. R. Von Hippel, "Dielectrics and Waves", 1954
B.K.P. Scaife, "Principles of dielectrics", 1998

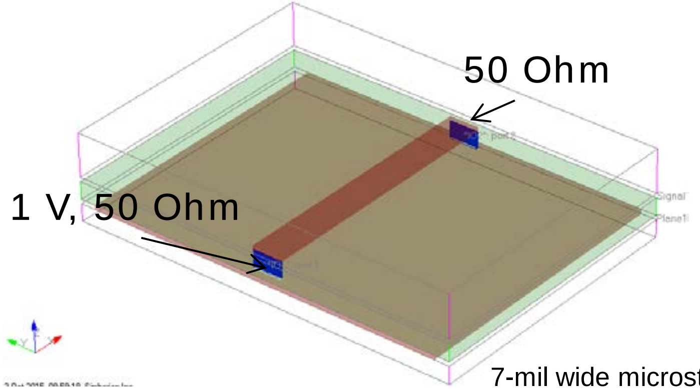
$$\nabla \times \bar{H} = \varepsilon_0 \frac{\partial \bar{E}}{\partial t} + \frac{\partial \bar{P}}{\partial t} + \sigma \bar{E}$$

Polarization Current – movements of bound charges

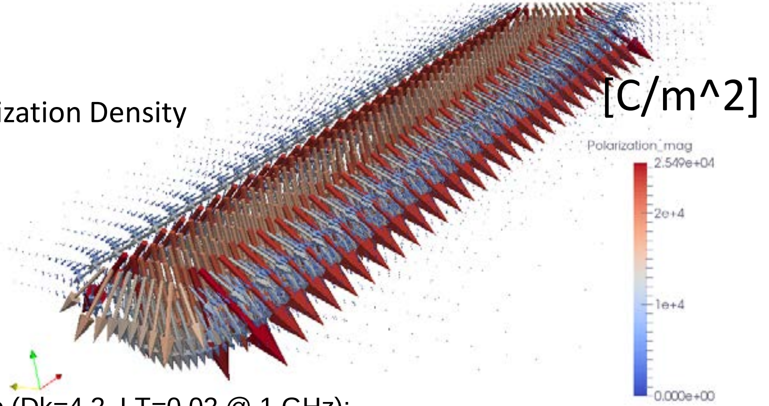
$\bar{P} = f\left(\bar{E}, \bar{H}, T, F, \ldots\right)$ *for LTI, Isotropic:* $\bar{P} = \varepsilon_0 \chi * \bar{E}$

χ - dielectric susceptibility (**always dispersive**)

Polarization current is real current!

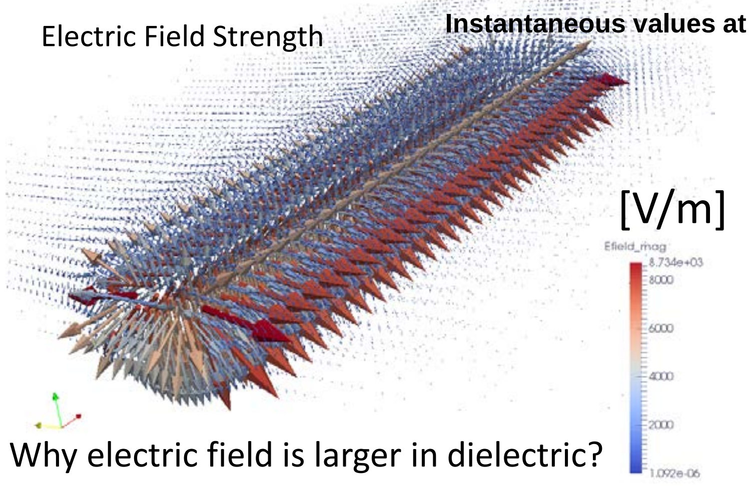


Polarization Density

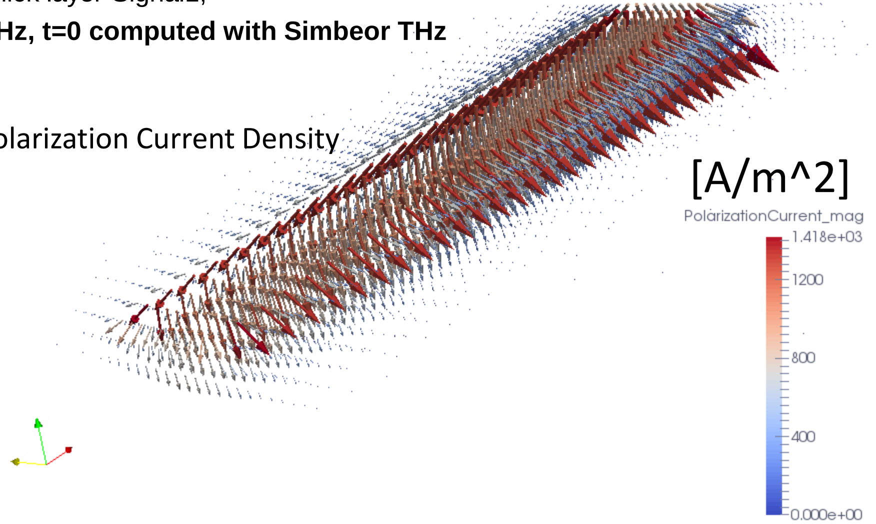


7-mil wide microstrip line on 4 mil dielectric (Dk=4.2, LT=0.02 @ 1 GHz);
Segment 60 mil long in 1 mil thick layer Signal1;
Instantaneous values at 1 GHz, t=0 computed with Simbeor THz

Electric Field Strength



Polarization Current Density



Why electric field is larger in dielectric?

Dielectrics and Conductors

- Dielectric temporal dispersion
  - Debye model
  - Modifications of Debye model
  - Multipole Debye model
  - Wideband Debye model
  - Lorentzian model
  - From DC to infinity
- Inhomogeneous dielectrics
- Anisotropic dielectrics

- Conductor temporal dispersion
  - Skin effect
  - Conductor roughness
    - Effective roughness layer
    - Modified Hammerstad model
    - Huray’s snowball model
  - Advanced conductor models
    - Ferromagnetics
    - Breaking the skin…

Dielectrics vs. Conductors

Dielectrics

- Electric polarization dominates
- Small number of free charges ~10^10 to ~10^16 1/m^3
- Small bulk conductivity ~10^-9 to ~10^-16 1/Ohm*m (large resistivity)
- Conductivity increases with the temperature

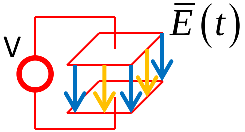
Semi-metals
Semiconductors

Conductors

- Almost no electric polarization up to ~10^16 Hz (shielding)
- Large number of free charges ~10^27 to ~10^29 1/m^3
- Large bulk conductivity ~10^6 to ~10^8 1/Ohm*m (small resistivity)
- Conductivity decreases with the temperature

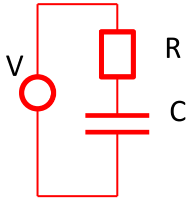
C.A. Balanis, Advanced engineering electromagnetics, 2012
I. S Rez, Y.M. Poplavko, Dielectrics (in Russian), 1989

Debye temporal dispersion



$$\frac{\partial \bar{P}(t)}{\partial t}+\frac{1}{\tau}\bar{P}(t)=\varepsilon_0\frac{\Delta\varepsilon}{\tau}\bar{E}(t)$$

$$\frac{\partial Q(t)}{\partial t}+\frac{1}{RC}Q(t)=\frac{1}{R}V(t)$$



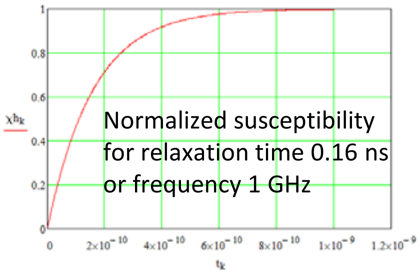
Normalized impulse response (susceptibility kernel):

$$\chi_\delta(t)=\frac{\Delta\varepsilon}{\tau}e^{-t/\tau},\ t\geq 0$$

$$C_\delta(t)=\frac{1}{R}e^{-t/\tau}$$ (effective capacitance)

Normalized step response:

$$\chi_h(t)=\Delta\varepsilon\left(1-e^{-t/\tau}\right),\ t\geq 0$$



$$C_h(t)=C\left(1-e^{-t/\tau}\right)$$

τ - relaxation time

$\Delta\varepsilon$ - difference between susceptibility at 0 and infinity

$\tau = RC$ - relaxation time

P. Debye, "Polar molecules", 1929. or H Frohlich, "Theory of dielectrics", 1949.

Generalization - polarization for any excitation (convolution):

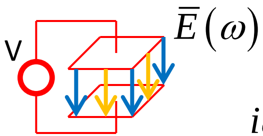
$$\bar{P}(t)=\varepsilon_0\int_{-\infty}^{t}\chi_\delta(t-t')\cdot\bar{E}(t')\cdot dt'$$

$$Q(t)=\int_{-\infty}^{t}C_\delta(t-t')\cdot V(t')\cdot dt'$$

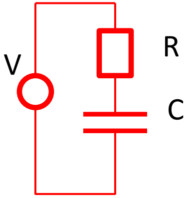
Debye temporal dispersion in frequency domain

$$\frac{\partial \bar{P}(t)}{\partial t}+\frac{1}{\tau}\bar{P}(t)=\varepsilon_0\frac{\Delta\varepsilon}{\tau}\bar{E}(t)$$

$$\frac{\partial Q(t)}{\partial t}+\frac{1}{RC}Q(t)=\frac{1}{R}V(t)$$



$$F(\omega,t)=F_0\cdot e^{i\omega t}$$



$$i\omega\cdot\bar{P}(\omega)+\frac{1}{\tau}\bar{P}(\omega)=\varepsilon_0\frac{\Delta\varepsilon}{\tau}\bar{E}(\omega)$$

$$i\omega\cdot Q(\omega)+\frac{1}{RC}Q(\omega)=\frac{1}{R}V(\omega)$$

Normalized impulse response (susceptibility):

$$\chi(\omega)=\frac{\Delta\varepsilon}{1+i\omega\tau}$$

Effective capacitance:

$$C(\omega)=\frac{C}{1+i\omega RC}$$

Generalization - solution for any excitation in frequency domain (LTI, isotropic):

$$\bar{P}(\omega)=\varepsilon_0\chi(\omega)\cdot\bar{E}(\omega)$$

$$Q(\omega)=C(\omega)\cdot V(\omega)$$

Generalization – Ampere's law in frequency domain

$$\nabla \times \bar{H} = \varepsilon_0 \frac{\partial \bar{E}}{\partial t} + \frac{\partial \bar{P}}{\partial t} + \sigma \bar{E}$$

$$\bar{P}(\omega) = \varepsilon_0 \chi(\omega) \cdot \bar{E}(\omega)$$

$$F(\omega, t) = F_0 \cdot e^{i\omega t}$$

$$\nabla \times \bar{H}(\omega) = i\omega\varepsilon_0 \bar{E}(\omega) + i\omega\varepsilon_0 \chi(\omega) \bar{E}(\omega) + \sigma \bar{E}(\omega)$$

$$\nabla \times \bar{H}(\omega) = i\omega\varepsilon_0 \left(1 + \chi(\omega) + \frac{\sigma}{i\omega\varepsilon_0} \right) \bar{E}(\omega)$$

$\varepsilon_0 \cong 8.8541878176 \cdot 10^{-12}$ - permittivity of vacuum (constant), by definition

$\varepsilon_r(\omega) = 1 + \chi(\omega)$ - relative permittivity

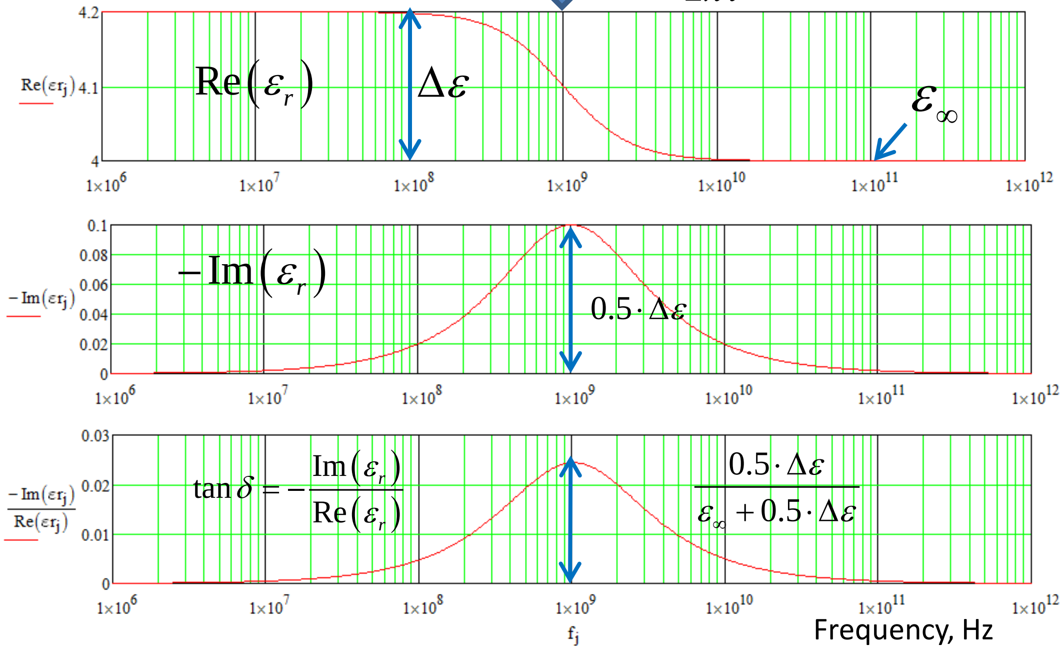
$\varepsilon_{rc}(\omega) = 1 + \chi(\omega) + \dfrac{\sigma}{i\omega\varepsilon_0}$ - relative "complex" permittivity

Not constant for all materials!!!

Permittivity of Debye dielectric

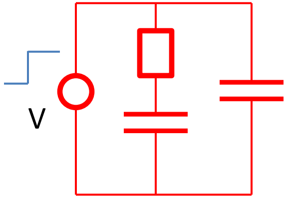
$$\varepsilon_r(\omega) = 1 + \chi(\omega) = 1 + \frac{\Delta\varepsilon}{1 + i\omega\tau} \Rightarrow \varepsilon_r(f) = 1 + \frac{\Delta\varepsilon}{1 + i\, f / f_r} \Rightarrow \varepsilon_r(f) = \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + i\, f / f_r}$$

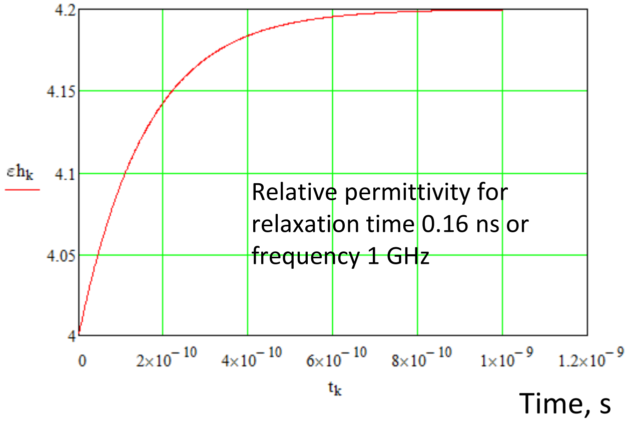
$$f_r = \frac{1}{2\pi\tau}$$



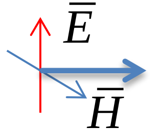
Example:

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





Plane wave in Debye dielectric

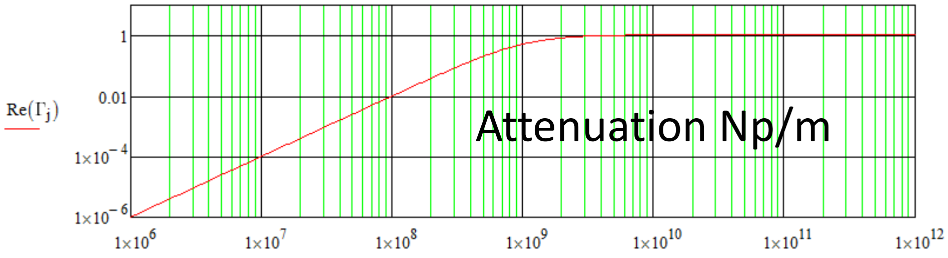


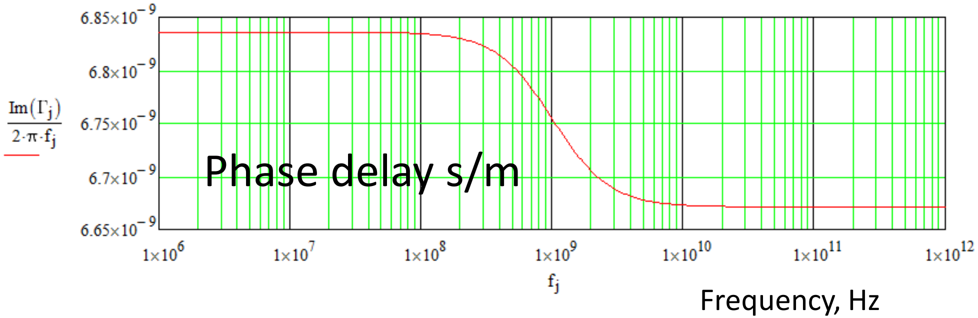
$$\varepsilon_r(f) = \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + i\, f / f_r} \quad \Rightarrow \quad \Gamma(f) = i2\pi f \sqrt{\varepsilon_r(f)\cdot\varepsilon_0\cdot\mu_0}$$

- plane wave propagation constant

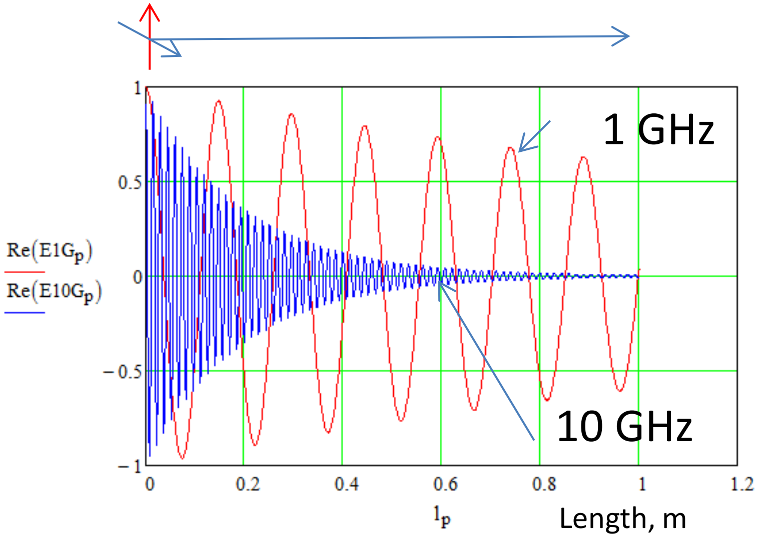
Example:

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





Instantaneous electric field along the wave propagation (normalized)



Empirical modifications of Debye model

Havriliak, S.; Negami, S. *"A complex plane representation of dielectric and mechanical relaxation processes in some polymers". Polymer N8: p 161–210,1967.*

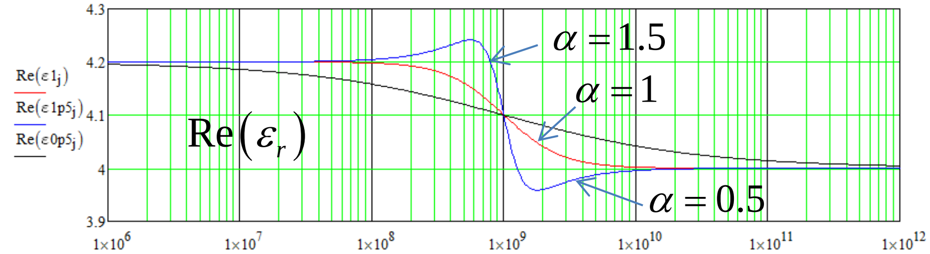
$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{\left(1+(i\omega\tau)^\alpha\right)^\beta}$$

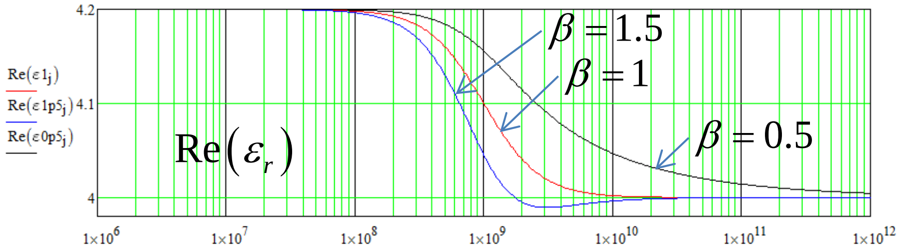
$\varepsilon_\infty = 4.0;\ \Delta\varepsilon = 0.2;\ f_r = 1GHz$

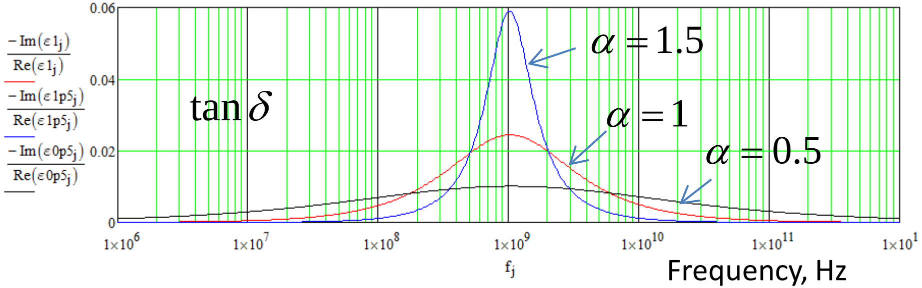
$\beta = 1$ $\qquad$ $\alpha = 1$

K.S. Cole, R.H. Cole, (1941) $\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{1+(i\omega\tau)^\alpha}$

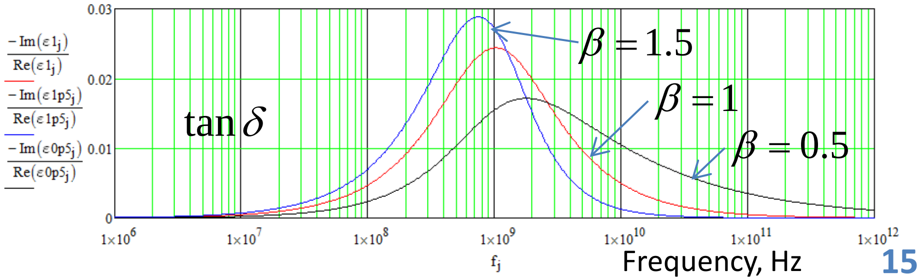
Cole-Davidson relaxation $\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{(1+i\omega\tau)^\beta}$







Frequency, Hz

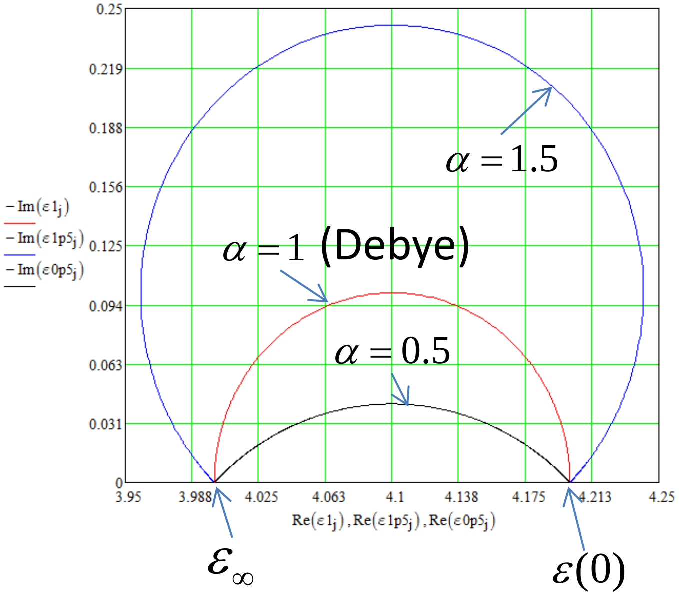


Frequency, Hz

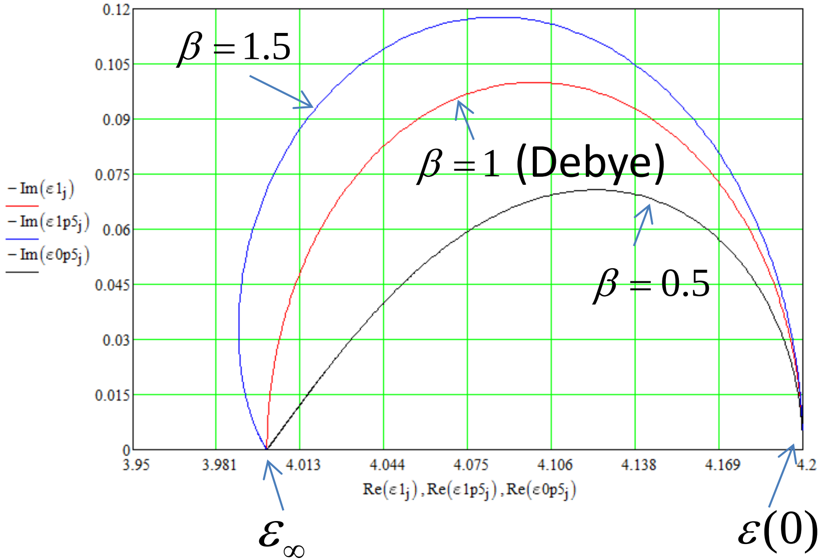
Cole-Cole plots

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

Cole-Cole model



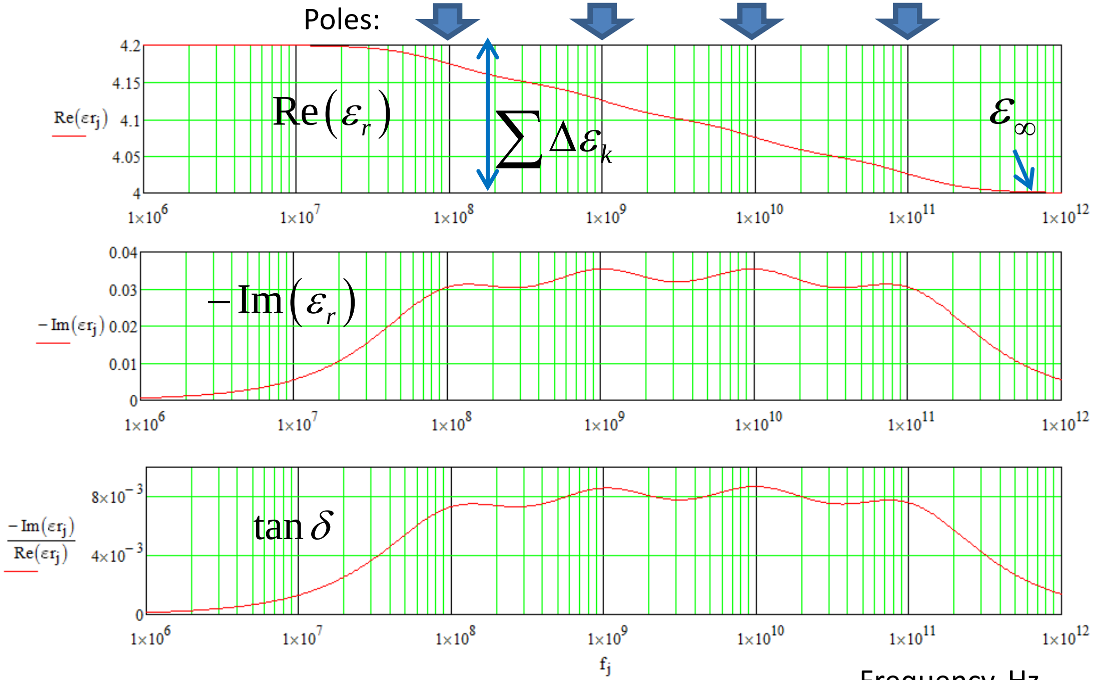
Cole-Davidson model

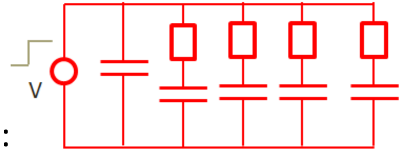


Multipole Debye model

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

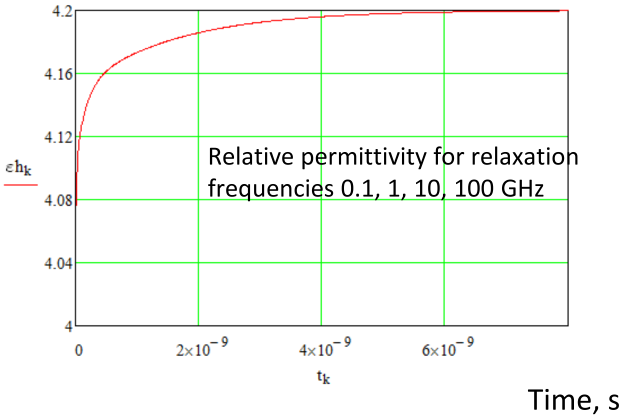
K relaxation poles, 2K+1 parameters





4-pole example:

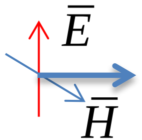
$\varepsilon_\infty = 4.0; \Delta\varepsilon_k = 0.05;$
$f_{r1} = 0.1;\ f_{r2} = 1;\ f_{r3} = 10;\ f_{r4} = 100;$ [GHz]



Plane wave in multipole Debye dielectric

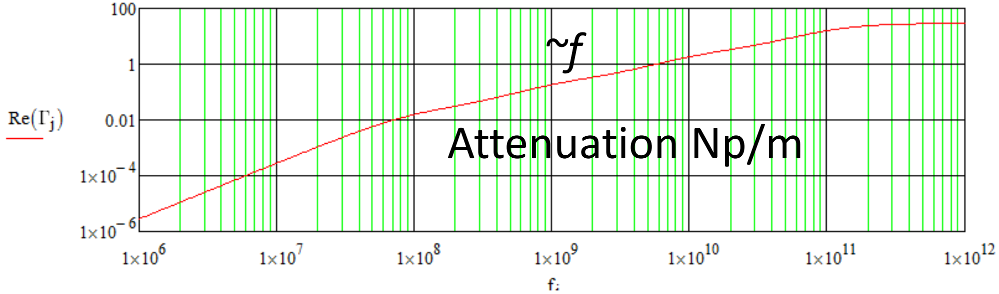
$$\varepsilon_r(f) = \varepsilon_\infty + \sum_{k=1}^{K} \frac{\Delta\varepsilon_k}{1 + i\, f / f_{rk}} \quad \Rightarrow \quad \Gamma(f) = i 2\pi f \sqrt{\varepsilon_r(f) \cdot \varepsilon_0 \cdot \mu_0}$$

- plane wave propagation constant



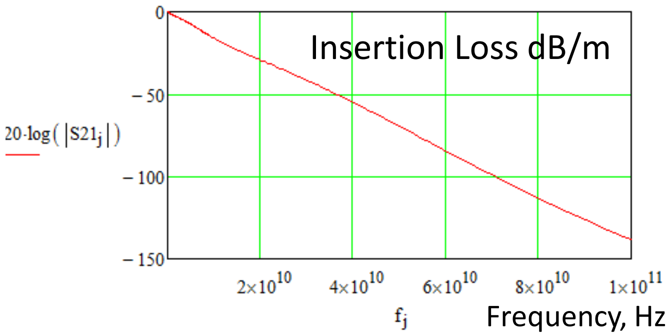
4-pole example:

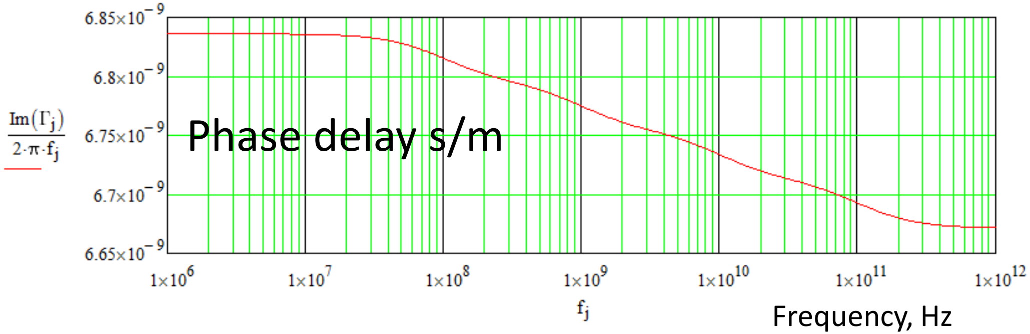
$$\varepsilon_\infty = 4.0; \Delta\varepsilon_k = 0.05;$$
$$f_{r1} = 0.1;\ f_{r2} = 1;\ f_{r3} = 10;\ f_{r4} = 100;\ [\text{GHz}]$$



Generalized transmission parameter for distance *l:*

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





Can we just fit Dk & LT points with multipole Debye model?

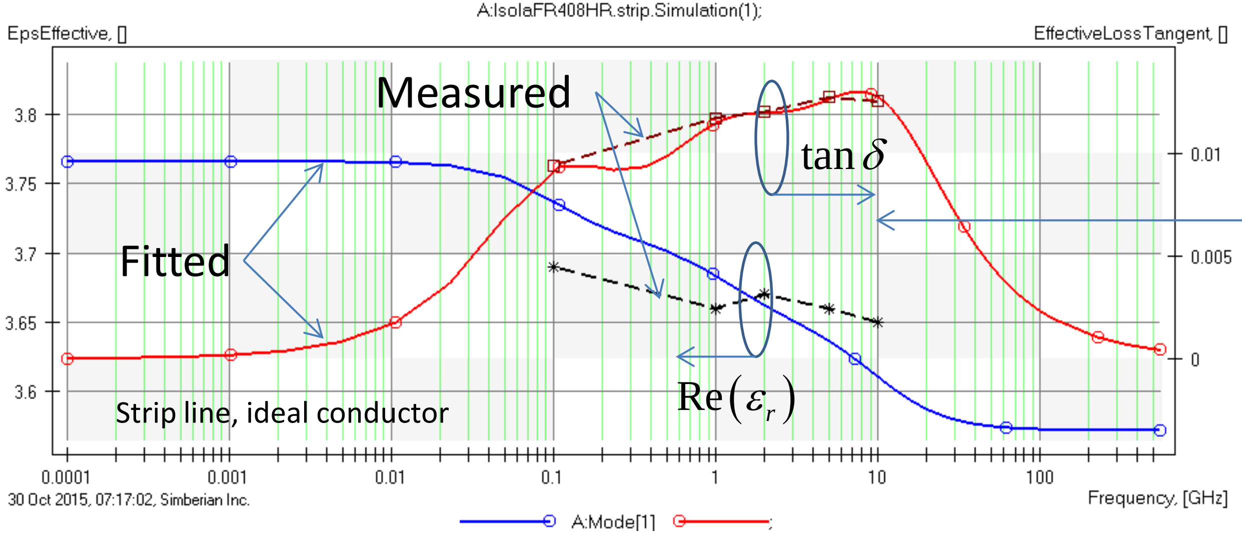
- **2 problems**

  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

From Isola's FR408HR specifications

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



No data to build model above 10 GHz!

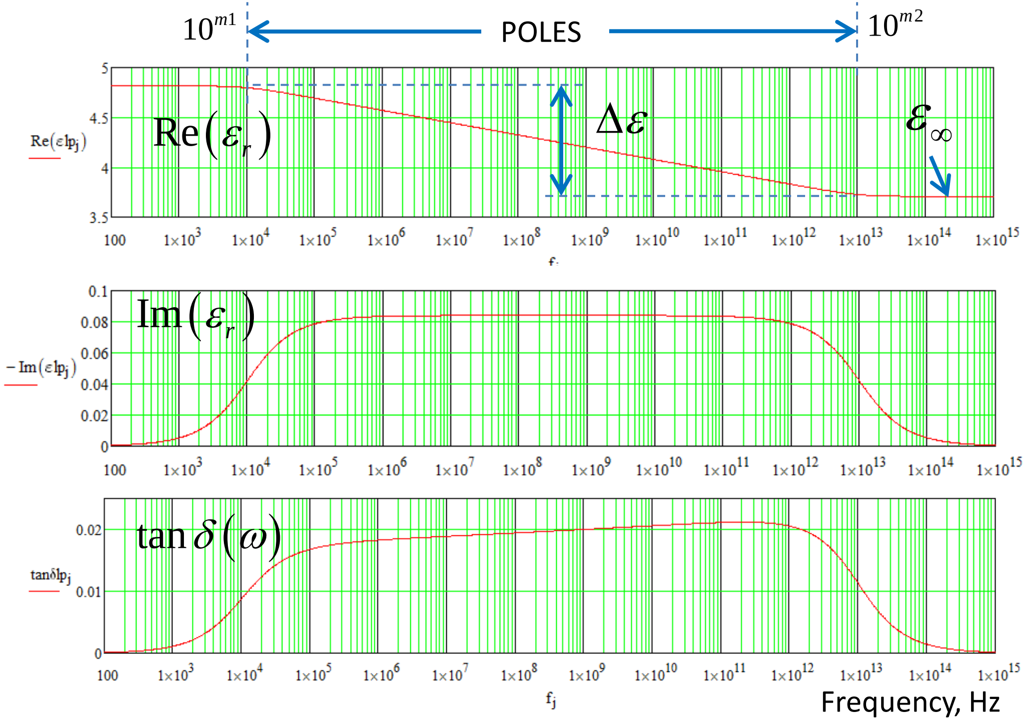
Computed with Simbeor THz

Wideband Debye model

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

Continuous relaxation poles from 10^m1 to 10^m2

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



Four parameters $\varepsilon_\infty, \Delta\varepsilon, m1, m2$

m1 and m2 are usually fixed to 4 and 12-13

Example:

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

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

Independently derived in 2 papers:

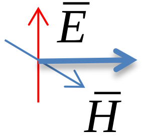
C. Svensson, G.E. Dermer, Time domain modeling of lossy interconnects, IEEE Trans. on Advanced Packaging, May 2001, N2, Vol. 24, pp.191-196.

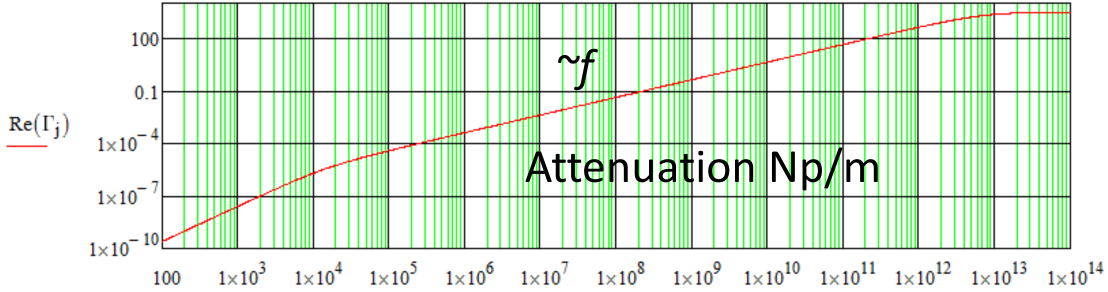
Djordjevic, R.M. Biljic, V.D. Likar-Smiljanic, T.K.Sarkar, IEEE Trans. on EMC, vol. 43, N4, 2001, p. 662-667.

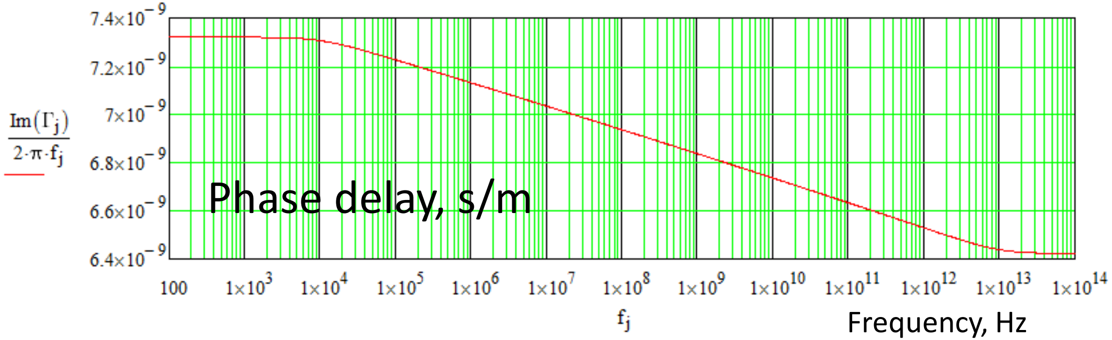
Plane wave in Wideband Debye dielectric

$$\varepsilon_r(f) = \varepsilon_\infty + \frac{\Delta\varepsilon}{(m_2 - m_1)\cdot\ln(10)}\cdot\ln\left[\frac{10^{m2} + if}{10^{m1} + if}\right] \Rightarrow \Gamma(f) = i2\pi f\sqrt{\varepsilon_r(f)\cdot\varepsilon_0\cdot\mu_0}$$

- plane wave propagation constant







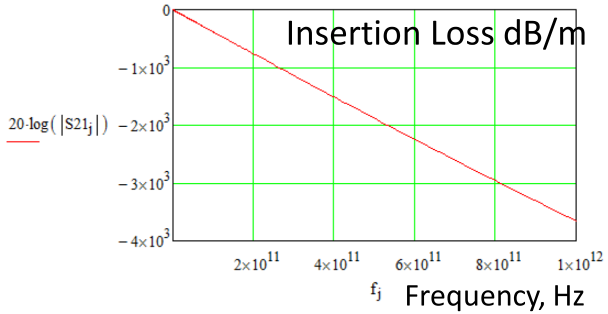
Example:

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

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

Generalized transmission parameter for distance *l*:

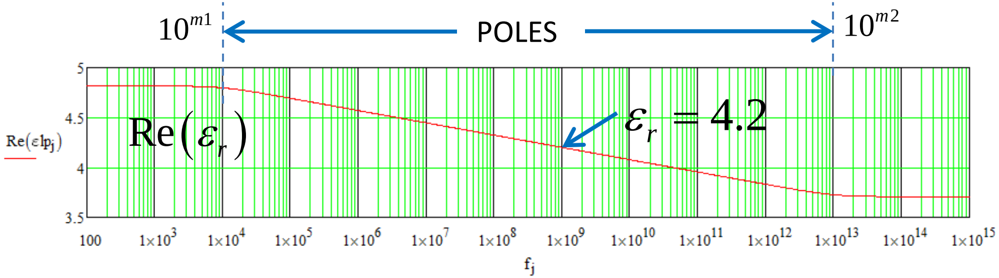
$$S21(\omega) = e^{-\Gamma\cdot l}$$

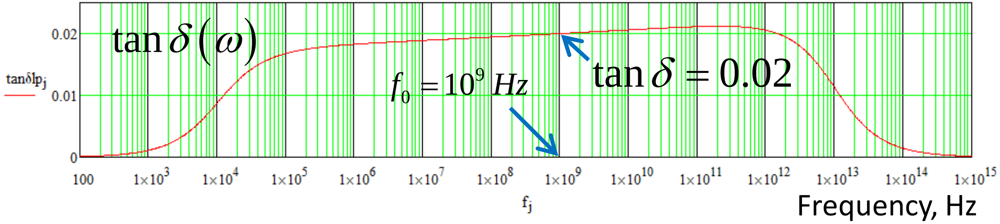


Wideband Debye model properties

Dk and LT at one point is sufficient to define the model!

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





m1 and m2 are usually fixed to 4 and 12-13

ε_∞ *and* $\Delta\varepsilon$ *computed with* ε_r *and* $\tan\delta$ *at* f_0 :

$$\varepsilon(\infty) = \varepsilon_r\left(1 + \tan\delta \cdot \frac{\mathrm{Re}(L)}{\mathrm{Im}(\ln[L])}\right)$$

$$\Delta\varepsilon = -\frac{\tan\delta \cdot \varepsilon_r \cdot \ln(10)\cdot[m_2 - m_1]}{\mathrm{Im}(L)}$$

$$\mathrm{L} = \ln\left[\frac{10^{m2} + if_0}{10^{m1} + if_0}\right]$$

Example:

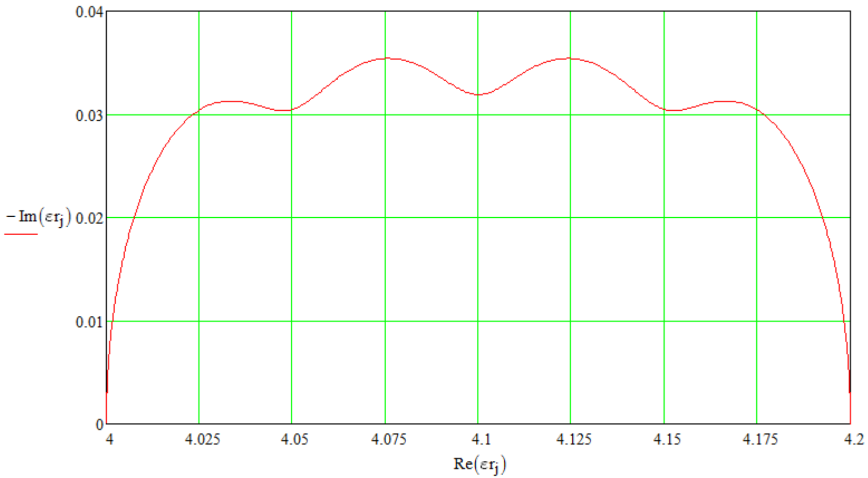
$\varepsilon_r = 4.2;\ \tan\delta = 0.02;\ f_0 = 10^9\ Hz; m1 = 4;\ m2 = 13;$

$\varepsilon_\infty = 3.707;\ \Delta\varepsilon = 1.108;$

Cole-Cole plots

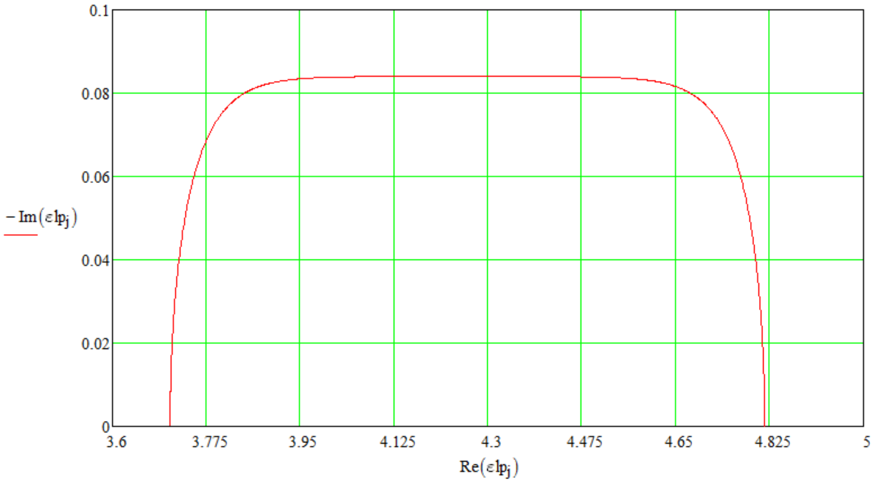
Multi-pole Debye

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



Wideband Debye

$\varepsilon_r = 4.2;\ \tan\delta = 0.02;\ f_0 = 10^9\ Hz; m1 = 4;\ m2 = 13;$
$\varepsilon_\infty = 3.707;\ \Delta\varepsilon = 1.108;$

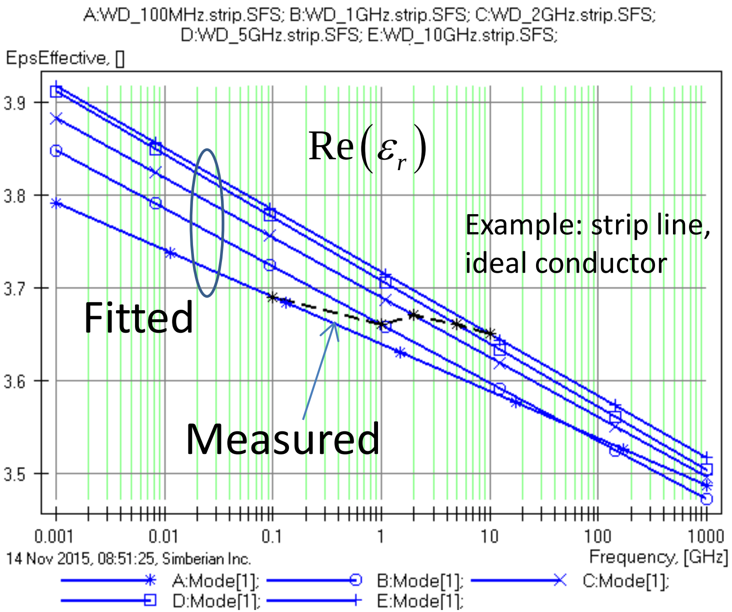


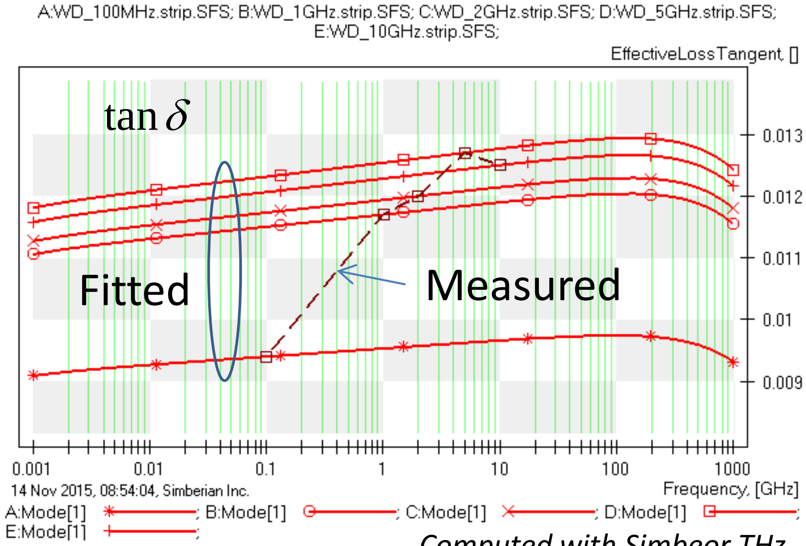
Definition of Wideband Debye with data from spreadsheet

- **Which point to chose to define the model?**
- **Ambiguous…**

From Isola's FR408HR specifications

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





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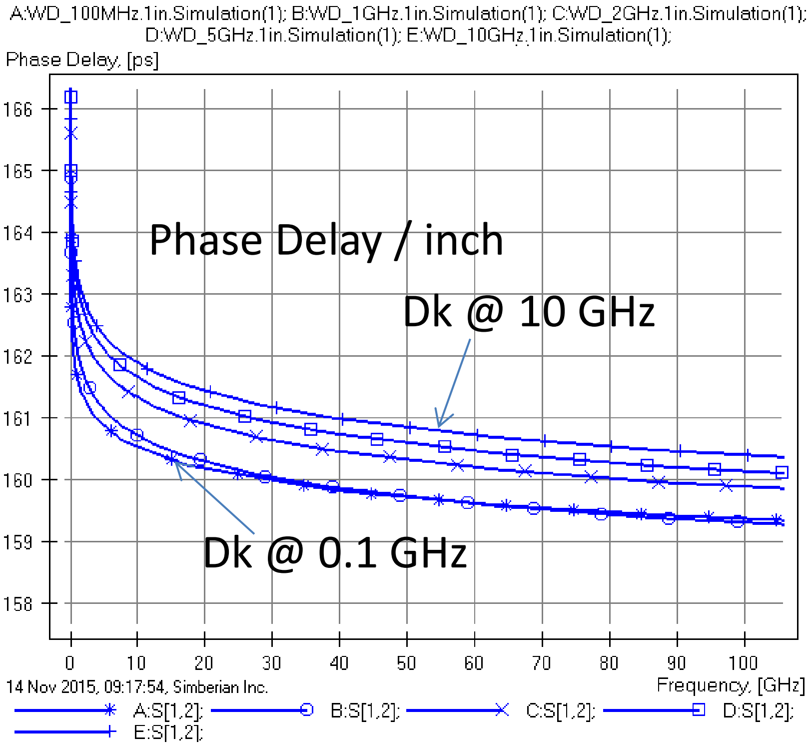
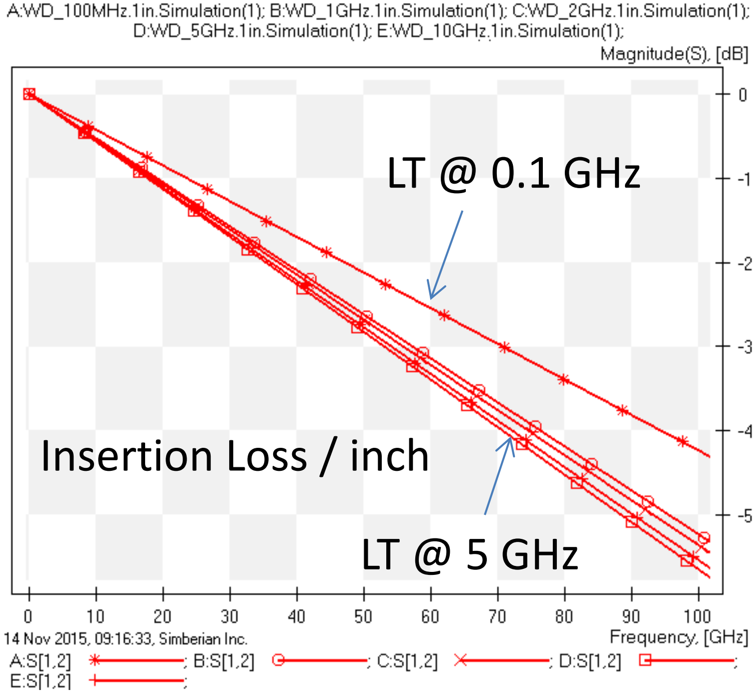
Definition of Wideband Debye with data from spreadsheet

Example: 1 inch of strip line, ideal conductor





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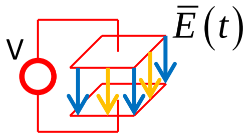
Lorentzian temporal dispersion



$$\frac{\partial^2 \bar{P}(t)}{\partial t^2} + 2\delta\omega_0 \frac{\partial \bar{P}(t)}{\partial t} + \omega_0^2 \bar{P}(t) = \varepsilon_0 \cdot \Delta\varepsilon \cdot \omega_0^2 \bar{E}(t)$$

Normalized impulse response (susceptibility):

$$\chi_\delta(t) = \frac{\Delta\varepsilon}{\sqrt{1-\delta^2}} e^{-\delta\omega_0 t} \sin\left(\sqrt{1-\delta^2}\,\omega_0 t\right), \quad t \ge 0$$

$$\chi(\omega) = \frac{\Delta\varepsilon \cdot \omega_0^2}{\omega_0^2 - \omega^2 + 2i\delta\omega_0\omega}$$

Normalized step response:

$$\chi_h(t) = \Delta\varepsilon\left(1 - \frac{1}{\sqrt{1-\delta^2}} e^{-\delta\omega_0 t} \sin\left(\sqrt{1-\delta^2}\,\omega_0 t + \varphi\right)\right), t \ge 0$$

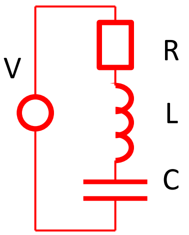
$$\varphi = \tan^{-1}\left(\frac{\sqrt{1-\delta^2}}{\delta}\right)$$

δ - damping factor (unit-less);
ω_0 - resonant frequency (radian);
$\Delta\varepsilon$ - difference between susceptibility at 0 and infinity

I.F.Almog, M.S.Bradley, V.Bulovic, The Lorentz Oscillator and its Applications

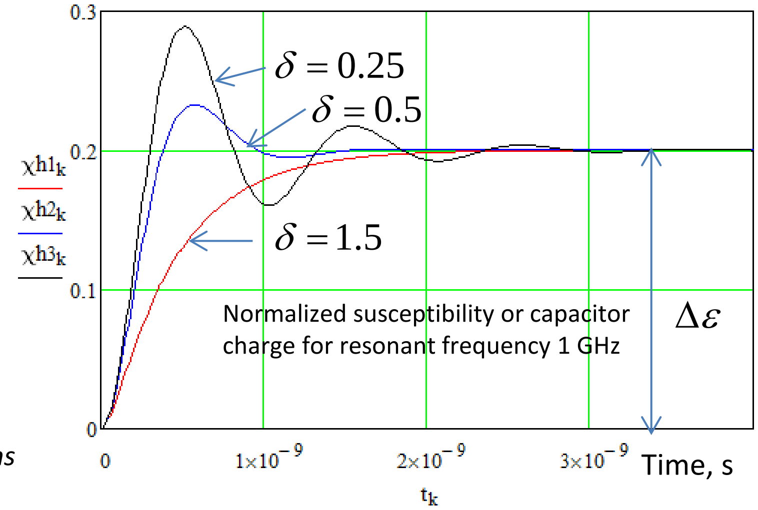
Capacitor charge:

$$\frac{\partial^2 Q(t)}{\partial t^2} + \frac{R}{L}\frac{\partial Q(t)}{\partial t} + \frac{1}{LC} Q(t) = \frac{1}{L} V(t)$$

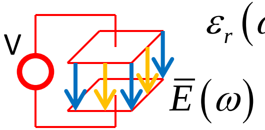


$$\omega_0 = 1/\sqrt{LC} \qquad \delta = \frac{R}{2}\sqrt{\frac{C}{L}}$$

$$\Delta\varepsilon = C$$

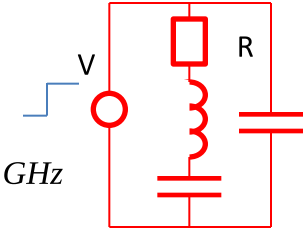


Permittivity of Lorentzian dielectric



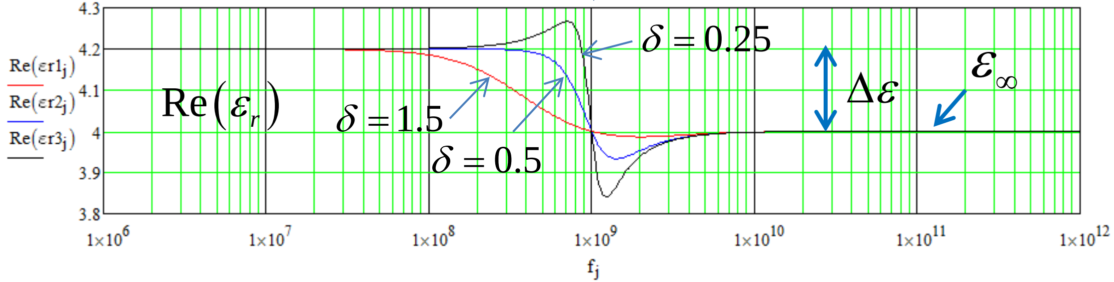
$$\varepsilon_r(\omega) = 1 + \chi(\omega) = 1 + \frac{\Delta\varepsilon \cdot \omega_0^2}{\omega_0^2 - \omega^2 + 2i\delta\omega_0\omega} \Rightarrow \varepsilon_r(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon \cdot f_r^2}{f_r^2 - f^2 + 2i\delta f_r f}$$

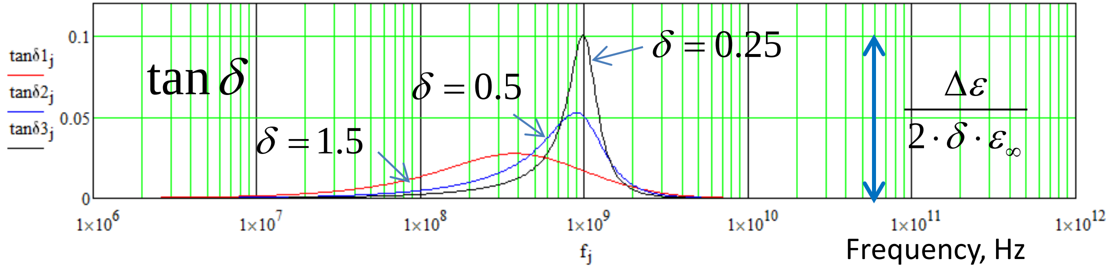
$$f_r = \frac{\omega_0}{2\pi}$$

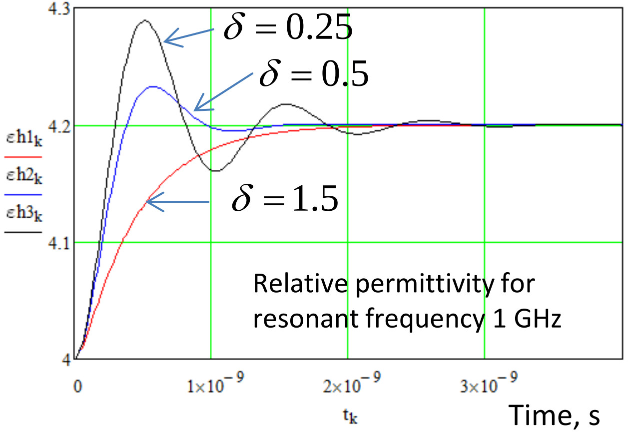


Example:

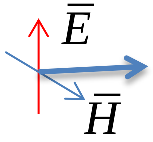
$\varepsilon_\infty = 4.0;\ \Delta\varepsilon = 0.2;\ f_r = 1GHz$





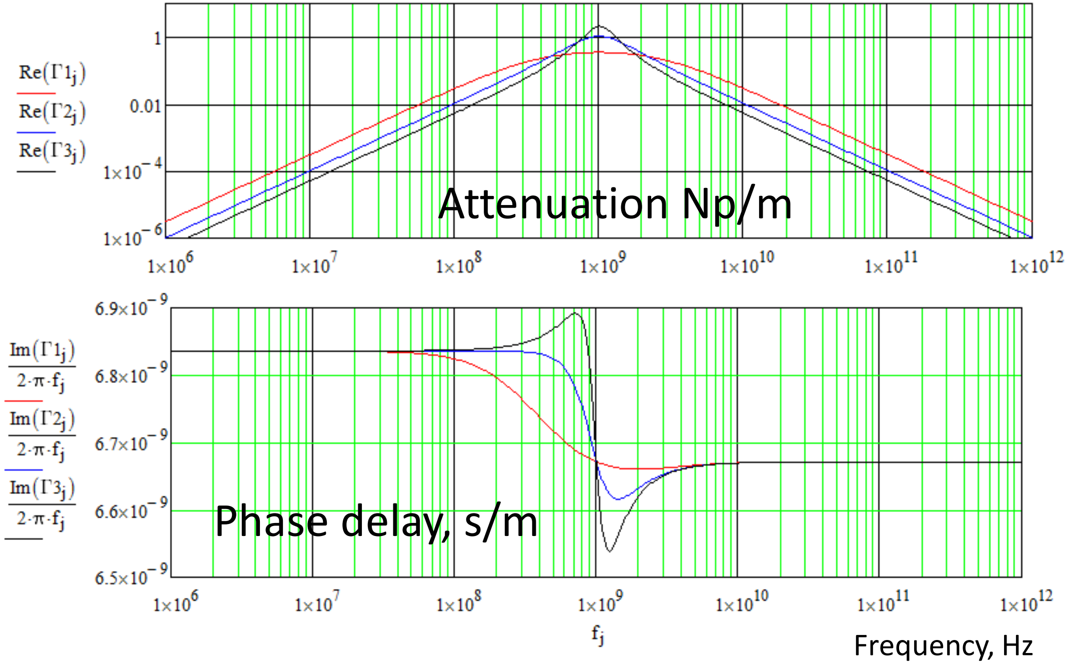


Plane wave in Lorentzian dielectric



$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon \cdot f_r^2}{f_r^2 - f^2 + 2i\delta f_r f} \Rightarrow \Gamma(f) = i2\pi f\sqrt{\varepsilon_r(f)\cdot\varepsilon_0\cdot\mu_0}$$

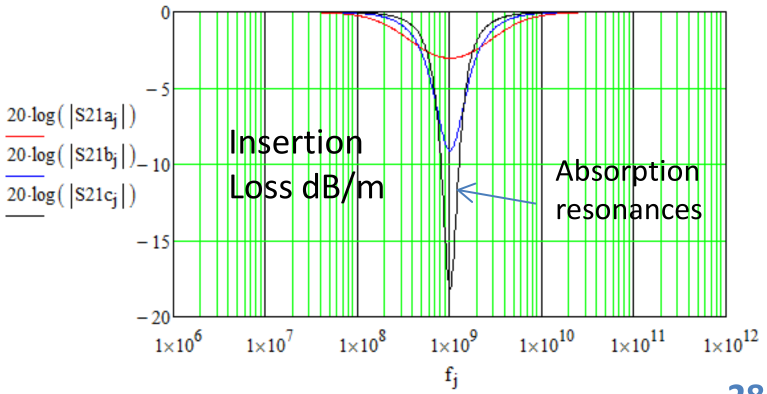
- plane wave propagation constant



Example:

$\varepsilon_\infty = 4.0;\ \Delta\varepsilon = 0.2;\ f_r = 1GHz$
$\delta = 1.5$ – *red curves*;
$\delta = 0.5$ – *blue curves*;
$\delta = 0.25$ – *black curves*;

Generalized transmission parameter for distance *l:*



Generalized models of dielectric

- Debye – Lorentzian without conductivity

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

2N+3K+1 variables to identify
Suitable for direct optimization

- Generic rational model with complex poles (no conductivity)

$$\varepsilon(f) = \varepsilon(\infty) + \frac{1}{2}\sum_{n=1}^{N}\left(\frac{R_n}{s - p_n} + \frac{R_n^*}{s - p_n^*}\right)$$

From 2N+1 to 4N+1 variables to identify;
Can be fitted to Dk and LT measured at N+1 - 2N+1 frequencies;

$s = i \cdot 2\pi f$ - complex frequency;
$p_n = \alpha_n + i \cdot 2\pi f_n$ - complex poles;
$R_n = Rr_n + i \cdot Ri_n$ - complex residues;

Both models enable easy frequency and time domain analysis!

Can we use specs to build generic rational model?

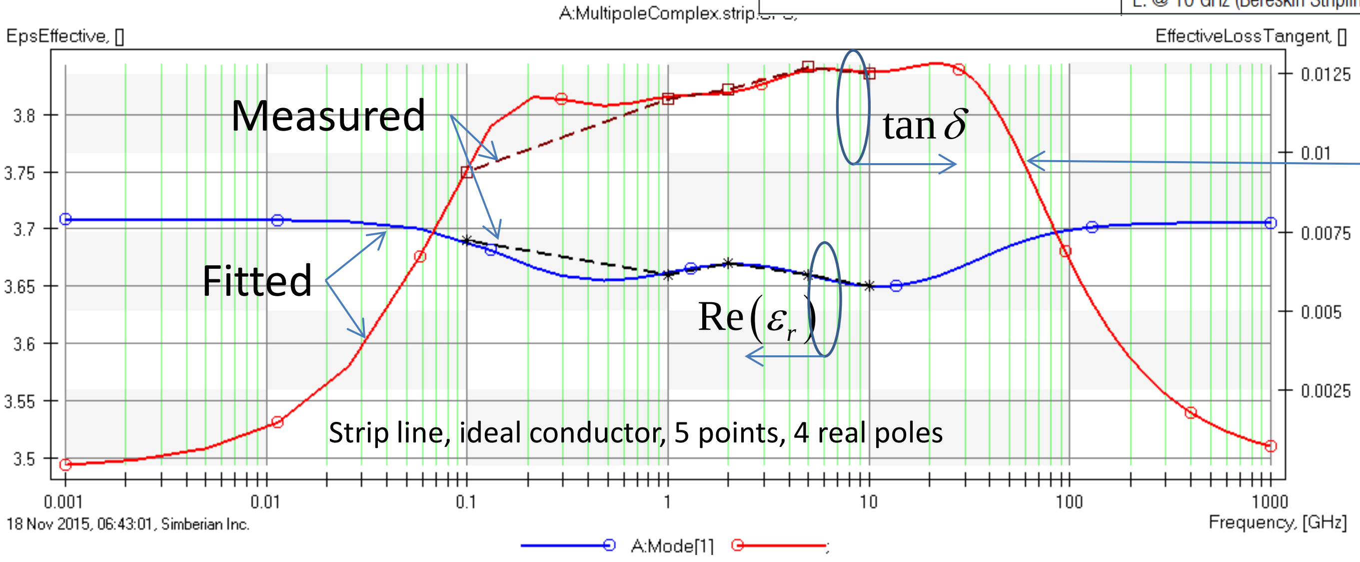
- **Better than Debye, but**

  The result is sensitive to measurement errors (requires dense data points)

  Bandwidth is still restricted by the first and the last frequency point

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



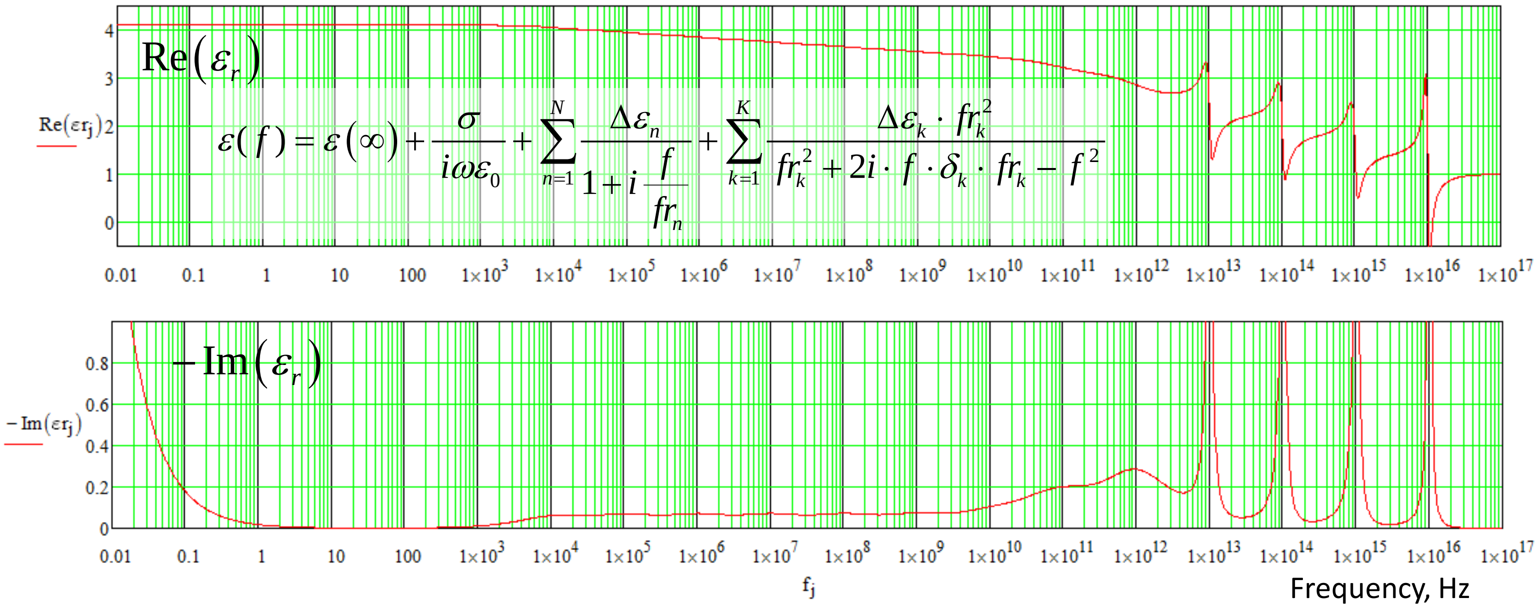
No data to have reliable model above 10 GHz!

Computed with Simbeor THz

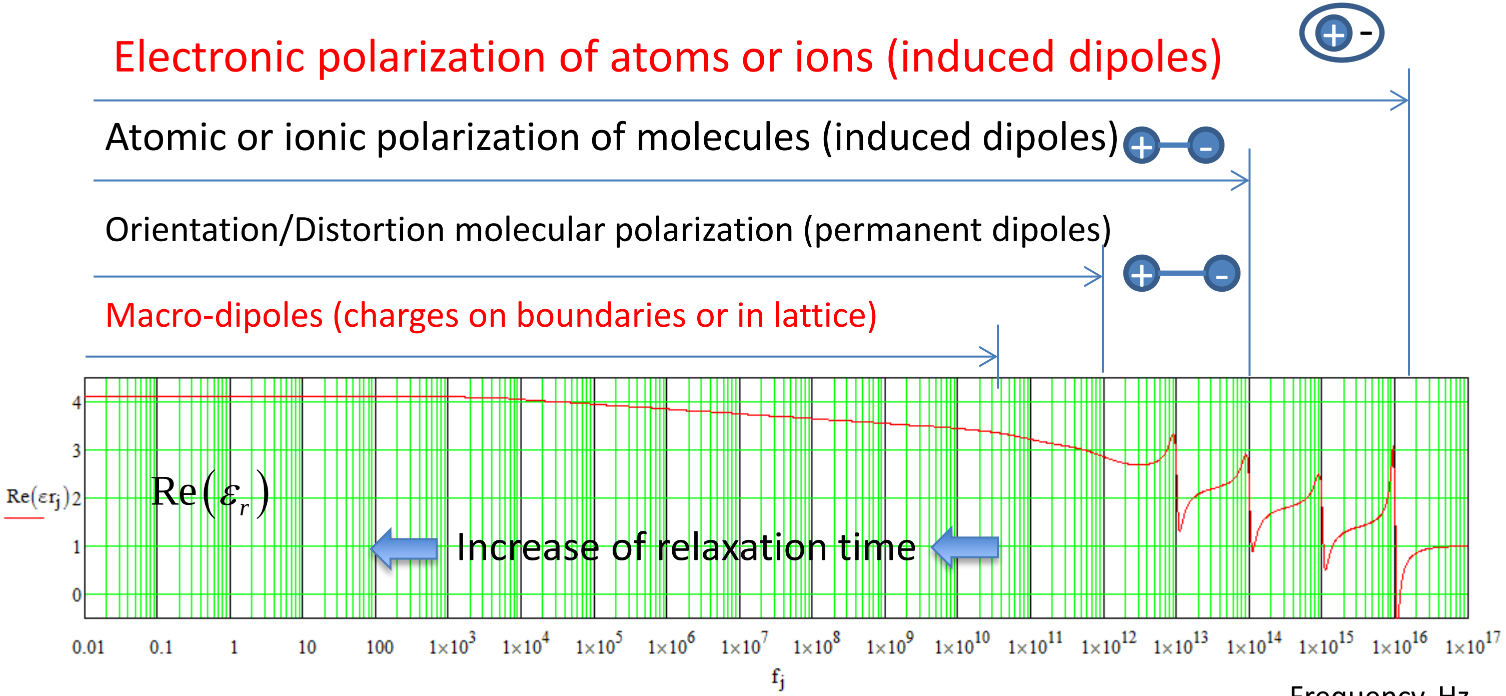
Dielectric models from DC to infinity

…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

conduction relaxation resonances



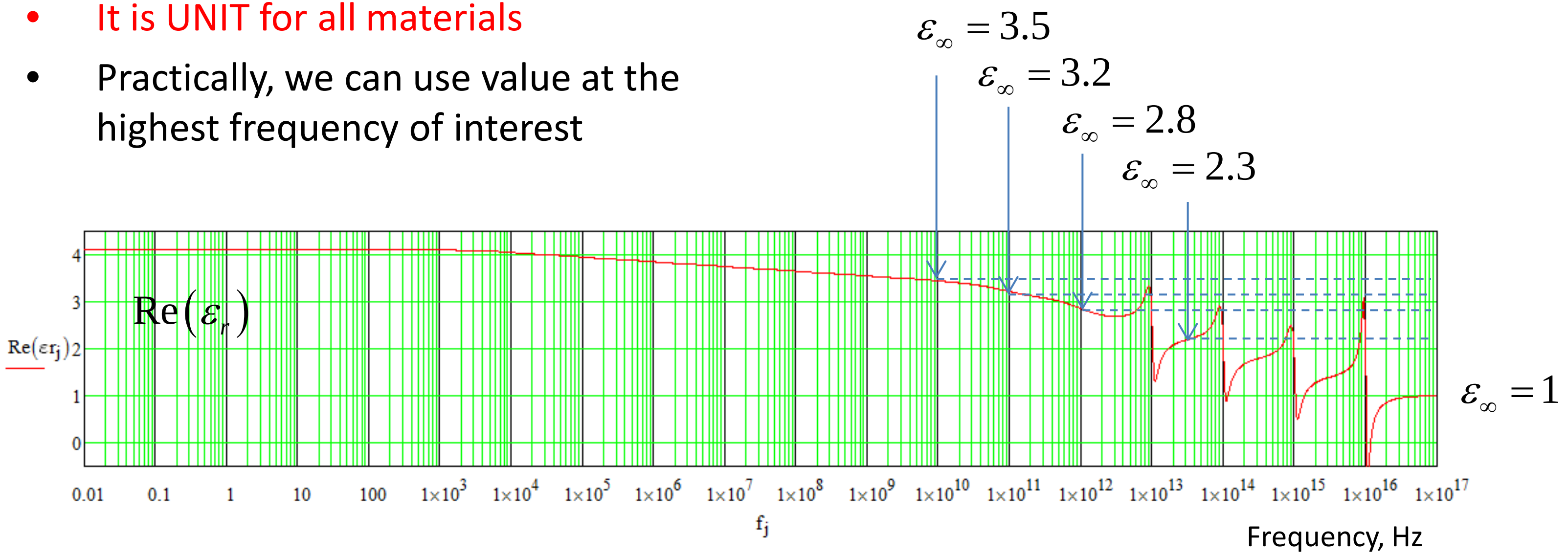
Polarization mechanisms



D.D. Pollock, Physical properties of materials for engineers, 1982, v III
C.A. Balanis, Advanced engineering electromagnetics, 2012

Dielectric constant at “infinity”

- It is UNIT for all materials
- Practically, we can use value at the highest frequency of interest



Value at “DC” should be define to have accurate value at the lowest frequency of interest

Causality

- Condition $\chi_\delta(t) = 0 \; at \; t < 0$ for the impulse response of susceptibility leads to Hilbert transform or Kramers-Kronig relations between the real and imaginary parts of the frequency-domain permittivity:

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{\varepsilon_i(\omega')}{\omega - \omega'} \cdot d\omega', \quad \varepsilon_i(\omega) = -\frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{\varepsilon_r(\omega') - \varepsilon_\infty}{\omega - \omega'} \cdot d\omega'$$

$$\varepsilon(\omega) = \varepsilon_r(\omega) + i\varepsilon_i(\omega) = \varepsilon_\infty + \chi(\omega)$$

$$PV = \lim_{\varepsilon \to 0}\left(\int_{-\infty}^{\omega-\varepsilon} + \int_{\omega+\varepsilon}^{+\infty} \right)$$

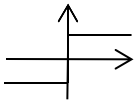
- Realness or impulse response:
  real part is even and imaginary is odd
  function of frequency

Kramers, H.A., Nature, v 117, 1926 p. 775..
Kronig, R. de L., J. Opt. Soc. Am. N12, 1926, p 547.

Derivation:

$$\chi_\delta(t) = sign(t) \cdot \chi_\delta(t),$$

$$sign(t) = \left| \begin{matrix} -1, & t < 0 \\ 1, & t > 0 \end{matrix} \right.$$



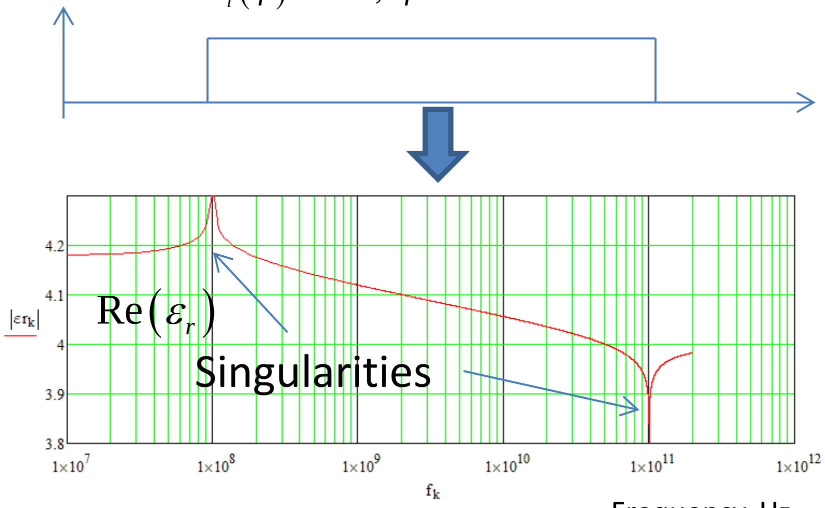
$$\chi(\omega) = F\{\chi_\delta(t)\} = \frac{1}{2\pi} F\{sign(t)\} * F\{\chi_\delta(t)\}$$

$$F\{sign(t)\} = \frac{2}{i\omega} \to \chi(\omega) = \frac{1}{i\pi} PV \int_{-\infty}^{\infty} \frac{\chi(\omega')}{\omega - \omega'} \cdot d\omega'$$

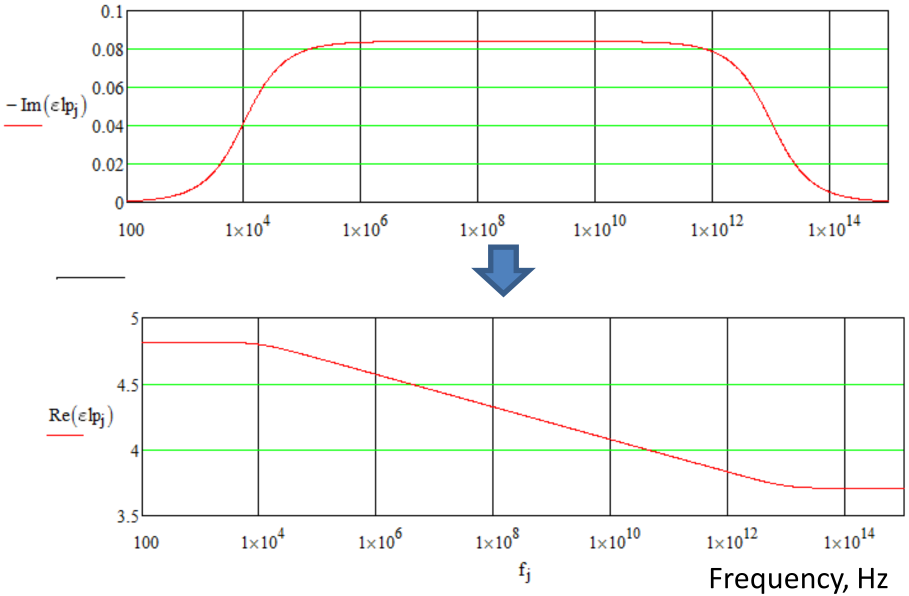
Use of K-K equations to restore real part

Linear growth of loss over some band -> constant imaginary part of permittivity

$$\varepsilon_i(f) = 0.02; \quad from\ 10^8 to 10^{11}\ Hz$$



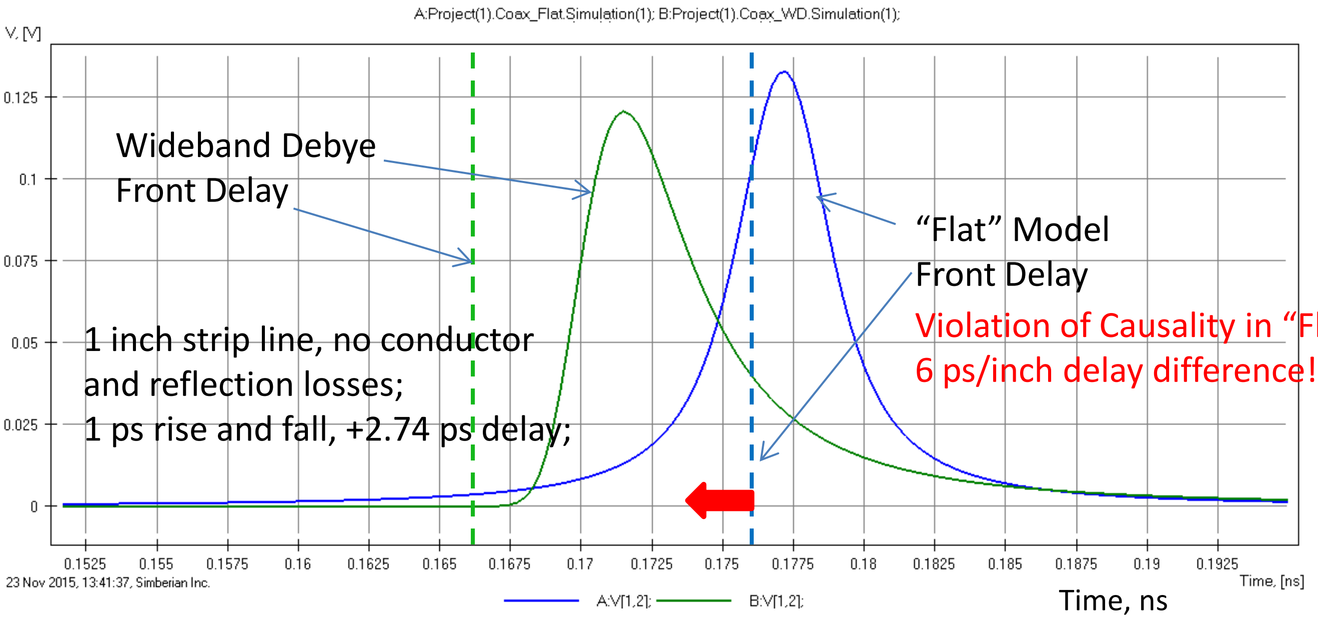
Add Debye slopes -> Wideband Debye model!



Another way to estimate causality

Front delay of the impulse response: $T_{front} = \frac{L\sqrt{\varepsilon_\infty}}{c}$ or min phase delay for S-par.

Wideband Debye model: $\varepsilon_r = 4.2;\ \tan\delta = 0.02;\ f_r = 1GHz;\ \varepsilon_\infty = 3.71;$ "Flat" model: $\varepsilon_r = 4.2;\ \tan\delta = 0.02;$



There must be no response before the Front Delay!

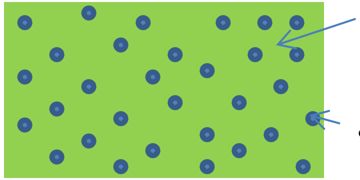
Violation of Causality in "Flat" model and
6 ps/inch delay difference!!!

Computed with Simbeor THz

See more at: M. Tsiklauri et al., Causality and Delay and Physics in Real Systems, IEEE Int. Symp. On EMC, 2014, p. 962-966.

Inhomogeneous dielectrics

- Practically all PCB/packaging materials are heterogeneous mixtures of components
- Two ways to deal with material the inhomogeneity:
  - **Direct electromagnetic analysis** – specify separate material models for homogeneous regions (too many parameters – not practical);
  - **Homogenization** – build macroscopic models for regions with fewer parameters;
- Two ways to build macroscopic models:
  - Empirical way – fit a broadband homogeneous model to measured data (easy);
  - Use mixing formulas or algorithms: construct macroscopic model from models of components if component models and mixture parameters are known:



$\varepsilon_1(\omega)$ host

$\varepsilon_2(\omega)$ inclusions

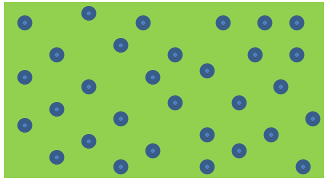
$$\bar{D} = \varepsilon_{mix}(\omega)\bar{E}$$

$\varepsilon_{mix}(\omega)$ - broadband model of mixture

Subject of intense investigations since mid-1800s: Mossotti, Clausius, Lorentz & Lorentz, Rayleigh, Garnett, Brugemann, Onsager, Wiener,… - see ***A. Sihvola, Electromagnetic mixing formulas and applications, 2008***

Mixing dielectrics – “simple” way

- Material density is computed as mass of mixture divided by volume (averaging)
- May be simple permittivity averaging work for dielectrics?



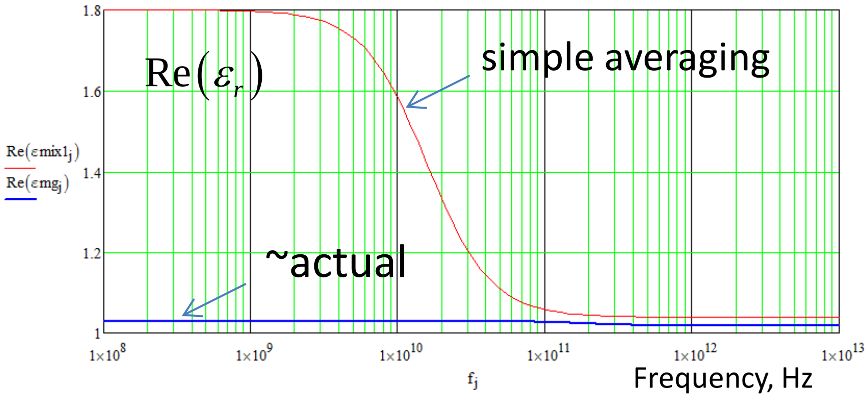
$$\varepsilon_{mix} = \sum_i v_i \varepsilon_i$$

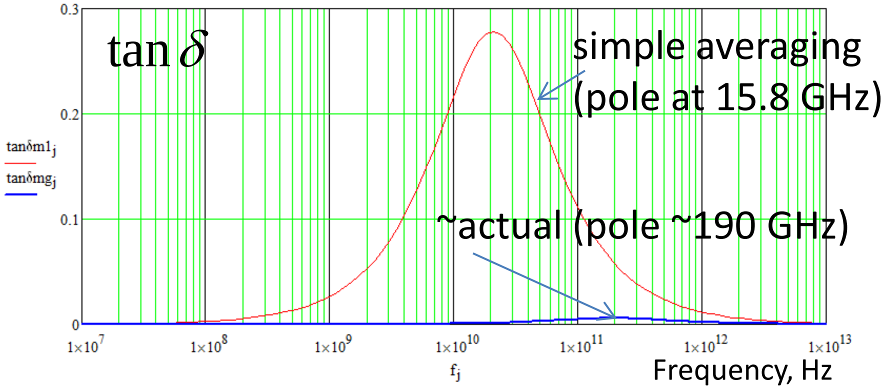
v_i - volume fraction of material *i*

Works only for very limited number of cases!

Example of failure in case of mixture with large difference of permittivities:

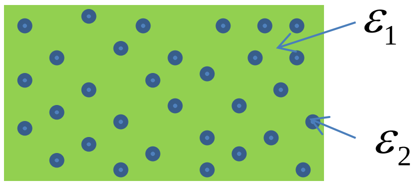
1% of water in air; one-pole Debye model of water: $\varepsilon_\infty = 4.9;\ \Delta\varepsilon = 76.1;\ f_r = 15.8GHz$





Mixing dielectrics – right way

- Average electric flux density and electric field! $\langle \bar{D} \rangle = \varepsilon_{mix} \langle \bar{E} \rangle$ $\quad \langle \bar{F} \rangle = \frac{1}{V}\int_V \bar{F} \cdot dv$



$\bar{E}_1$ electric field in host

$\bar{E}_2$ electric field in inclusions

v volume fraction of inclusions

Example of fields averaging for spherical inclusions:

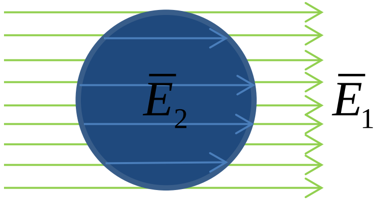
$$\langle \bar{D} \rangle = v\varepsilon_2 \bar{E}_2 + (1-v)\varepsilon_1 \bar{E}_1$$

$$\langle \bar{E} \rangle = v \cdot \bar{E}_2 + (1-v) \cdot \bar{E}_1$$

Electric field in sphere:

$$\bar{E}_2 = \frac{3\varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \cdot \bar{E}_1$$

Field distortions is zero on average!



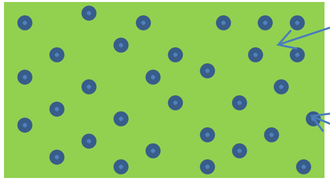
Maxwell Garnett mixing formula (derived by James Clerk Maxwell Garnett, 1880-1958):

$$\varepsilon_{mix} = \varepsilon_1 + 3v\varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1 - v(\varepsilon_2 - \varepsilon_1)}$$

J.C.Maxwell Garnett, Colours in metal glasses and metal films, Trans. of the Royal Soc., CCIII, 1904, p. 385-340.

Bounds on permittivity of mixtures

- Bounds for statistically homogeneous and isotropic mixture



ε_1

$\varepsilon_1 < \varepsilon_2$

ε_2

v volume fraction of inclusions

Hashin-Shtrikman bounds are based on a variational treatment of the energy functional (3D):

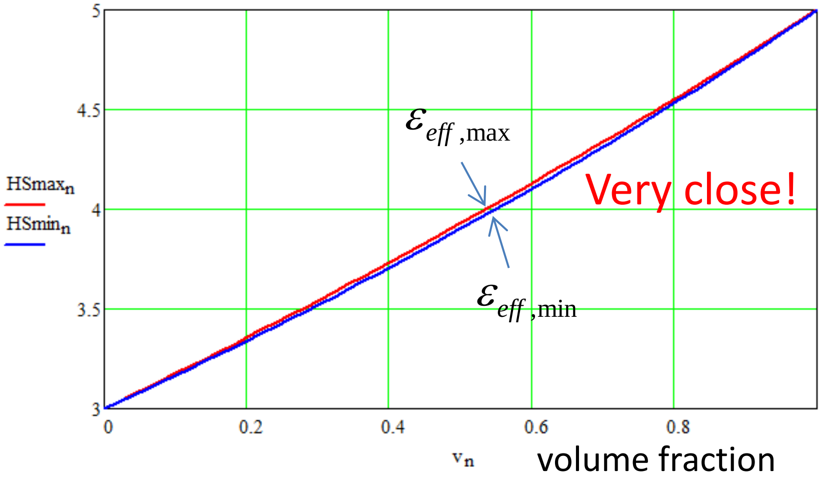
$$\varepsilon_{eff,\max} = \varepsilon_2 + \frac{1-v}{\dfrac{1}{\varepsilon_1 - \varepsilon_2} + \dfrac{v}{3\cdot\varepsilon_2}}$$

$$\varepsilon_{eff,\min} = \varepsilon_1 + \frac{v}{\dfrac{1}{\varepsilon_2 - \varepsilon_1} + \dfrac{1-v}{3\cdot\varepsilon_1}}$$

These are the Maxwell Garnett's equations!

$$\varepsilon_{mix} = \varepsilon_1 + 3v\varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1 - v(\varepsilon_2 - \varepsilon_1)}$$

Example (glass in resin): $\varepsilon_1 = 3;\ \varepsilon_2 = 5;$

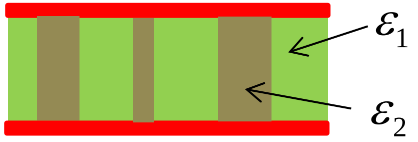


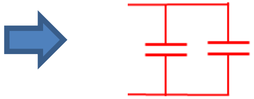
Z. Hashin, S. Shtrikman, "A variational approach to the theory of the effective magnetic permeability of multiphase materials," J. Appl. Phys., vol. 33, no. 10, pp. 3125–3131, 1962.

Bounds on permittivity of mixtures

- **The loosest bounds for isotropic mixture** defined by Otto Wiener

Wiener bounds are calculated for structured cases





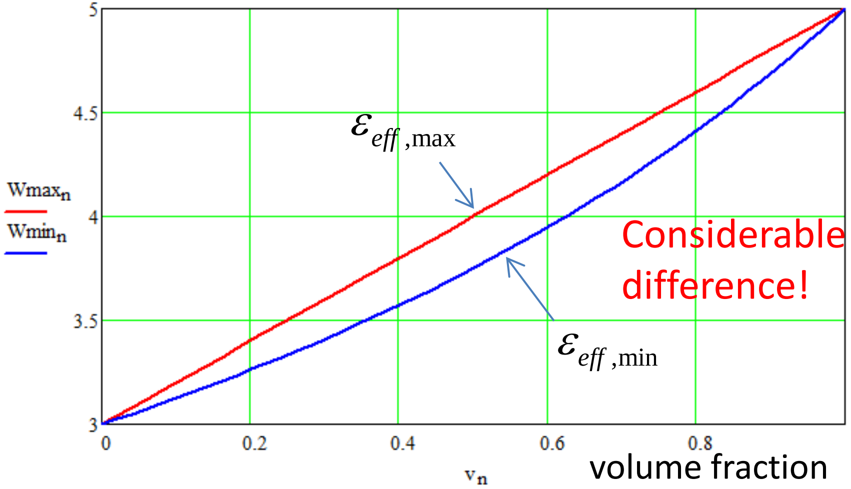
parallel rule

$$\varepsilon_{eff,\max} = v \cdot \varepsilon_2 + (1 - v) \cdot \varepsilon_1$$

v volume fraction of inclusions

$$\varepsilon_{eff,\min} = \frac{\varepsilon_1 \cdot \varepsilon_2}{v \cdot \varepsilon_1 + (1 - v) \cdot \varepsilon_2}$$

Example (glass in resin): $\varepsilon_1 = 3;\ \varepsilon_2 = 5;$

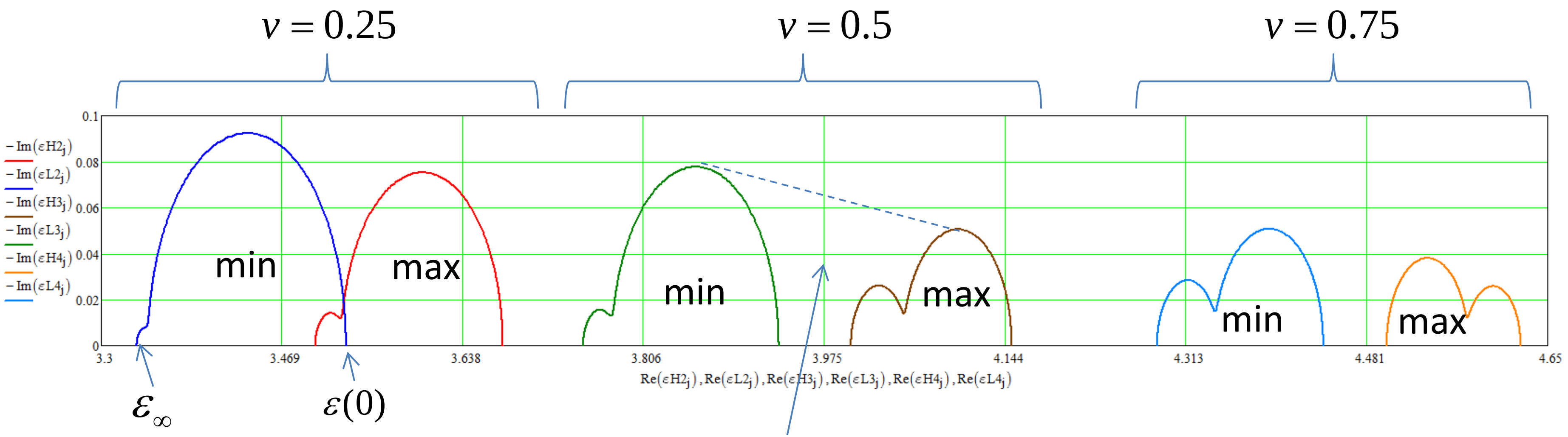


O. Wiener, “Zur theorie der refraktionskonstanten,” Berichteüber Verhandlungen Königlich-Sächsischen Gesellschaft Wisseschaften Leipzig, pp. 256–277, 1910.

Mixing with dispersion

- Wiener bounds for mixture with 2 components

Example (glass in resin): Debye models $\varepsilon_{1\infty} = 3;\ \Delta\varepsilon = 0.2;\ f_r = 1GHz;\ \varepsilon_{2\infty} = 5;\ \Delta\varepsilon = 0.1;\ f_r = 100GHz$



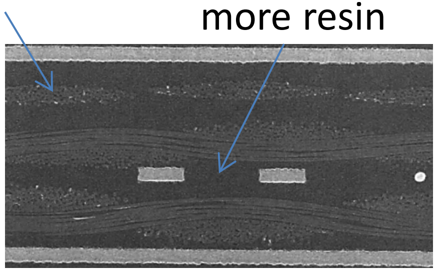
Actual model is somewhere between the bounds
– may be considerable difference!

Homogenization scale – feature size

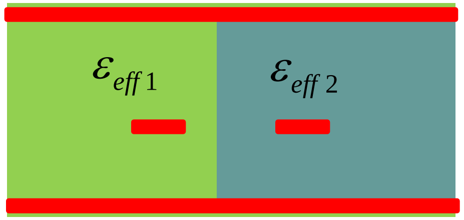
- **Homogenization area must be much smaller than the analyzed feature size**
- Dielectric inhomogeneity in cross-section may cause signal degradation at higher data rates or frequencies – skew, mode conversion, anisotropy…

more glass fiber

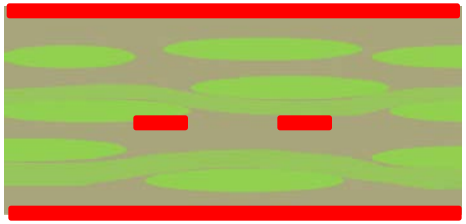
more resin



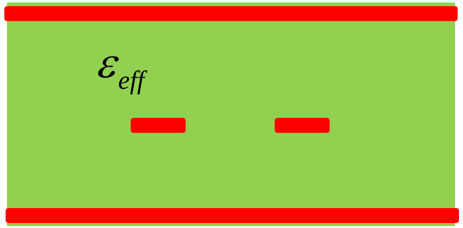
Imbalanced effective dielectrics



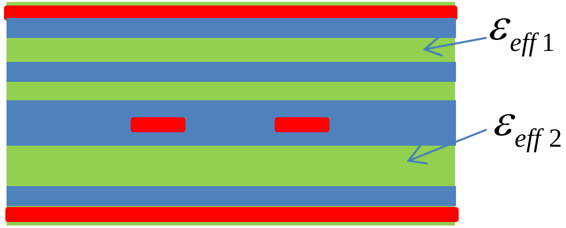
More and more details is required to extend model frequency range…



Homogeneous effective dielectric



Layered effective dielectrics



Example of worst case analysis

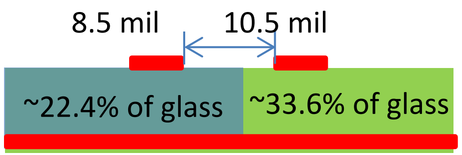
Project(1)
Materials: T=20[°C],...
"Copper", RR=1
"Air"
"Resin", Dk=3.14, LT=0.02, PLM=WD, Dk(0)=3.78, Dk(inf)=2.77
"E-Glass", Dk=5.6, LT=0.01, PLM=WD, Dk(0)=6.17, Dk(inf)=5.35
"NPG-170D-2116x1-E", "HashinShtrikmanAverage", "Resin"(0.72), "E-Glass"(0.28)
StackUp: LU=[mil], NL=4, T=18.94[mil]
1| Signal: "Signal1", T=1.2, Ins="Air", Cond="Copper"
2| Medium: T=5, Ins="NPG-170D-2116x1-E"
3| Plane: "Plane1", Cond="Copper", T=0.77, Ins="NPG-170D-2116x1-E"

model for resin

model for glass

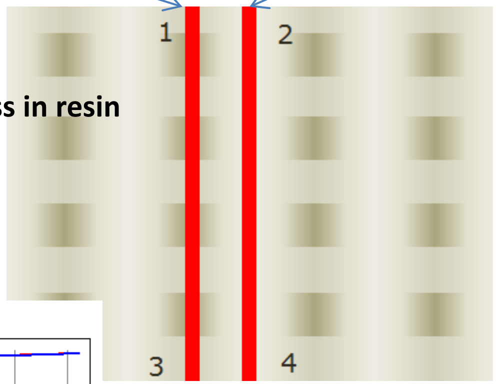
Mixture model with **28% average volume content** of glass in resin

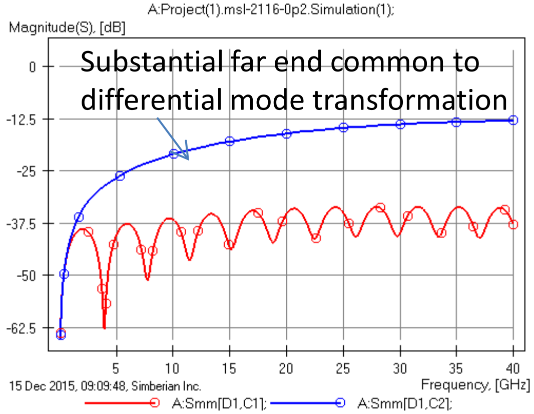
Model with +- 20% imbalance of glass in resin

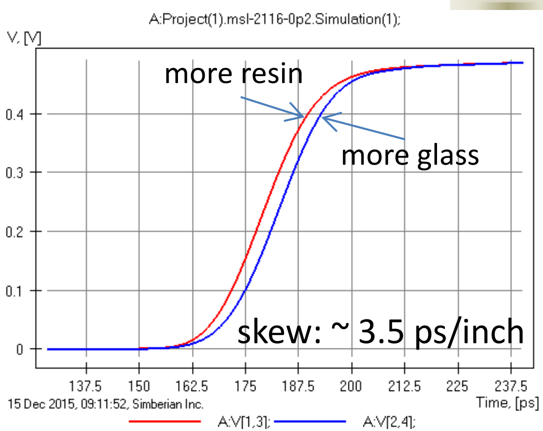


more resin

more glass







Computed with Simbeor THz

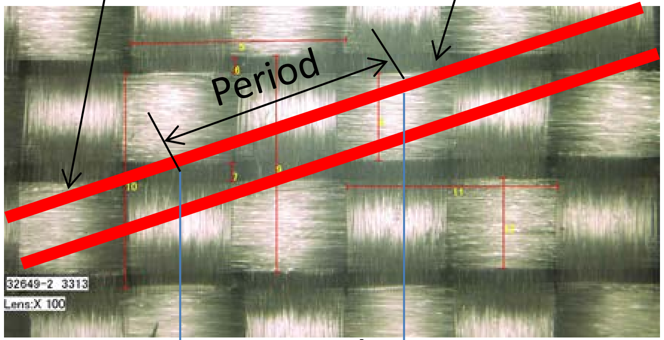
See more at: Y. Shlepnev, C. Nwachukwu, "Modelling jitter induced by fibre weave effect in PCB dielectrics", Proc. of 2014 IEEE Int. Symp. on EMC, 2014.

Homogenization scale – wavelength

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

more glass fiber at humps

more resin in valleys

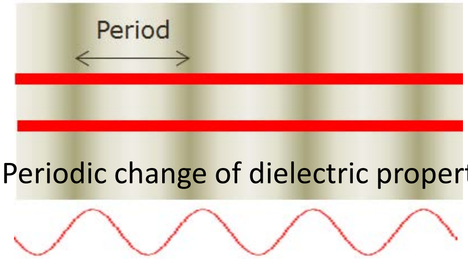


2116

20 mil

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

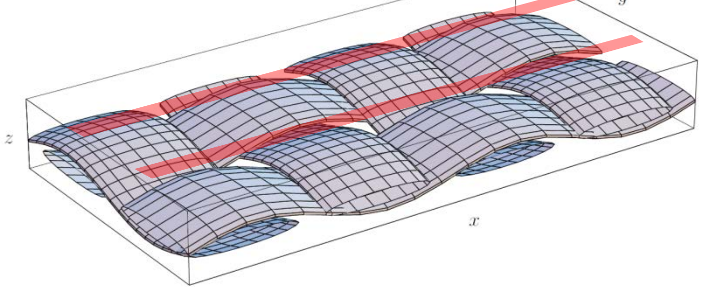
1D or 2D non-uniform t-line models



Resonance at
Period = Wavelength/2

Periodic change of dielectric properties

3D models



Example of periodicity effect analysis

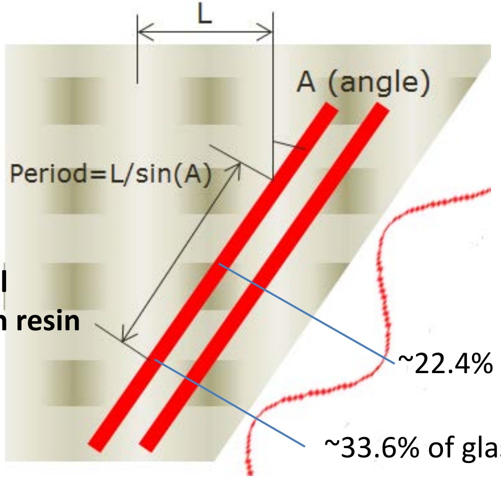
Project(1)
- Materials: T=20[°C],...
  - "Copper", RR=1
  - "Air"
  - "Resin", Dk=3.14, LT=0.02, PLM=WD, Dk(0)=3.78, Dk(inf)=2.77
  - "E-Glass", Dk=5.6, LT=0.01, PLM=WD, Dk(0)=6.17, Dk(inf)=5.35
  - "NPG-170D-2116x1-E", "HashinShtrikmanAverage", "Resin"(0.72), "E-Glass"(0.28)
- StackUp: LU=[mil], NL=4, T=18.94[mil]
  - 1| Signal: "Signal1", T=1.2, Ins="Air", Cond="Copper"
  - 2| Medium: T=5, Ins="NPG-170D-2116x1-E"
  - 3| Plane: "Plane1", Cond="Copper", T=0.77, Ins="NPG-170D-2116x1-E"

model for resin

model for glass

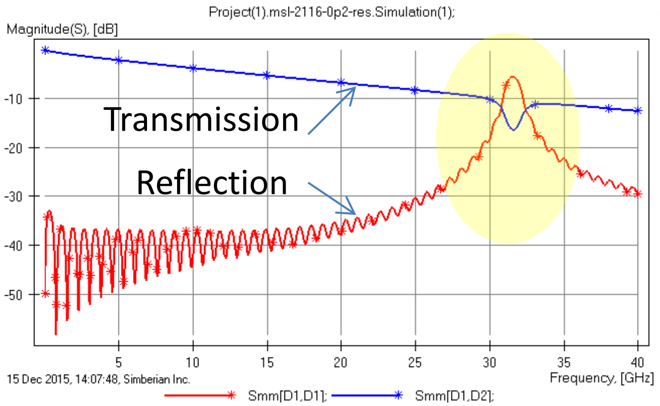
Mixture model with **28% average volume content** of glass in resin

Model with +- 20% sinusoidal periodic imbalance of glass in resin



~22.4% of glass

~33.6% of glass



Reflective resonance - No absorption as in Lorentzian dielectric model!

Microstrip structure: traces at 9 deg.; Period 120 mil, resonance at ~32 GHz

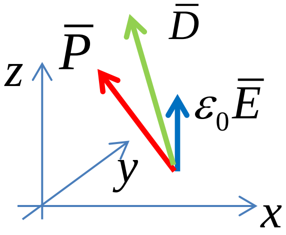
Computed with Simbeor THz

See more at: Y. Shlepnev, C. Nwachukwu, "Modelling jitter induced by fibre weave effect in PCB dielectrics", Proc. of 2014 IEEE Int. Symp. on EMC, 2014.

Anisotropic dielectrics

"Anisotropic solid is not an isotropic solid" – Lord Kelvin, 1904

- Anisotropy is dependency of polarization on electric field direction



$$\bar{D} = \varepsilon_0 \cdot \bar{E} + \bar{P} = \varepsilon_0 \left(1 + \tilde{\chi}\right) \cdot \bar{E} \Rightarrow \bar{D} = \tilde{\varepsilon} \cdot \bar{E}$$

$$\tilde{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix}$$

Permittivity is 3x3 matrix, dyadic or second-rank tensor – 9 **dispersive parameters** in general

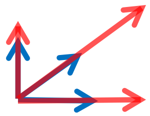
1. Reciprocal material – 6 parameters or less

$$\tilde{\varepsilon} = \tilde{\varepsilon}^t = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{xy} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{xz} & \varepsilon_{yz} & \varepsilon_{zz} \end{bmatrix}$$

Practically all anisotropic dielectrics are reciprocal

2. Biaxial material – 3 parameters

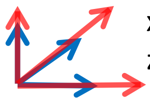
$$\begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix}$$



Orthorhombic (monoclinic, triclinic) lattices and **PCB laminates**!

3. Uniaxial material – 2 parameters

$$\begin{bmatrix} \varepsilon_{=} & 0 & 0 \\ 0 & \varepsilon_{=} & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{bmatrix}$$



x and y are identical, z is different

Tetragonal, hexagonal, rhombohedral lattices and **PCB laminates**!

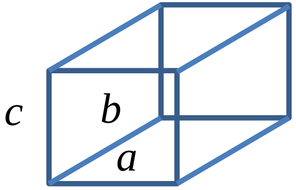
T.G. Mackay, Electromagnetic Anisotropy and Bianisotropy: A Field Guide, 2006

Anisotropy: biaxial dielectric

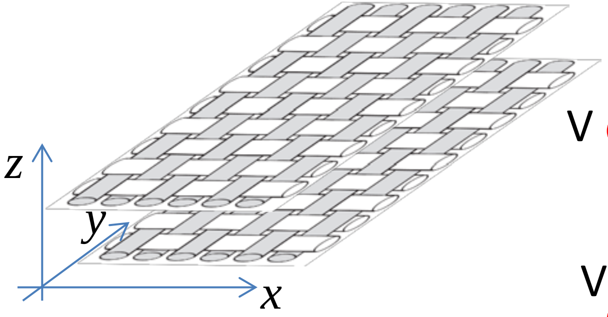
- Homogenization of PCB dielectric along the coordinate axes

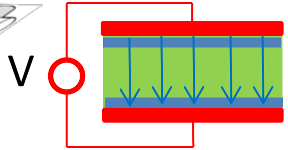
Orthorhombic system with optical axes as coordinate axes:

$a \,!\!= b \,!\!= c$



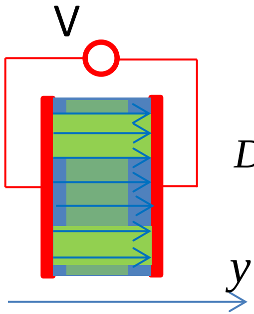
Fiber glass fabric with different filling and warp yarns:



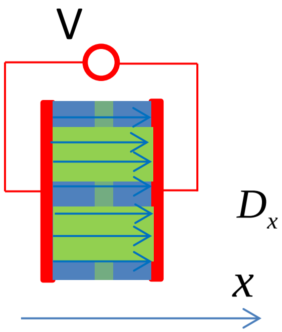


$$D_z = \varepsilon_{zz} \cdot E_z$$

Series mixing rule
(Weiner min)



$$D_y = \varepsilon_{yy} \cdot E_y$$

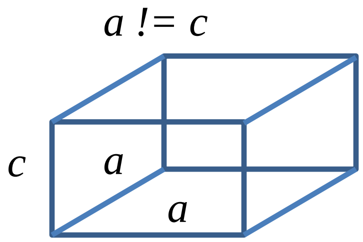


$$D_x = \varepsilon_{xx} \cdot E_x$$

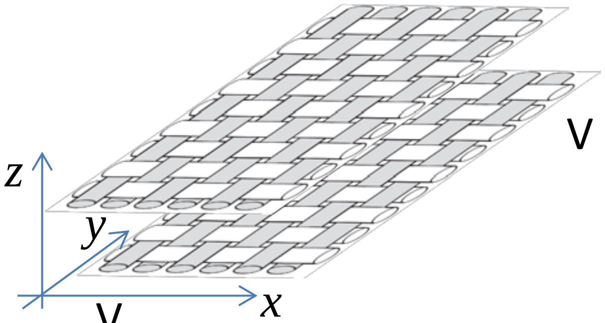
Anisotropy: uniaxial dielectric

- In and out of plane homogenization of PCB dielectric

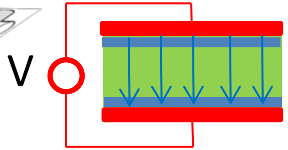
Tetragonal system with optical axes as coordinate axes:



Fiber glass fabric with similar filling and warp yarns:



Out of plane value:

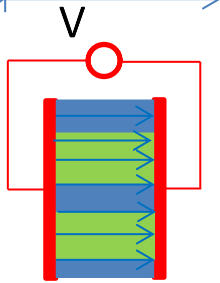


$$D_z = \varepsilon_{\perp} \cdot E_z$$

Series mixing rule (Weiner Min)

This value is usually is measured with wide strip line resonator (in spreadsheets)!

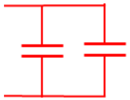
$$\varepsilon_{eff,\min} = \frac{\varepsilon_1 \cdot \varepsilon_2}{v \cdot \varepsilon_1 + (1-v) \cdot \varepsilon_2}$$



In plane value:

$$D_{x,y} = \varepsilon_{=} \cdot E_{x,y}$$

Parallel mixing rule (Weiner Max)



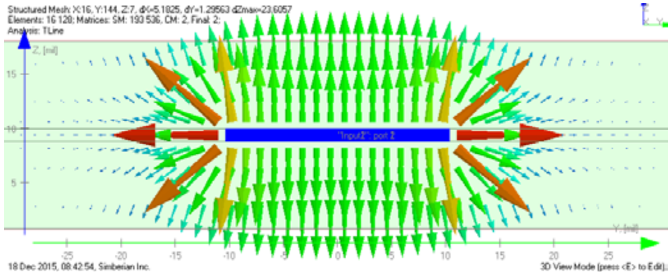
$$\varepsilon_{eff,\max} = v \cdot \varepsilon_2 + (1-v) \cdot \varepsilon_1$$

M.Y. Koledintseva, S. Hinaga, and J.L. Drewniak, "Effect of anisotropy on extracted dielectric properties of PCB laminate dielectrics", IEEE Symp. on EMC, Long Beach, CA, Aug. 14-19, 2011, pp. 514-517

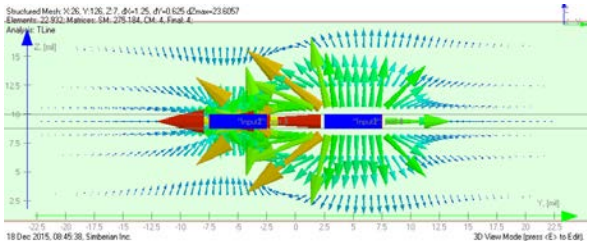
Fields in PCB structures

- X, Y and Z components of electric field depend on geometry

E-field in wide strip (25 Ohm at 10 GHz)

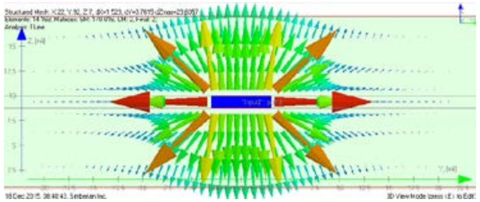


E-field of strip differentia mode (85 Ohm at 10 GHz)

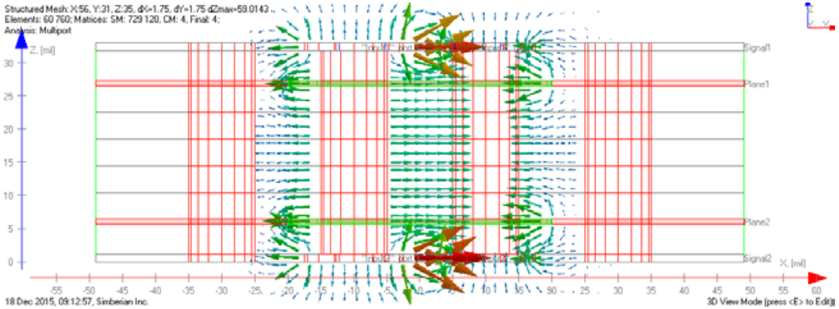


Computed with Simbeor THz

E-field in narrow strip (50 Ohm at 10 GHz)



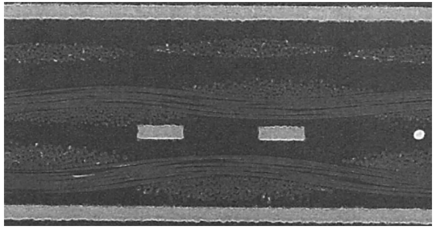
E-field in differential vias



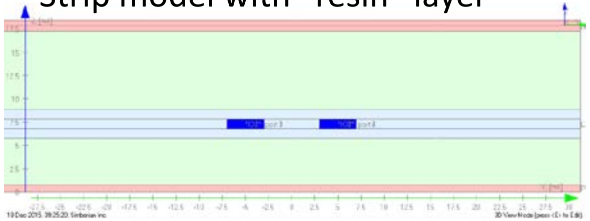
Effective permittivity will depend on geometry too (it is averaging of the fields)

Alternative to anisotropic model

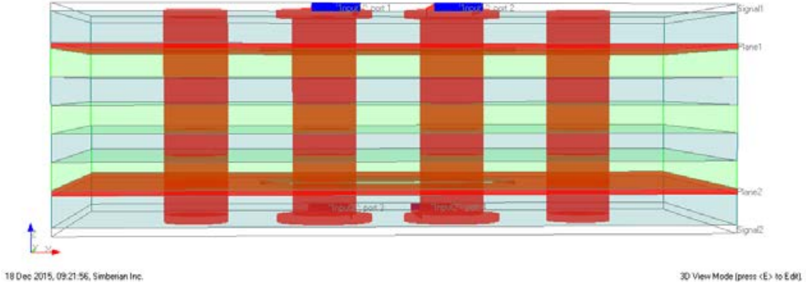
- **Layered dielectric model**



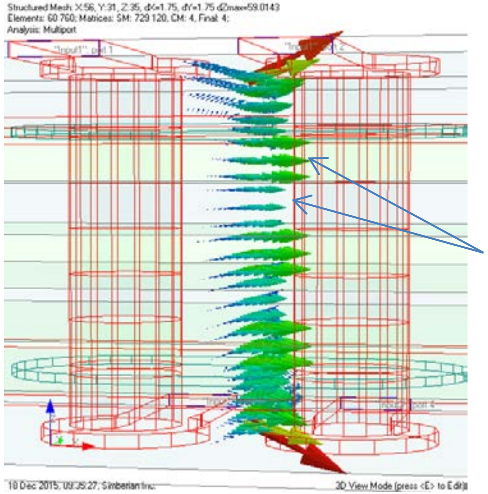
Strip model with “resin” layer



Via model with “resin” and “glass” mixture layers



Polarization current between 2 diff. vias at 10 GHz



Substantial difference in current through layers with different permittivity

Computed with Simbeor THz

Which model is better for PCB?

Homogeneous

$$\langle \overline{D} \rangle = \varepsilon_{mix} \langle \overline{E} \rangle$$

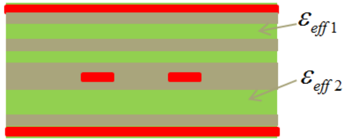
Simplest – one permittivity

Anisotropic

$$\begin{pmatrix} D_x \\ D_y \\ D_z \end{pmatrix} = \begin{bmatrix} \varepsilon_{=} & 0 & 0 \\ 0 & \varepsilon_{=} & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{bmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

2 permittivities

Layered



2 or more permittivities and layer thicknesses

If dielectric components have substantially different permittivities:

Depends on geometry, multiple models may be required for different cross-sections, vias,…

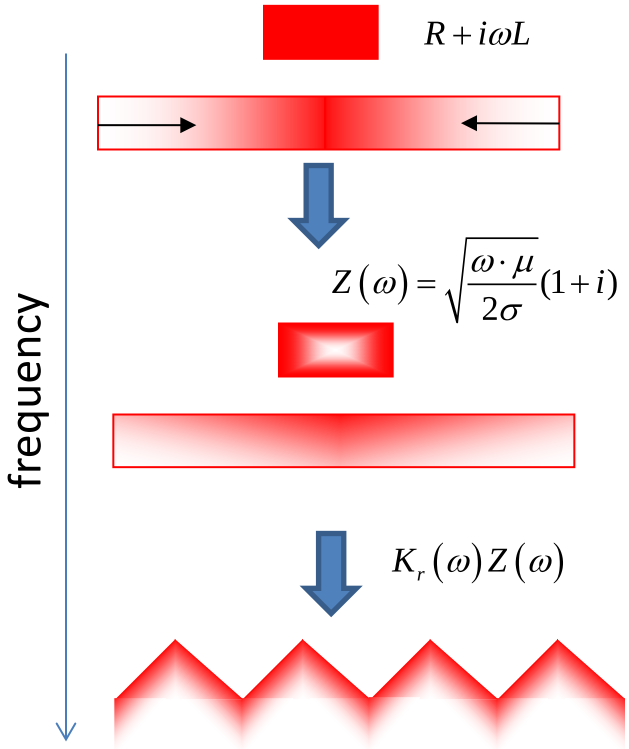
Accurate for extended range of geometries

Less accurate if feature size is smaller than the homogenization area (close traces or elements of vias)

Most accurate and universal

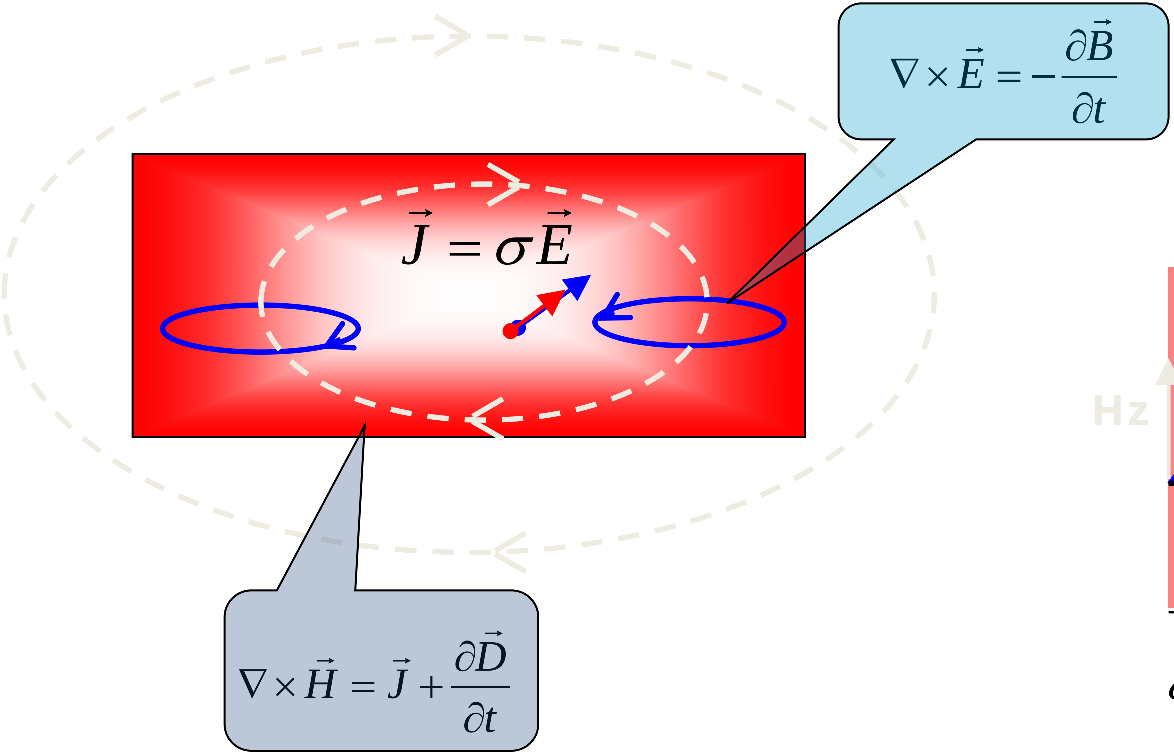
Conductor dispersion effects

- 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 (Nickel)
- Plasmonic effects above 1 THz – (Drude model)

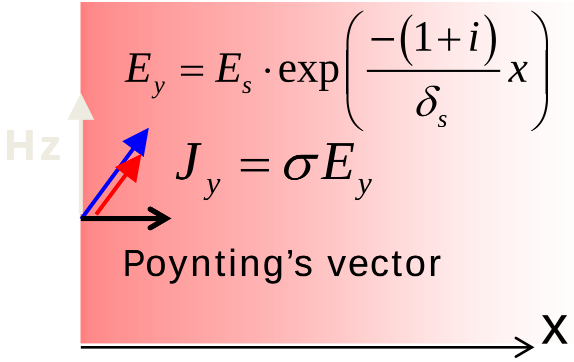


Skin effect = Maxwell's eq. +Ohm's law

Current cancelation:



Plane-wave view:

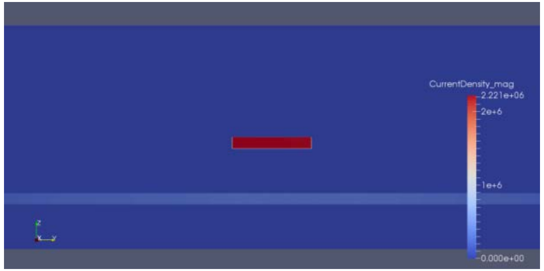


$$\delta_s = \frac{1}{\sqrt{\pi f \mu \sigma}}$$ Skin depth

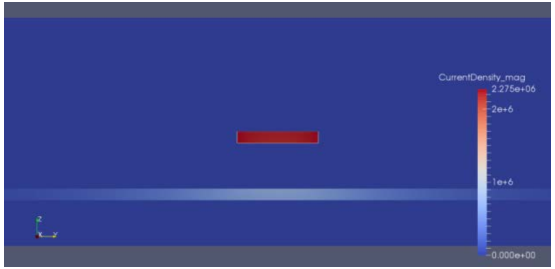
Example: currents in microstrip

t=1 mil, w=7 mil, current density in [A/m^2], 1V + 50 Ohm excitation

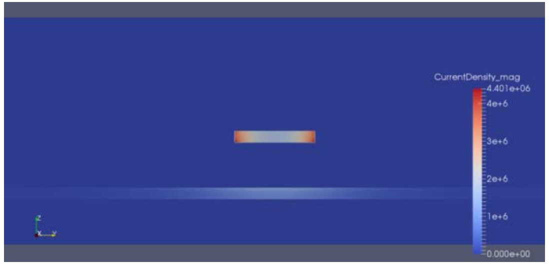
1 KHz - skin depth 82*t



1 MHz - skin depth 2.6*t

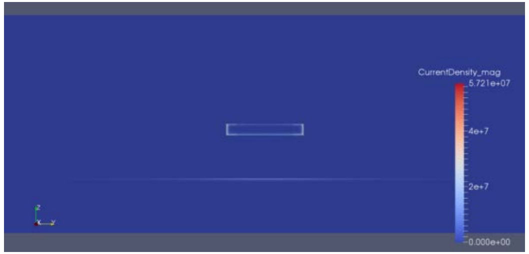


10 MHz - skin depth 0.82*t

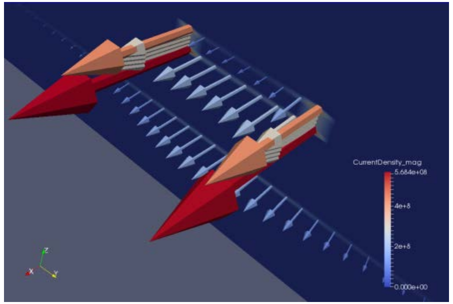


100 MHz - skin depth 0.26*t

1 GHz - skin depth 0.082*t



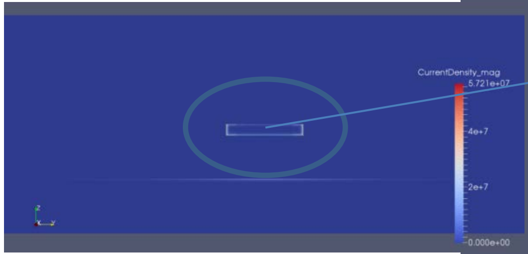
100 GHz - skin depth 0.0082*t;
peak current density in cross-section:

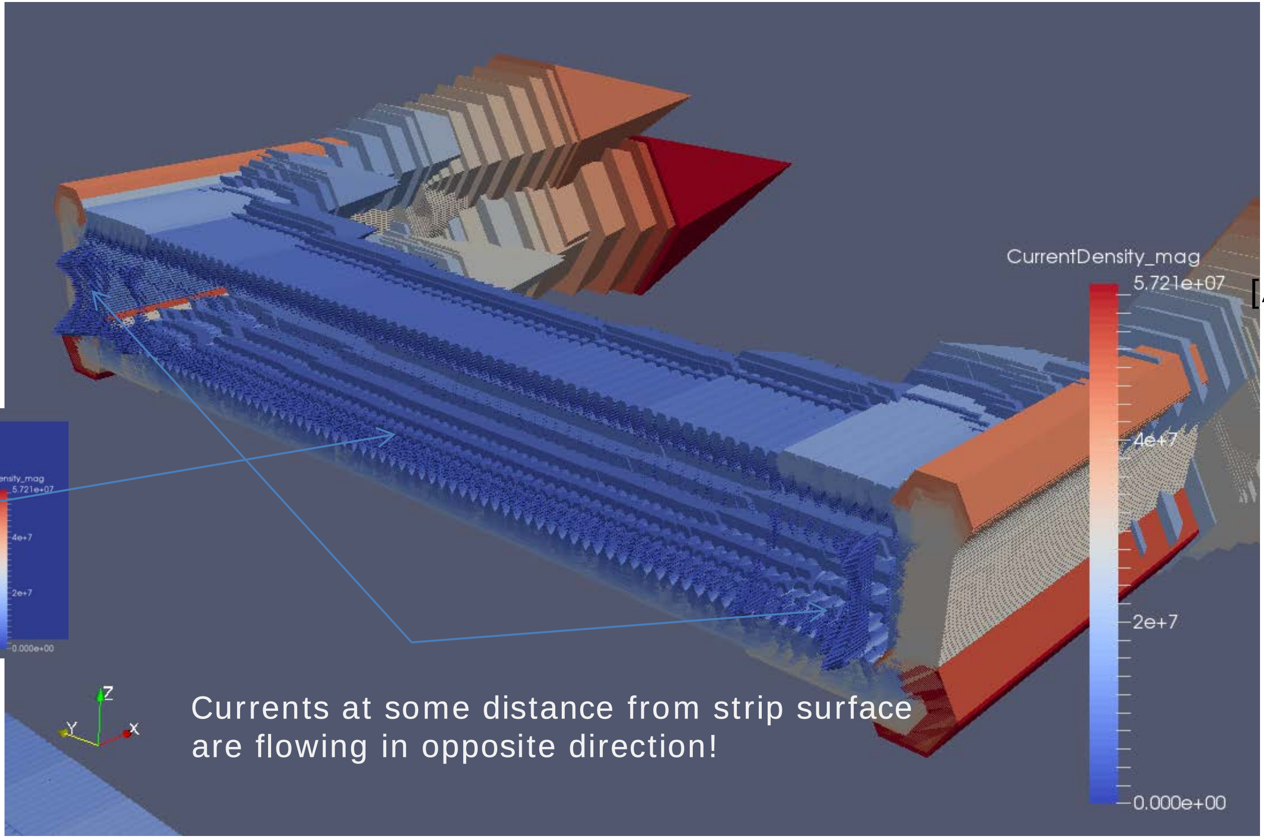


Computed with Simbeor THz

Current reversal in conductor

1 GHz - skin depth 0.082*t

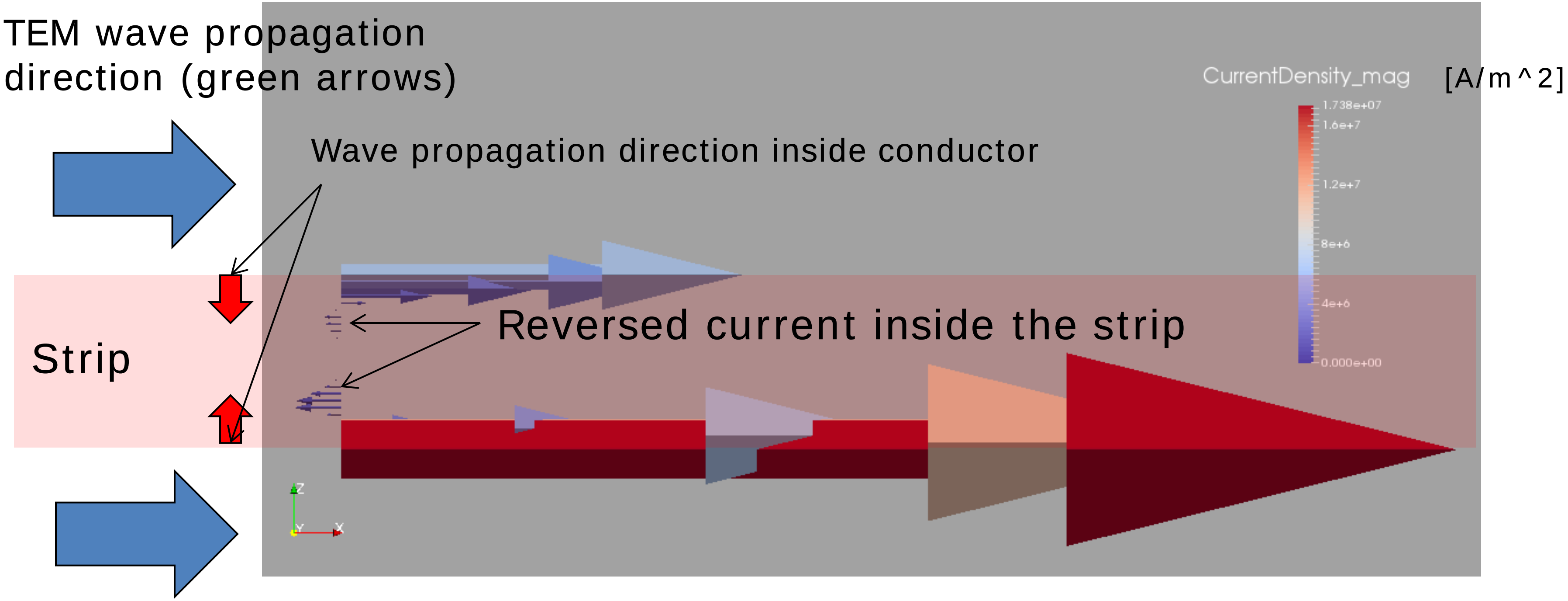




[A/m^2]

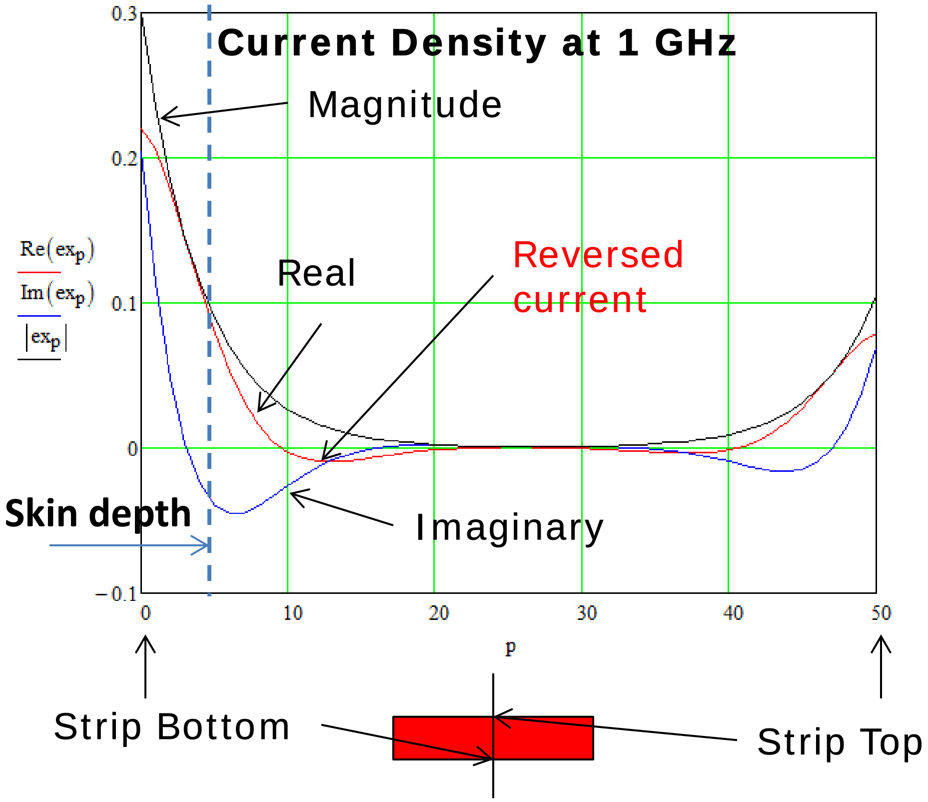
Currents at some distance from strip surface
are flowing in opposite direction!

Current reversal in conductor



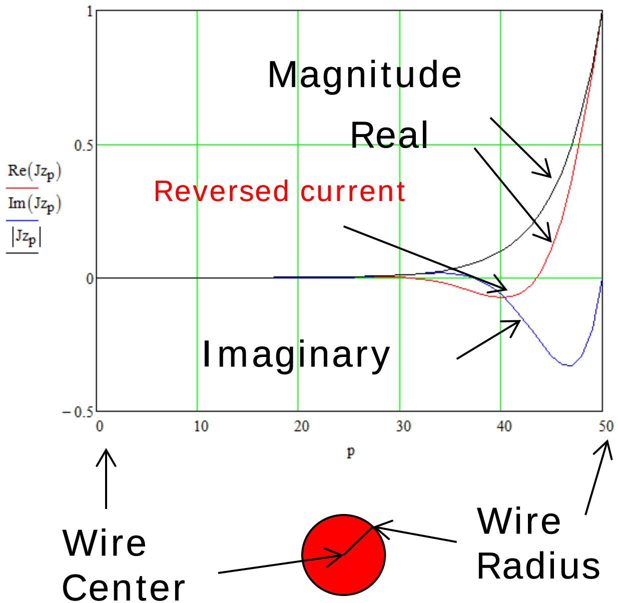
Delay of the wave propagating into the strip explain the current reverse and the internal inductance
1 GHz, Skin Depth 0.082*t (conductor thickness is 12.2 of SD)

Current reversal in conductor



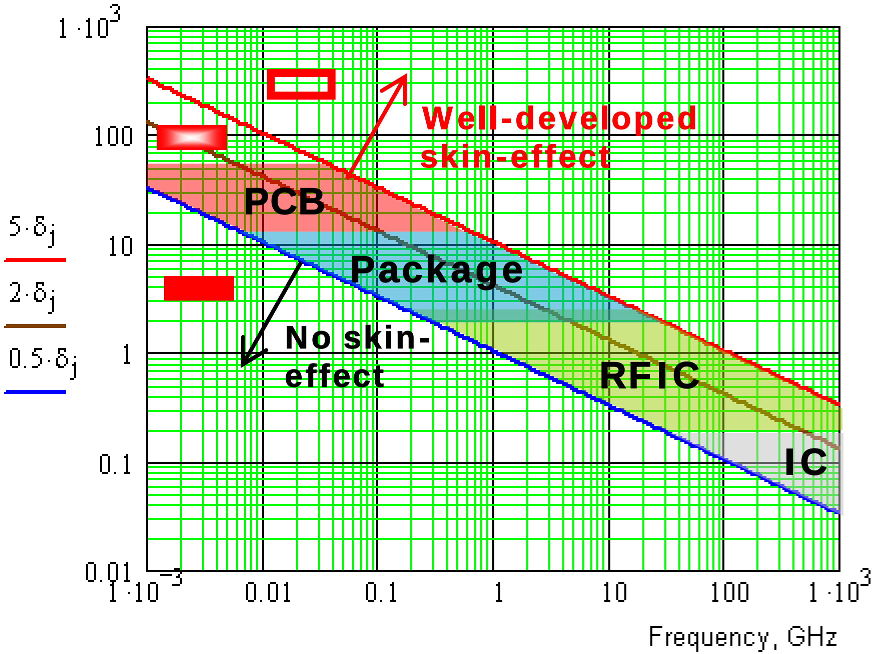
Real negative part means direction opposite to the surface currents!

Similar to the current in round wire



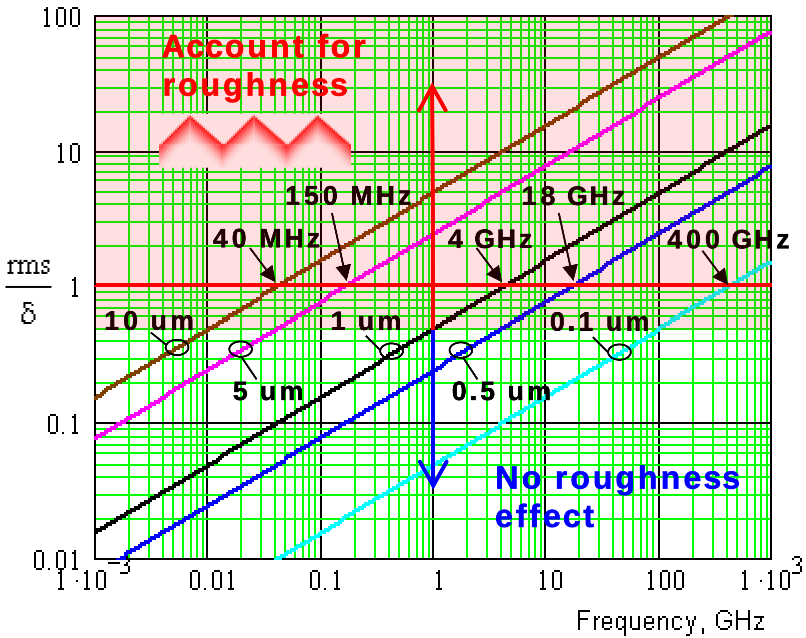
Skin-effect and roughness

Transition from 0.5 skin depth to 2 and 5 skin depths for copper interconnects on PCB, Package, RFIC and IC



Interconnect or plane thickness in micrometers vs. Frequency in GHz

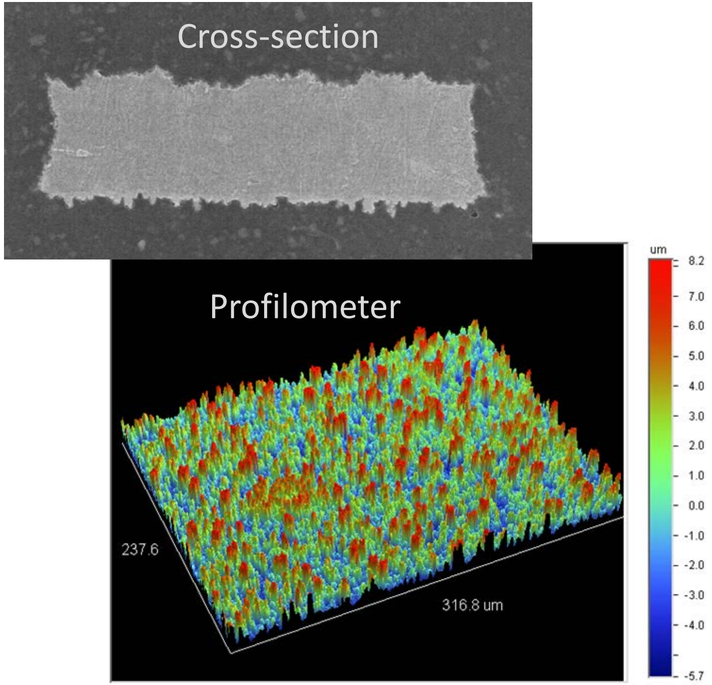
Ratio of skin depth to r.m.s. surface roughness in micrometers vs. frequency in GHz



Roughness has to be accounted if rms value is comparable with the skin depth (0.5-1 of skin depth)

Roughness modeling

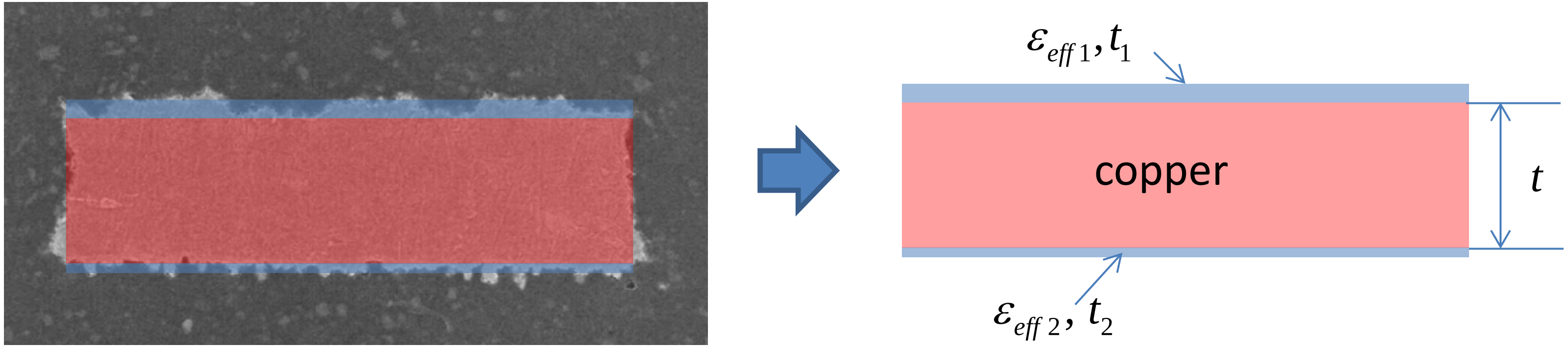
- Direct electromagnetic analysis is simply not possible (very approximate)
- “Effective dielectric roughness” layer
- Roughness correction coefficients:
  - Modified Hammerstad model
  - Huray’s snowball model
  - Hemispherical model
  - Sandstroem’s model
  - Stochastic models
  - Periodic frequency selective surfaces…



See references at: Y. Shlepnev, C. Nwachukwu, Practical methodology for analyzing the effect of conductor roughness on signal losses and dispersion in interconnects, DesignCon2012

Effective Roughness Dielectric (ERD)

Layer with mixture of conductor and dielectric material is turned into layer with "effective" dielectric parameters



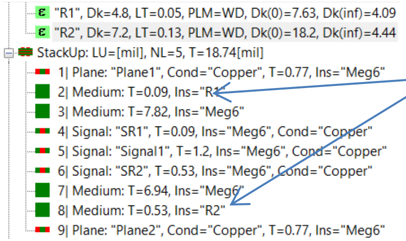
Eliminates uncertainties of the conductor/dielectric boundary;

Too many parameters, difficult to identify;

Introduced in M.Y. Koledintseva, A. Ramzadze, A. Gafarov, S. De, S. Hinaga, J.L. Drewniak, PCB conductor surface roughness as a layer with effective material parameters. – in Proc. IEEE Symp. Electromagn. Compat., Pittsburg, PA, USA, 2012, p. 138-142.

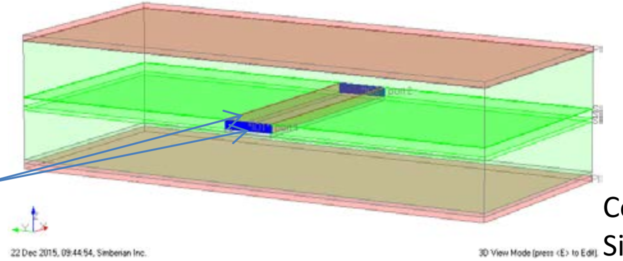
Example of analysis with ERD

ERD parameters for STD copper are defined in A.V. Rakov, S. De, M.Y. Koledintseva, S. Hinaga, J.L. Drewniak, R.J. Stanley, Quantification of conductor surface roughness profiles in printed circuit boards, IEEE Trans. on EMC, v. 57, N2, 2015, p. 264-273.

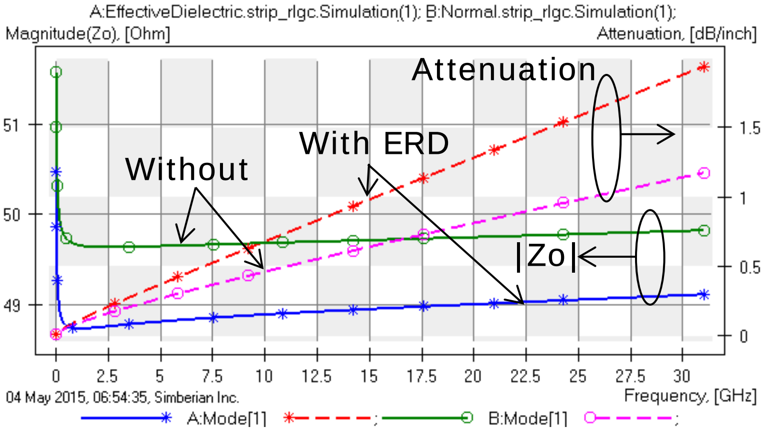


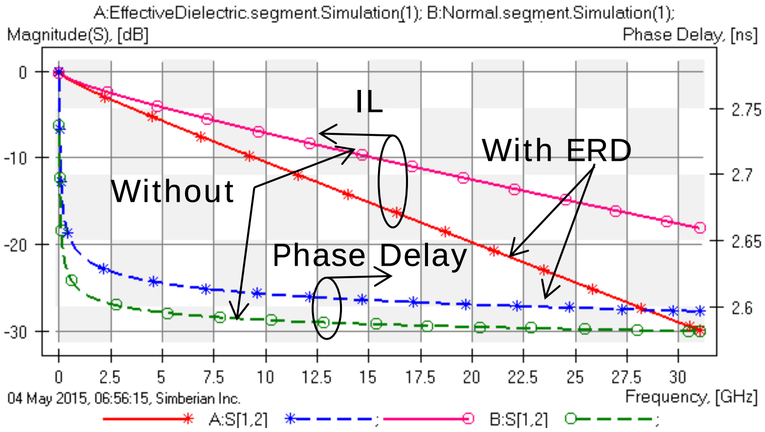
ERD layer next to planes

ERD strips above and below copper strip



Computed with Simbeor THz





Causal increase in attenuation, phase delay and decrease in impedance!

Modified Hammerstad model

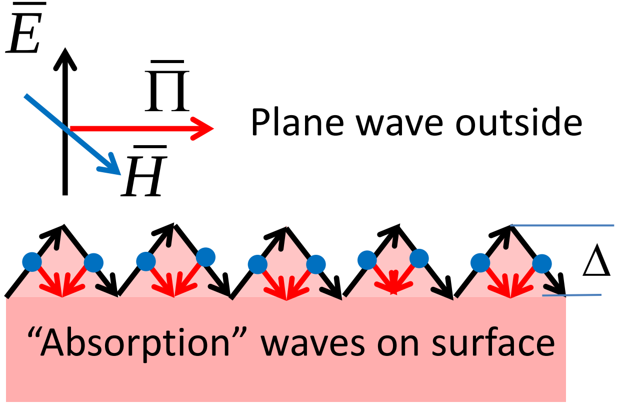
Roughness correction coefficient – increase of absorption by *Ksr*:

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

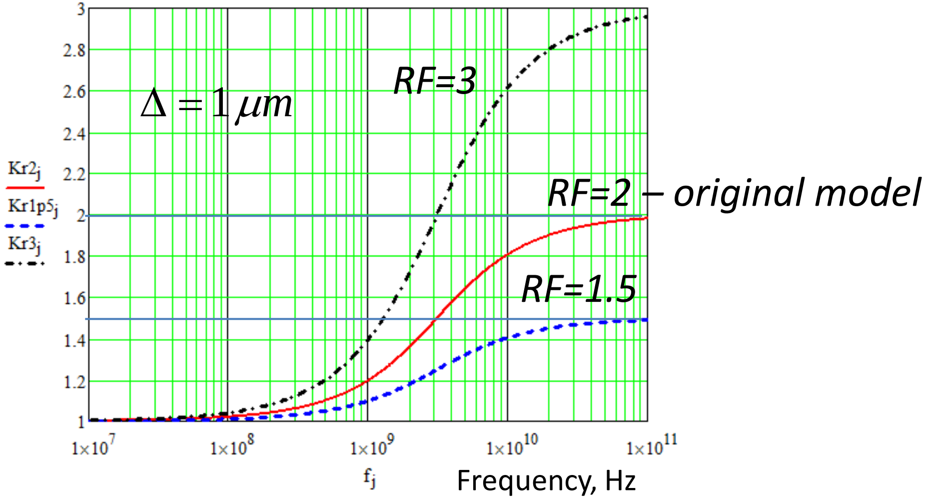
Conductor skin-depth $\delta_s = \sqrt{\frac{1}{\pi \cdot f \cdot \mu \cdot \sigma}}$

Δ ~ root mean square peak-to-valley distance

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



Bumps are much smaller than wavelength!



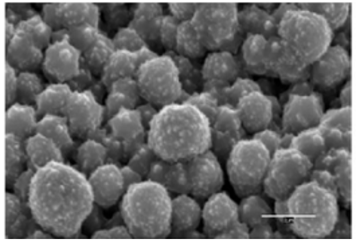
Modified model suggested in Y. Shlepnev, C. Nwachukwu, Roughness characterization for interconnect analysis. - Proc. of the 2011 IEEE Int. Symp. on EMC, Long Beach, CA, USA, August, 2011, p. 518-523

Huray's snowball model

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

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

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

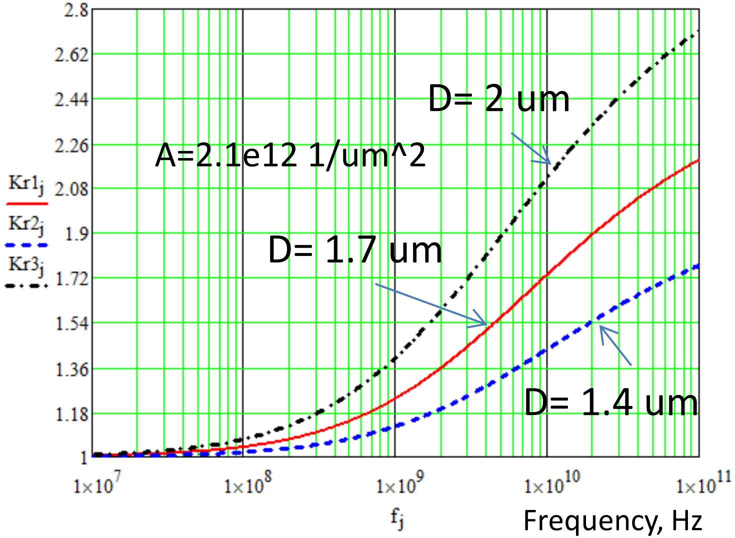


Amatte/Ahex can be accounted for by resistivity;
Can be simplified to model with 2 parameters per ball (*Ai* and *Di*):

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

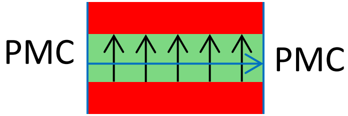
$$A_i = \frac{3\pi N_i}{2A_{hex}}$$

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

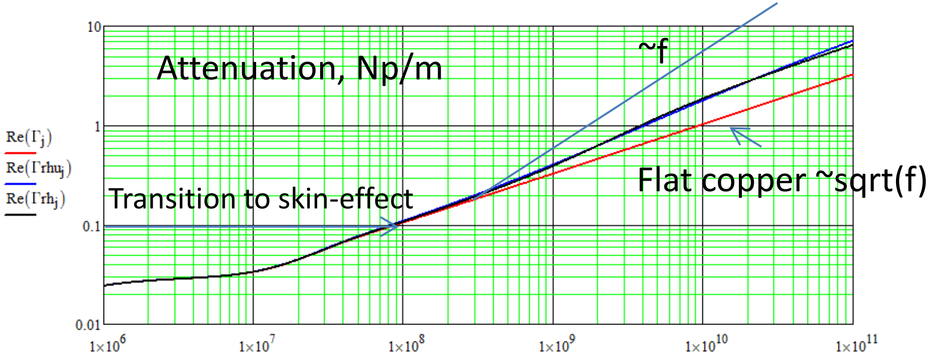


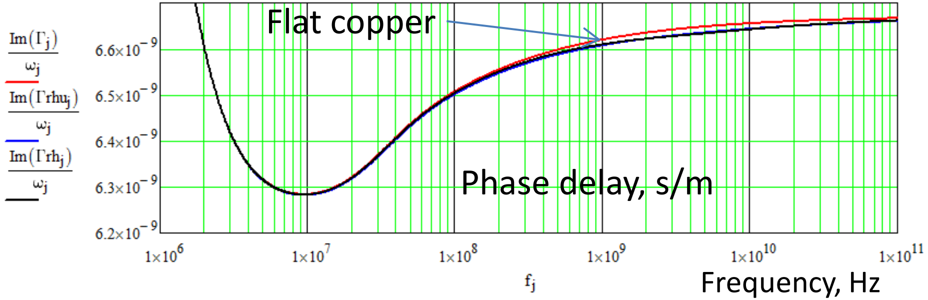
Dispersion with rough conductors

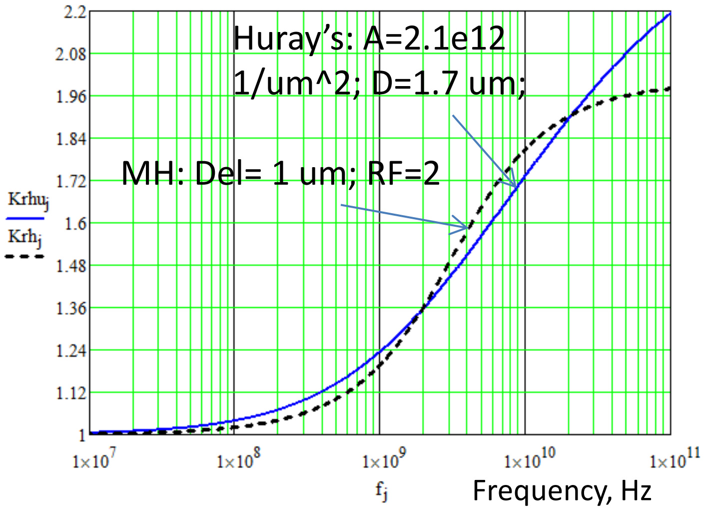
"Oliner's waveguide – ideal to investigate RCCs



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







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

Use of roughness correction coefficients

- Apply it to attenuation: Simplest; Non causal, applicable for t-lines only;
- Apply it to internal conductor part of p.u.l. impedance:

$$Z_r(f) = K_r \cdot Z_s + i\omega \cdot L(\infty) \left[\frac{Ohm}{m}\right]$$

Kr is impedance roughness correction coefficient (Huray, Modified Hammerstad,…);
Zs – conductor p.u.l. impedance matrix;

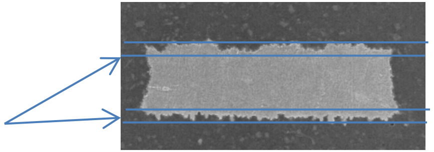
Simple, causal;
Does not account for actual current distribution on conductor, applicable for t-lines only;

- Apply to conductor surface impedance operator (Simbeor)

$$Z_{cs}'' = K_{sr}^{1/2} \cdot Z_{cs} \cdot K_{sr}^{1/2}$$

Ksr – diagonal matrix with roughness correction coefficients on diagonal (Huray, Modified Hammerstad,…);
Zcs – conductor surface impedance operator (matrix);

Causal, accounts for actual current distribution;
Difficult to implement, no capacitive effect;
Boundary uncertainty in all approaches with RCC;



What is bulk resistivity?

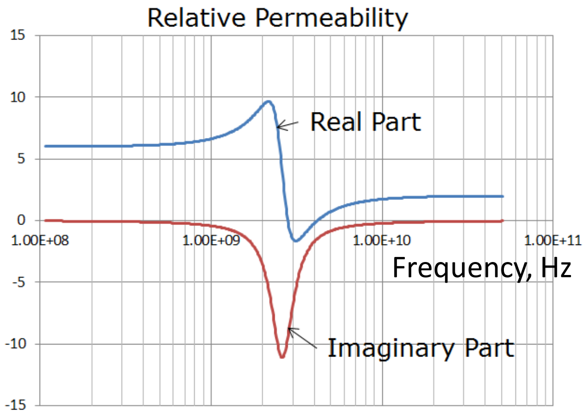
See details in Y. Shlepnev, C. Nwachukwu, Roughness characterization for interconnect analysis. - Proc. of the 2011 IEEE Int. Symp. on EMC, Long Beach, CA, USA, August, 2011, p. 518-523

Ferromagnetics: Nickel magnetization

- Magnetic permeability dispersion equations are derived by Landau and Lifshits from description moving boundaries of oppositely magnetized layers in ferromagnetic metal:

$$\mu(f) = \mu_h + (\mu_l - \mu_h) \cdot \frac{f_0^2 + i \cdot f \cdot \gamma}{f_0^2 + 2i \cdot f \cdot \gamma - f^2}$$

μ_l – permeability at low frequencies; μ_h – permeability at high frequencies;
f_0 – resonance frequency [Hz]; γ – damping coefficient [Hz]

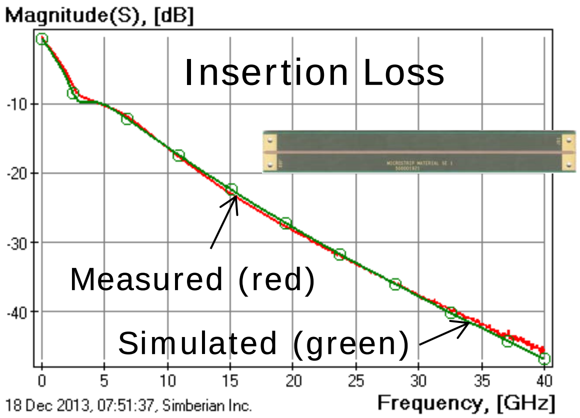


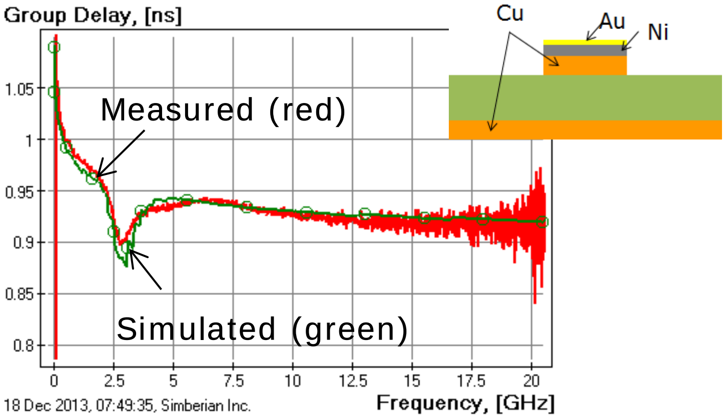
- Lorentz model may be also acceptable for resonance description
- Can be combined with Debye model at lower frequencies and Lorentz model at the millimeter frequencies

L. Landau, E. Lifshits, On the theory of the dispersion of magnetic permeability in ferromagnetic bodies, Phys. Zeitsch. der Sow., v. 8, p. 153-169, 1935.
Y. Shlepnev, S. McMorrow, Nickel characterization for interconnect analysis. - Proc. of the 2011 IEEE International Symposium on EMC, 2011, p. 524-529.

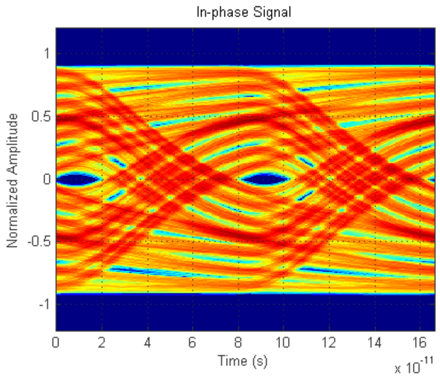
Example: 150 mm microstrip link with ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper;

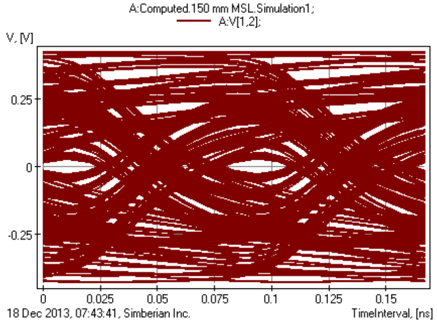
Simulation with identified dielectric model and Landau-Lifshits model for Ni layer:





12 Gb/s
Measured



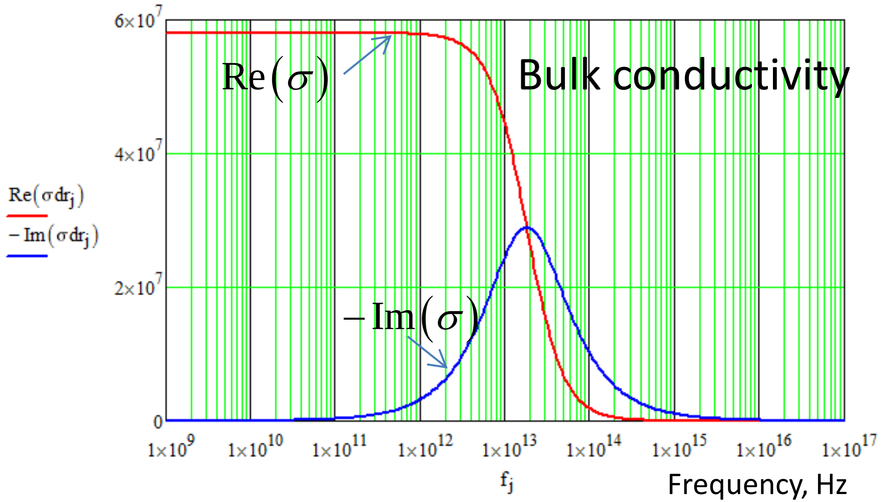


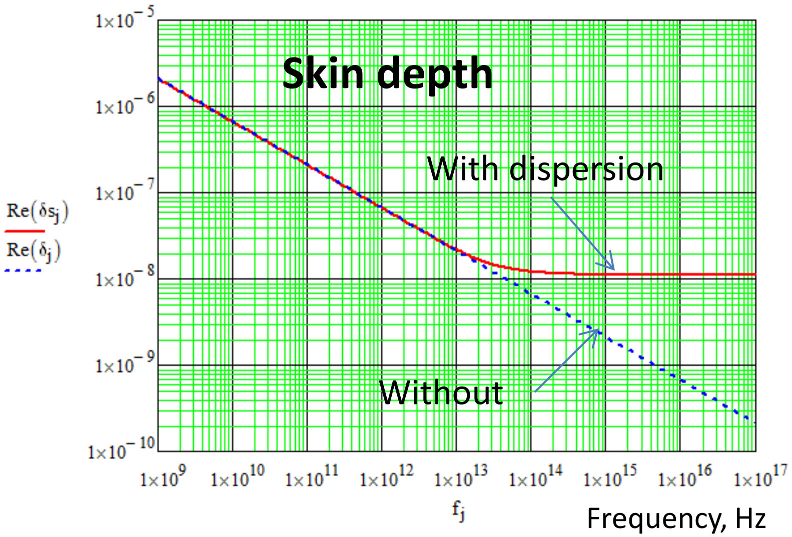
12 Gb/s
Simulated

Breaking the skin: Drude model

$J_{free} = \sigma \bar{E}$ Bulk conductivity with temporal dispersion: $\sigma(f) = \dfrac{\sigma_0}{1 + i\, f / f_r}$

Relaxation frequency for copper is about ~18 THz, relaxation time ~9 fs





Good introduction: C.T.A. Johnk, Engineering electromagnetic – fields and waves, 1975

Outstanding questions

- How to identify broadband dielectric model?
- How to identify conductor roughness parameters?
- How to separate dielectric, conductor and conductor roughness models?
- Can roughness losses be accounted in dielectric model?
- Which roughness model is more accurate?
- Other questions?...

Find some answers are in Simberian app notes at www.simberian.com

PCB materials and model identification techniques

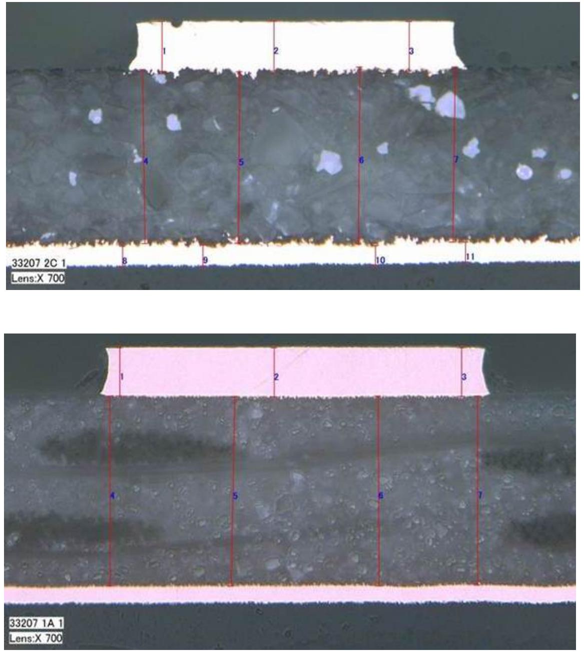
- Composition of PCB Dielectric Materials
- Overview of the material property identification techniques
- Identification with GMS-parameters

Presented by Chudy Nwachukwu, Isola

Composition of PCB Dielectrics

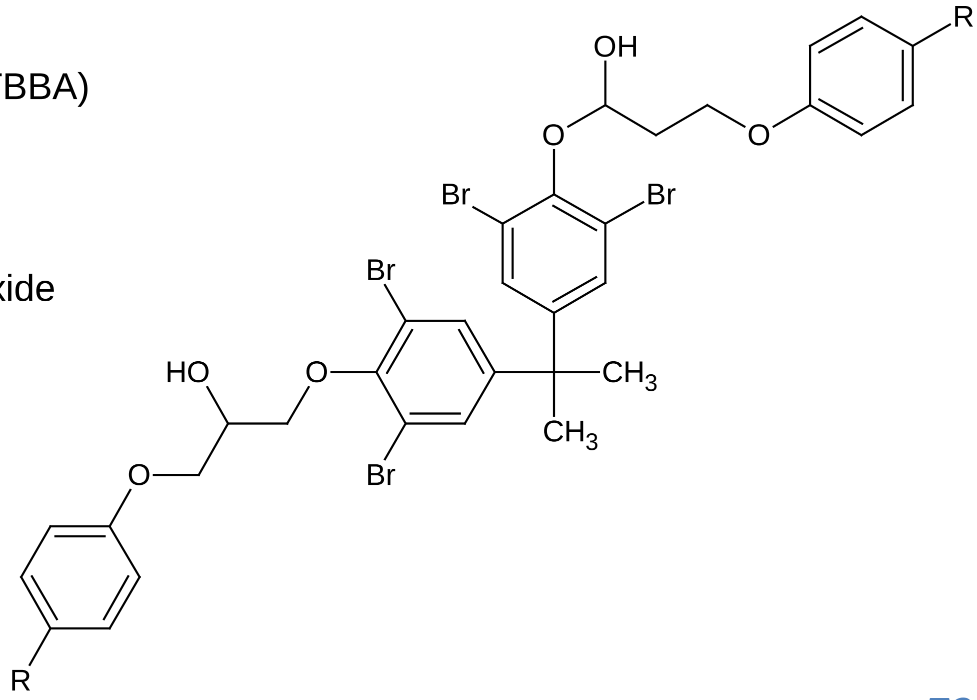
- Just to name a few…
  - Flex Polyimide
  - Flex Fluoropolymer / Polyimide composite
  - Liquid Crystal Polymer (LCP)
  - Ceramic Filled Polymer on Fiberglass
  - Glass Microfiber Reinforced PTFE
  - Micro-dispersed Ceramic in PTFE composite w/fiberglass
  - Ceramic filled PTFE on woven fiberglass
  - PTFE on woven fiberglass
  - Ceramic-filled Epoxy on fiberglass
  - High Tg Thermoset resin w/fiberglass reinforcement

Cross-section Images

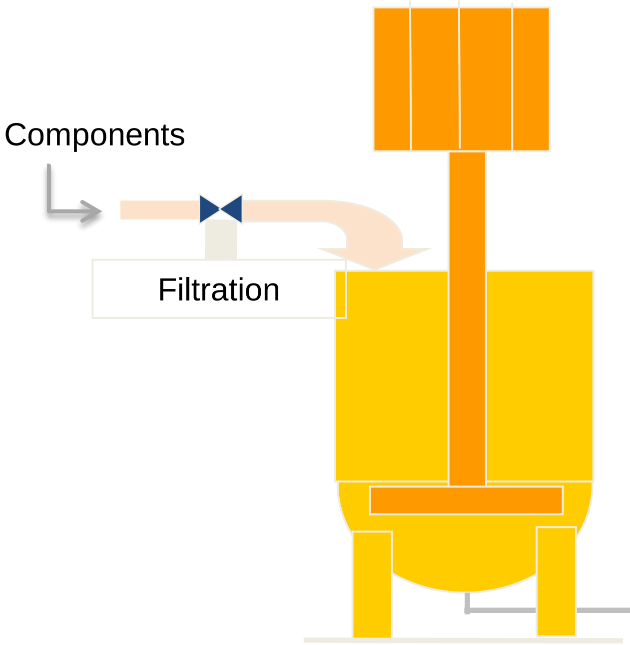


Resin Chemistry – What's in it?

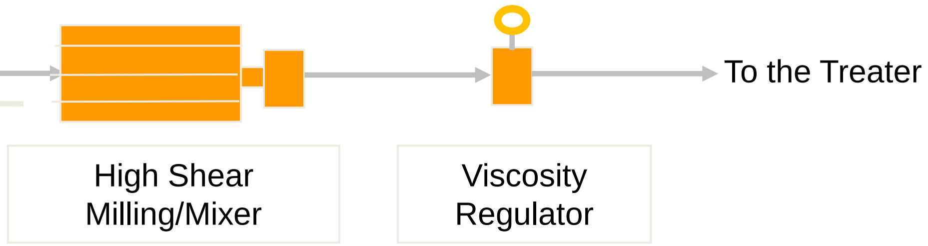
- Flame Retardants
  - Brominated – Tetrabromobisphenol A (TBBA)
  - Low Halogen / Halogen Free
    - Phosphorous and Nitrogen based
    - Aluminum and Magnesium hydroxide
- Filler components
  - Aluminum Silicate
  - Talc
  - Rubber
  - Glass microspheres
  - Boron Nitride



Compounding / Mixing Process



- Woven Filter – removes contaminants in liquid components.
- Magnetic Filter – removes ferrous contaminates.
- High Shear Milling/Mixing – ensures homogenous mixing of all components (solvent, catalysts, hardeners).
- Viscosity measurement and feedback

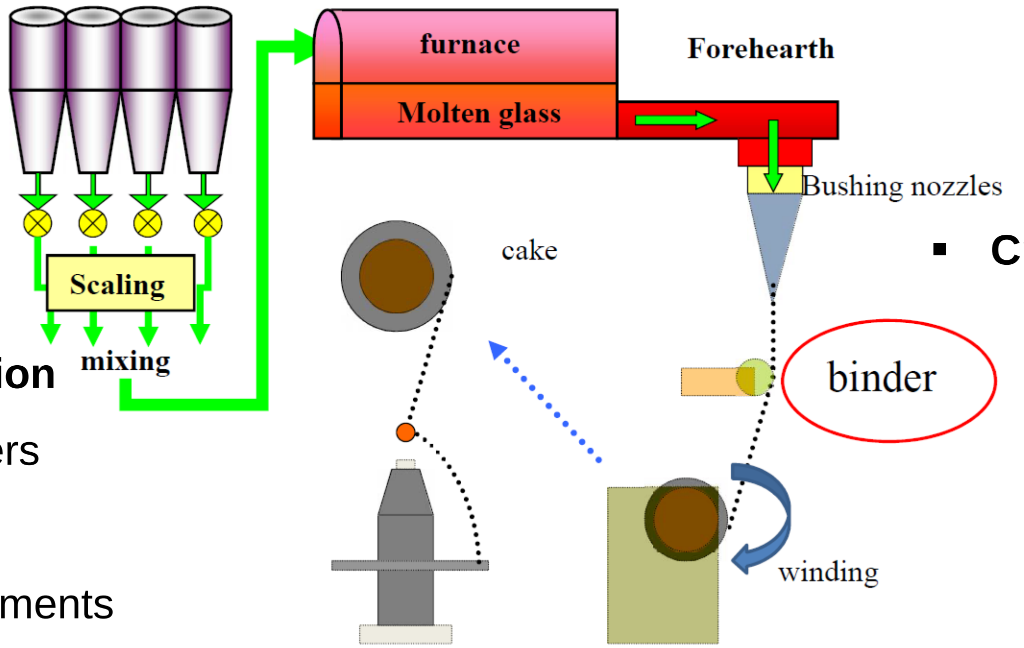


Composition – Fiberglass Weave

	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%

Property	Unit	E-Glass	Low DK Glass	Low CTE Glass
DK	Freq (1 GHz)	6.8	4.8	5.4
DF	Freq (1 GHz)	0.0035	0.0015	0.0043
Tensile Modulus	Gpa	75	64	86
Thermal Expansion	ppm/ºC	5.6	3.3	2.8

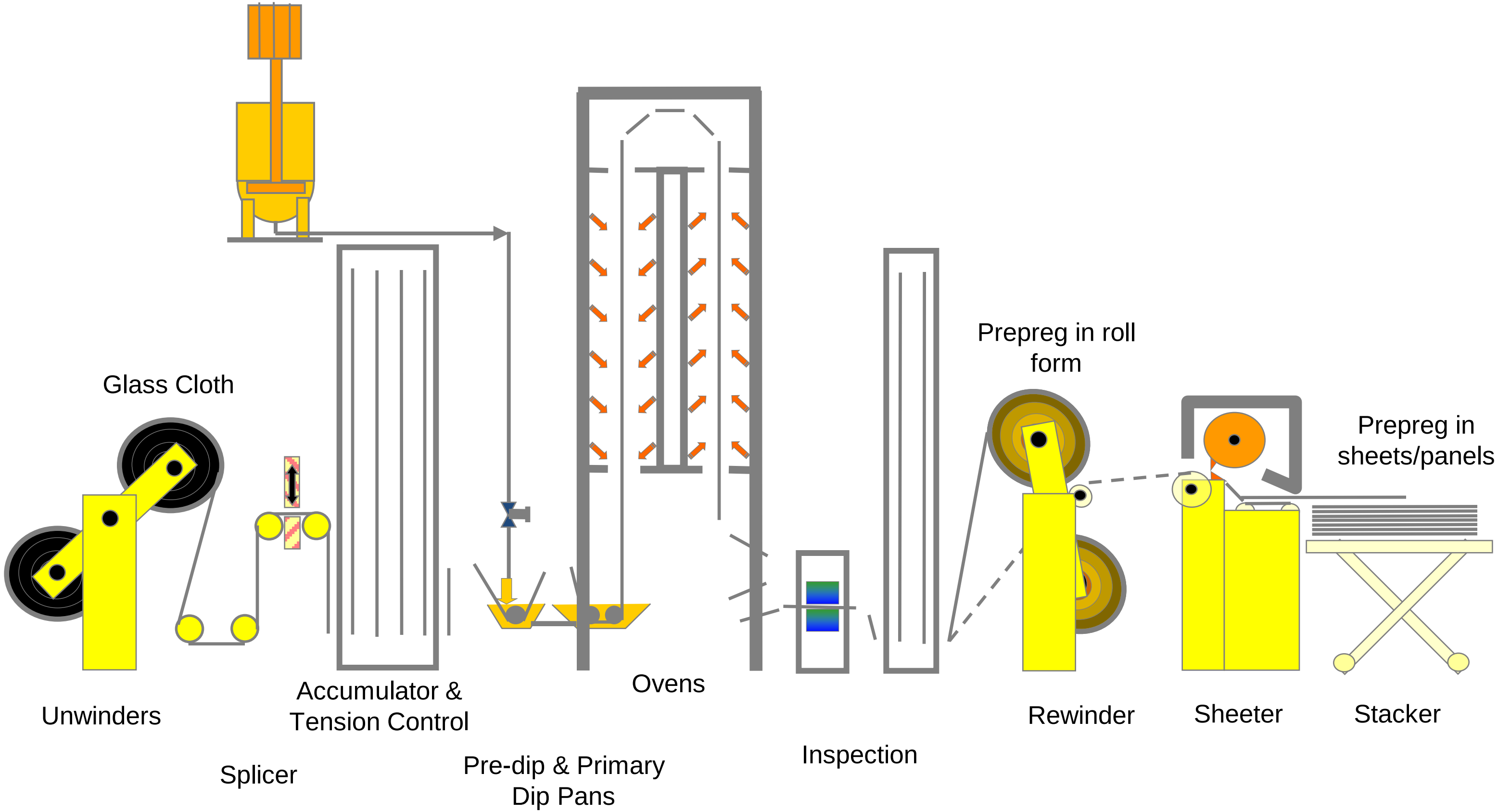
Fabric Manufacturing Process



- **Quality Inspection**
  - Hollow Fibers
  - Yarn twist
  - Broken Filaments
  - Impurities

- **Critical Measures**
  - Woven glass styles
  - Electrical properties
  - PCB Process-ability
  - Cost & Availability

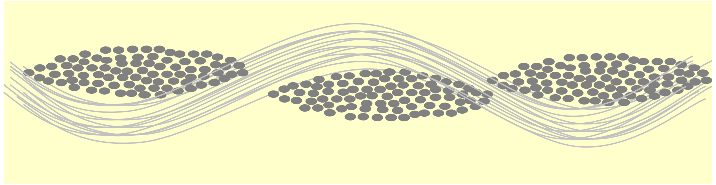
B-Stage Treating



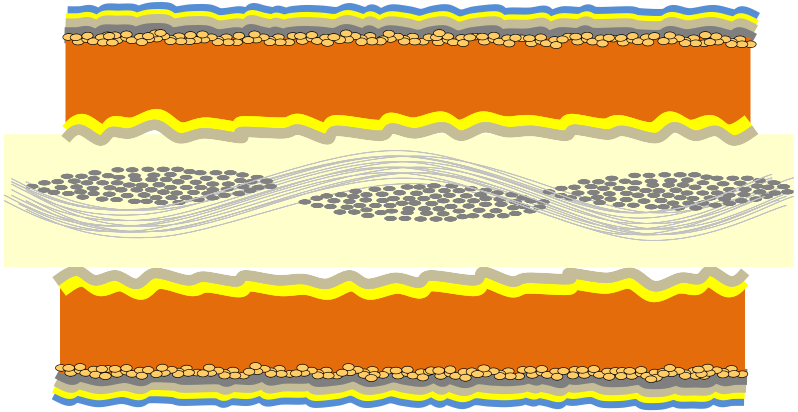
Material Identification Techniques

- 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

Characterizing "Effective" Permittivity

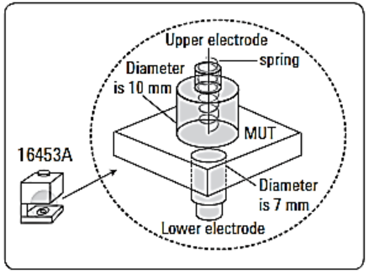


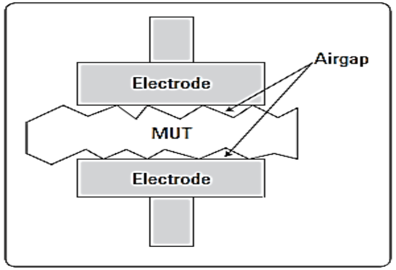
- Unclad Dielectric Testing
  - Capacitance Test Method
  - Coupled Stripline "Berezkin"
  - Resonant Cavity Structures
  - Free-space Transmission



- Copper-clad Dielectric Testing
  - Short Pulse Propagation (SPP)
  - Generalized Modal S-Parameter (GMSP)

Capacitance Test Method (1 MHz – 1 GHz)



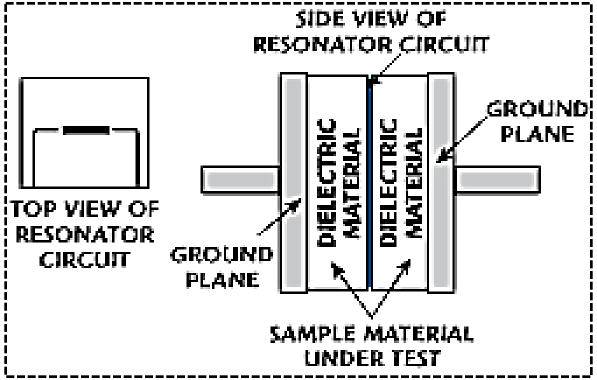


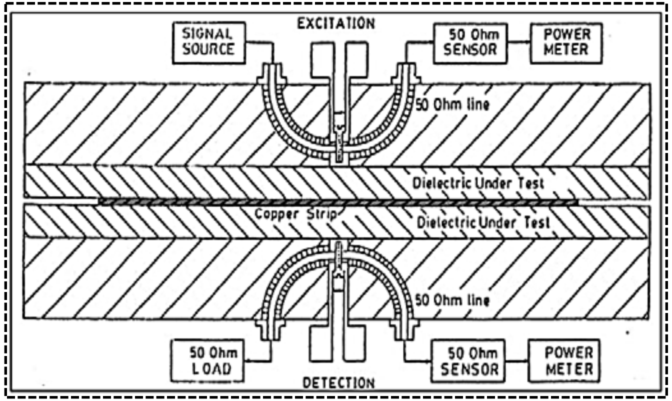
- Parallel Plate Fixture
  - Admittance is modeled as parallel “G” || “C”
  - Capacitance is modeled as parallel plate “C”
    - Effect of fringing fields are neglected.
  - Presence of dielectric sample changes impedance of the parallel plate capacitor.
  - Accuracy for the test method is critically dependent on thickness uniformity of the dielectric sample.

Coupled Stripline Fixture (1 GHz – 22 GHz)

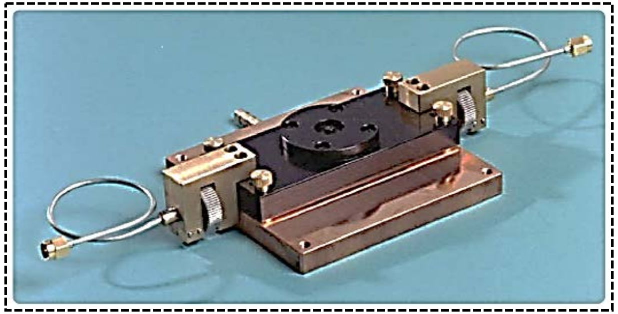
- Clamped Resonator Circuit
  - Resonator microstrip circuit is printed on dielectric material with known permittivity (eg: PTFE), and can introduce air gaps.
- Berezkin Test Method
  - The resonator in this case is a copper strip.
  - $$Relative\ Permittivity\ (\varepsilon_r) = \left(\frac{c}{2.54 f_s (L+\Delta L)}\right)^2$$
  - $$Loss\ Tangent\ (\tan\delta) = \frac{1}{Q_s} - \frac{1}{Q_c},$$

$L = physical\ length\ of\ resonator\ copper\ strip\ (meters)$
$\Delta L = effective\ increase\ in\ resonator\ length\ from\ fringing\ field\ (meters);$
$Q_s = Quality\ Factor\ of\ the\ Cavity\ with\ Sample$
$Q_c = Quality\ Factor\ of\ the\ Unloaded\ Cavity.$

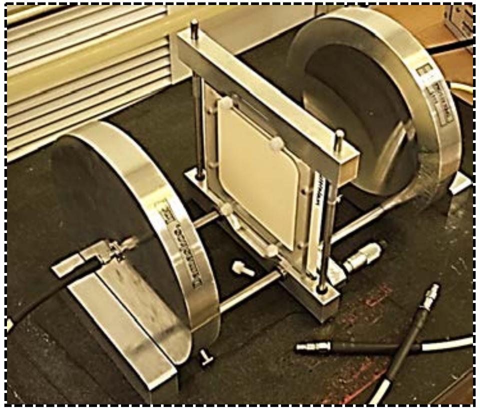




Resonant Cavity Methods (3 GHz - 40 GHz)



- Split Post Cavity
  - Each cavity is designed with a specific Q factor and measures in-plane dielectric permittivity.
  - Discrete frequency measurements (example: 3, 7, 10, 15.5 & 22.5 GHz).



Courtesy of Damaskos Inc.

- Open Resonator

$$Loss\ Tangent\ (\tan\delta) = \left(\frac{\varepsilon_r''}{\varepsilon_r'}\right) = \frac{1}{Q}$$

$$Real\ Relative\ Permittivity\ (\varepsilon_r') = \frac{V_c(f_c - f_s)}{2V_s f_s} V_c + 1,$$

$$Quality\ Factor\ of\ Unloaded\ Cavity\ (Q_c) = \frac{f_c}{\Delta f}$$

$$Quality\ Factor\ of\ Cavity\ with\ Sample\ (Q_s) = \frac{f_s}{\Delta f'},$$

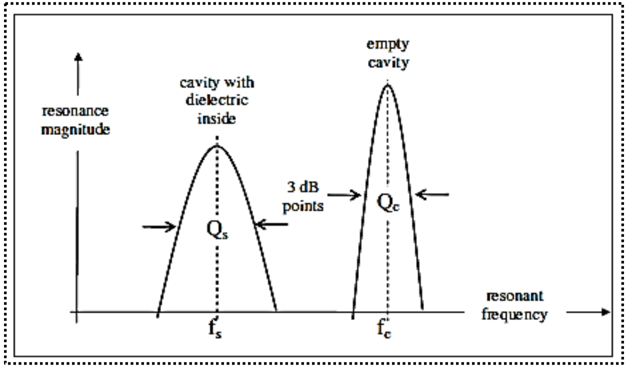
$$V_c = Volume\ of\ Cavity,$$

$$V_s = Volume\ of\ Sample,$$

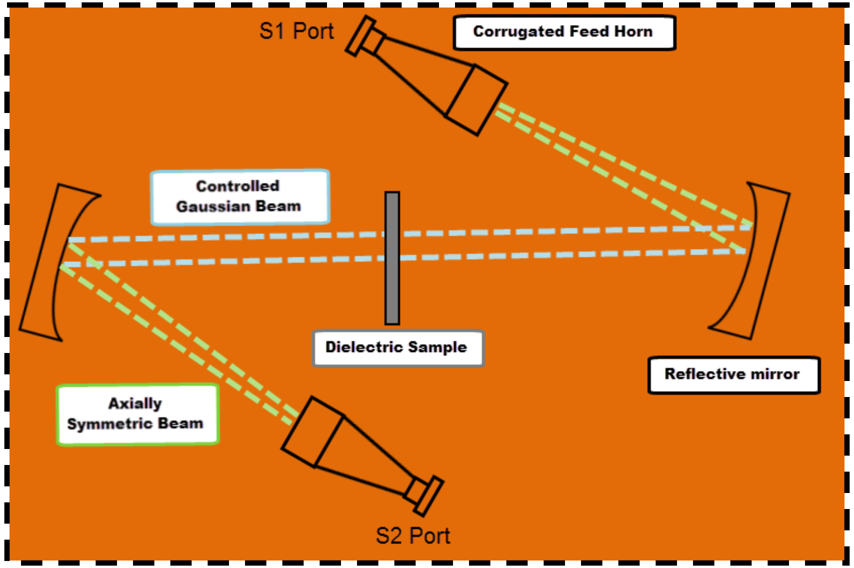
$$f_c = resonant\ frequency\ of\ unloaded\ the\ cavity\ (Hz),$$

$$f_s = resonant\ frequency\ of\ the\ cavity\ with\ sampe\ (Hz),$$

$$\Delta f = f_{upper\ half\ power\ cutoff\ (3\ dB)} - f_{lower\ half\ power\ cutoff\ (3\ dB)}.$$



Free-space Quasi Optical (18 GHz – 110 GHz)



- Measurement Steps:
  - Isolation – blocking the beam propagation path with a metal plate to account for diffraction effects residual reflections.
  - Reference – measuring through transmission (S21) parameters without material under test to account for the permittivity contributions of air.
  - Time domain gating – Mathematical elimination of multipath signals using the sum of distance between horn antennas and dielectric sample (eg: +/- 2ns).

Sample data from Unclad Dielectric testing

Core Constructions	Resin Content (%)	Thickness (inch)	Thickness (mm)	Dielectric Constant(DK) / Dissipation Factor(DF) 100 MHz	500 MHz	1.0 GHz	2.0 GHz	5.0 GHz	10.0 GHz	15.0 GHz	20.0 GHz
2x3313	68.0	0.0100	0.2540	3.55 0.0025	3.55 0.0026	3.55 0.0028	3.54 0.0029	3.54 0.0030	3.54 0.0031	3.54 0.0031	3.54 0.0031
Prepreg Constructions	**Resin Content (%)**	**Thickness (inch)**	**Thickness (mm)**	**Dielectric Constant(DK) / Dissipation Factor(DF) 100 MHz**	**500 MHz**	**1.0 GHz**	**2.0 GHz**	**5.0 GHz**	**10.0 GHz**	**15.0 GHz**	**20.0 GHz**
2116	60.5	0.0051	0.1285	3.65 0.0027	3.65 0.0029	3.64 0.0030	3.64 0.0031	3.64 0.0032	3.64 0.0033	3.64 0.0033	3.64 0.0033
2116	66.5	0.0061	0.1555	3.57 0.0025	3.57 0.0027	3.56 0.0029	3.56 0.0029	3.56 0.0031	3.56 0.0031	3.56 0.0031	3.56 0.0031

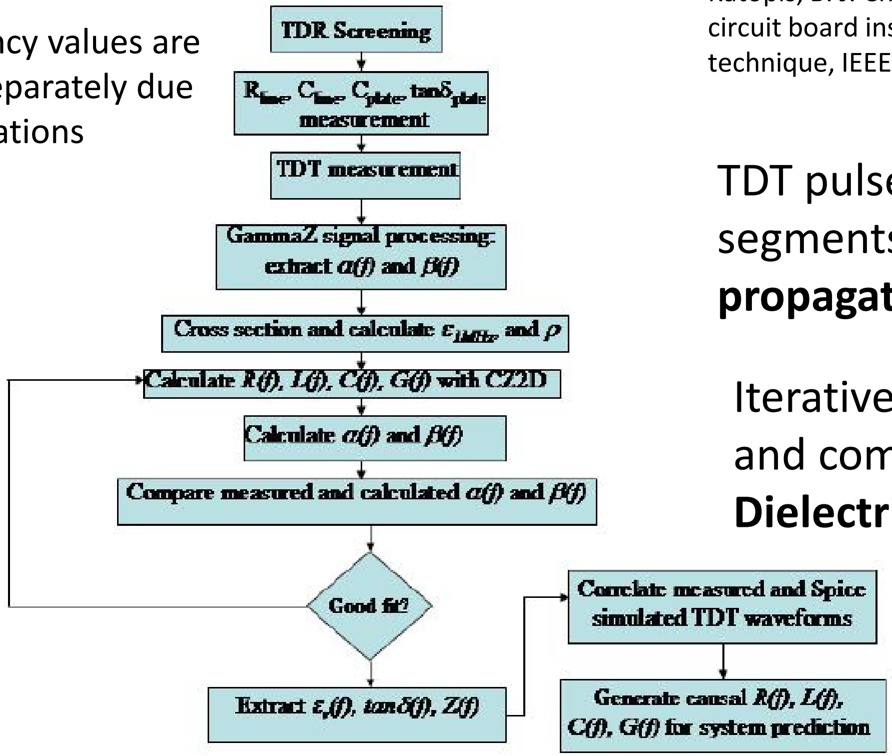
Core Constructions	Resin Content (%)	Thickness (inch)	Thickness (mm)	Dielectric Constant(DK) / Dissipation Factor(DF) 100 MHz	500 MHz	1.0 GHz	2.0 GHz	5.0 GHz	10.0 GHz	15.0 GHz	20.0 GHz
2x3313	62.0	0.0100	0.2540	3.34 0.0027	3.34 0.0027	3.34 0.0027	3.34 0.0027	3.34 0.0027	3.34 0.0027	3.34 0.0027	3.34 0.0027
Prepreg Constructions	**Resin Content (%)**	**Thickness (inch)**	**Thickness (mm)**	**Dielectric Constant(DK) / Dissipation Factor(DF) 100 MHz**	**500 MHz**	**1.0 GHz**	**2.0 GHz**	**5.0 GHz**	**10.0 GHz**	**15.0 GHz**	**20.0 GHz**
1086	65.0	0.0036	0.0914	3.27 0.0025	3.27 0.0025	3.27 0.0025	3.27 0.0025	3.27 0.0025	3.27 0.0025	3.27 0.0025	3.27 0.0025

Short Pulse Propagation (SPP)

Step-by-Step Procedure for Short-Pulse-Propagation-Based Complex Permittivity Extraction

The following flowchart summarizes the extraction process:

Low frequency values are identified separately due to TDT limitations

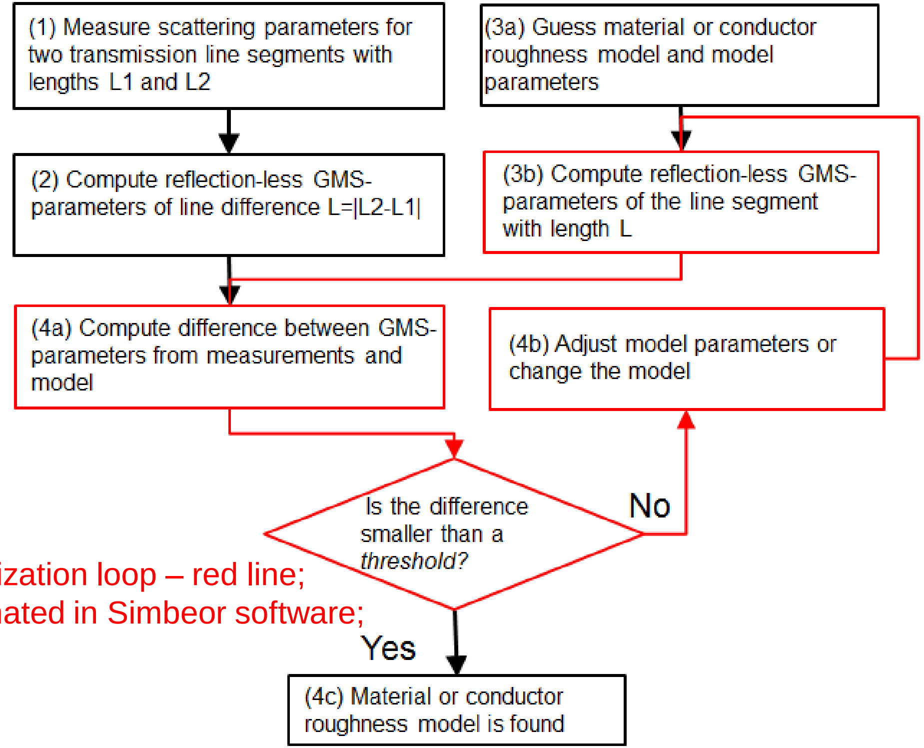


A. Deutsch, T.-M. Winkel, G. V. Kopcsay, C. W. Surovic, B. J. Rubin, G. A. Katopis, B. J. Chamberlin, R. S. Krabbenhoft, Extraction of and for printed circuit board insulators up to 30 GHz using the short-pulse propagation technique, IEEE Trans. on Adv. Packaging, vol. 28, 2005, N 1, p. 4-12.

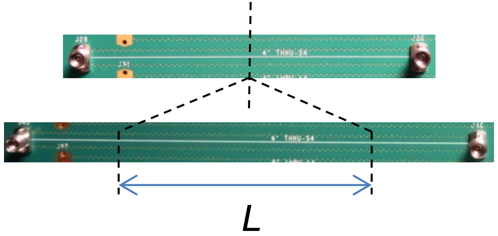
TDT pulse responses of 2 line segments -> **Gamma (complex propagation constant)**

Iterative matching of measured and computed Gamma -> **Dielectric Model**

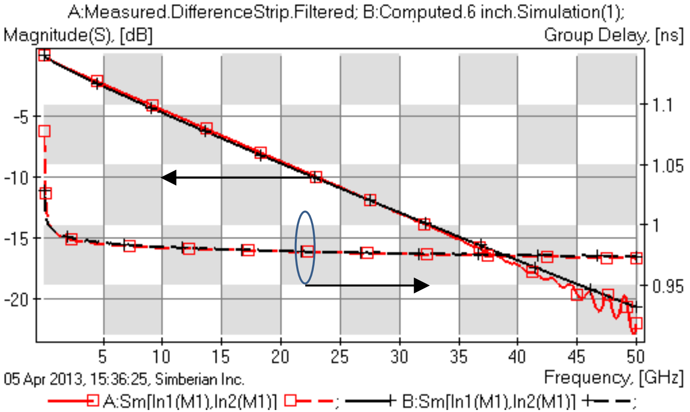
GMS-Parameters



Optimization loop – red line;
Automated in Simbeor software;



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



See details at: Y. Shlepnev, A. Neves, T. Dagostino, S. McMorrow, Practical identification of dispersive dielectric models with generalized modal S-parameters for analysis of interconnects in 6-100 Gb/s applications, DesignCon 2009, available at www.simberian.com

Y. Shlepnev, PCB and package design up to 50 GHz: Identifying dielectric and conductor roughness models, The PCB Design Magazine, February 2014, p. 12-28.

Comparison of GMS and SPP techniques

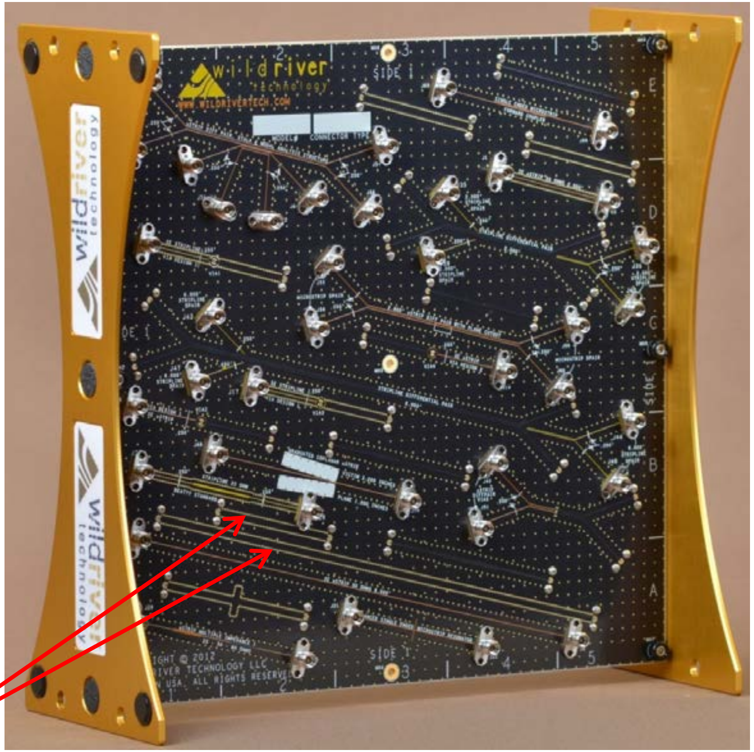
- Commonalities:
  - Same test fixture can be used (2 segments)
  - Numerical transmission line model is used in both techniques
  - Resistance measurement at DC can be used to identify bulk resistivity in both techniques
- Differences:
  - Measured S-parameters are used to extract GMS-parameters (VNA), but short pulse TDT measurements are used in SPP technique to extract complex propagation constants
  - SPP uses measurements at 1 MHz to have low frequency asymptotes of dielectric constant - not needed with the GMS-parameters if S-parameters are measured starting from sufficiently low frequency
- If S-parameters are used to extract Gamma from GMS-parameters, such technique may be considered as a variation of SPP methodology – "SPP Light"
  - Identification with GMS-parameters and "SPP Light" should produce nearly identical results if **same t-line model is used**

Details in Y. Shlepnev, Broadband material model identification with GMS-parameters, EPEPS 2015.

Example of identification

- Project(1)
  - Materials: T=20["C],...
    - "1OZ_COPPER", RR=1
    - "PLATED_1OZ_COPPER", RR=1
    - "Air"
    - "Solder_Mask", Dk=3.85, LT=0.02, PLM=WD, Dk(0)=4.64, Dk(inf)=3.4
    - "FR408HR_SL", Dk=3.66, LT=0.0117, PLM=WD, Dk(0)=4.1, Dk(inf)=3.41
    - "FR408HR_MS", Dk=3.66, LT=0.0117, PLM=WD, Dk(0)=4.1, Dk(inf)=3.41
  - StackUp: LU=[mil], NL=8, T=93.6[mil], CSM=("Solder_Mask", 2.5[mil])
    - 1| Signal: "TOP", T=2.25, Ins="Air", Cond="PLATED_1OZ_COPPER"
    - 2| Medium: T=7.55, Ins="FR408HR_MS", DIE_003
    - 3| Plane: "PLANE_2", Cond="1OZ_COPPER", T=1.3, Ins="FR408HR_SL"
    - 4| Medium: T=12, Ins="FR408HR_SL", DIE_005
    - 5| Signal: "SIGNAL_3", T=1.3, Ins="FR408HR_SL", Cond="1OZ_COPPER"
    - 6| Medium: T=10.6, Ins="FR408HR_SL", DIE_007
    - 7| Plane: "PLANE_4", Cond="1OZ_COPPER", T=1.3, Ins="FR408HR_SL"
    - 8| Medium: T=21, Ins="FR408HR_SL", DIE_009
    - 9| Plane: "PLANE_5", Cond="1OZ_COPPER", T=1.3, Ins="FR408HR_SL"
    - 10| Medium: T=10.6, Ins="FR408HR_SL", DIE_011
    - 11| Signal: "SIGNAL_6", T=1.3, Ins="FR408HR_SL", Cond="1OZ_COPPER"
    - 12| Medium: T=12, Ins="FR408HR_SL", DIE_013
    - 13| Plane: "PLANE_7", Cond="1OZ_COPPER", T=1.3, Ins="FR408HR_SL"
    - 14| Medium: T=7.55, Ins="FR408HR_MS", DIE_015
    - 15| Signal: "BOTTOM", T=2.25, Ins="Air", Cond="PLATED_1OZ_COPPER"

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



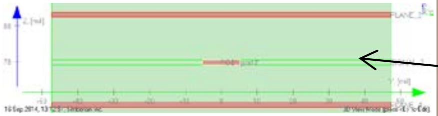
From Isola FR408HR specifications

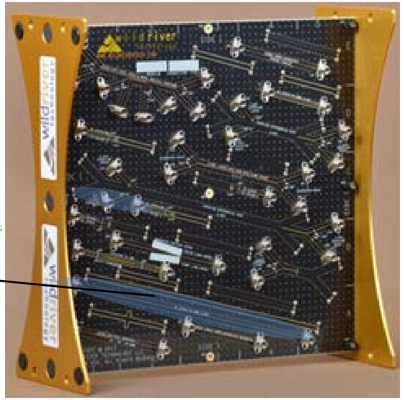
Dk, Permittivity (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A)	3.69
	B. @ 1 GHz (HP4291A)	3.66
	C. @ 2 GHz (Bereskin Stripline)	3.67
	D. @ 5 GHz (Bereskin Stripline)	3.66
	E. @ 10 GHz (Bereskin Stripline)	3.65
Df, Loss Tangent (Laminate & prepreg as laminated) Tested at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

10.5 (11) mil strip lines; microstrips 13.5 (14.5) mil; Use measured S-parameters for 2 segments (2 inch and 8 inch); No data for conductor roughness model;

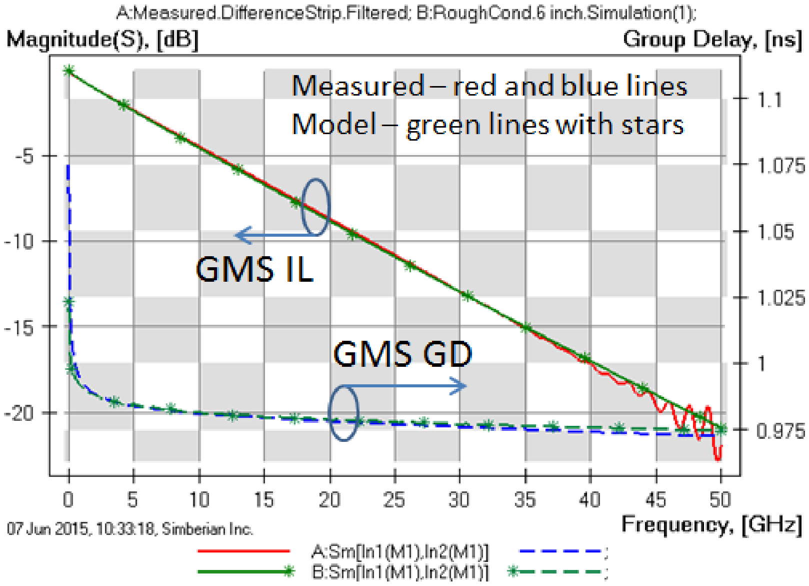
Identification with GMS and SPP

- 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

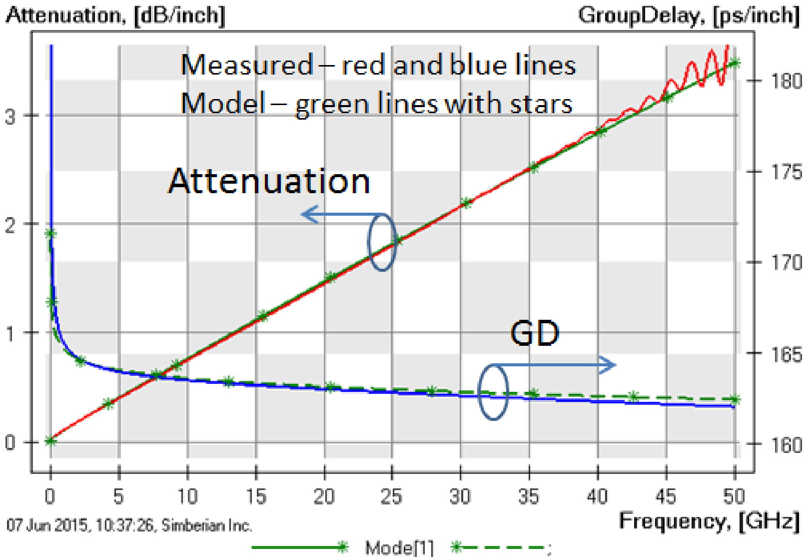




GMS-parameters



Gamma (SPP Light)

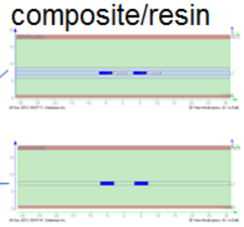


Models are usable above 50 GHz!

Models identified with GMS-parameters

- Wideband Debye (WD) with dielectric and roughness losses:

Model Parameters / Board Types	WD Dielectric Constant @ 1 GHz	WD Loss Tangent @ 1 GHz
FR408HR with RTF copper, inhomogeneous	3.95/3.5 (3.66)	0.01/0.012 (0.0117)
FR408HR with RTF copper	3.76 (3.66)	0.012 (0.0117)
Megtron-6 with HVLP copper	3.69 (3.6)	0.0065 (0.002)
Megtron-6 with RTF copper	3.75 (3.6)	0.0083 (0.002)
Nelco N4000-13EPSI with RTF copper	3.425 (3.4)	0.011 (0.008)



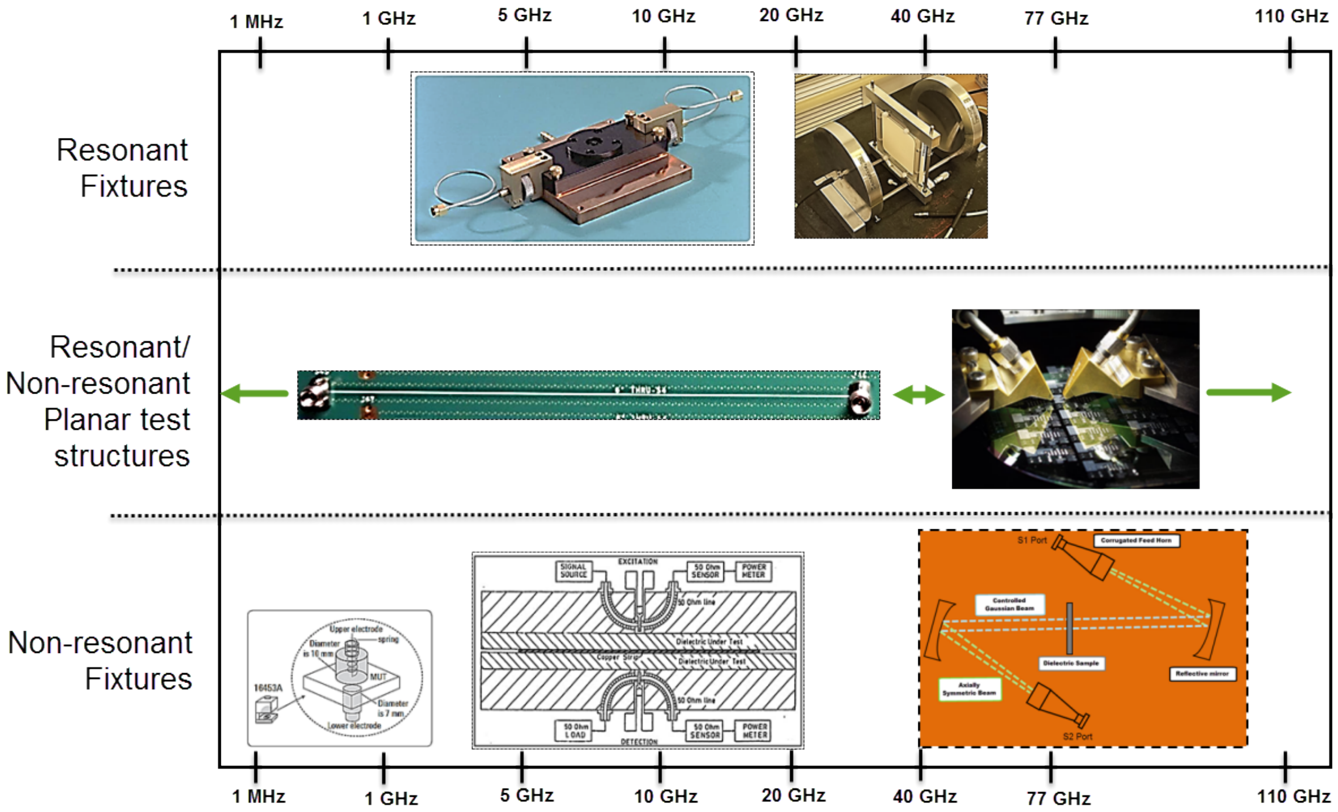
- **Wideband Debye (WD) dielectric with loss tangent from specs and Modified Hammerstad model (MH) for conductor roughness losses:**

Model Parameters / Board Types	WD Dielectric Constant @ 1 GHz	WD Loss Tangent @ 1 GHz	MH Roughness (SR, rms) (um)	MH Roughness Factor (RF)
Megtron-6 with HVLP copper	3.64 (3.6)	0.002	0.38	3.15
Megtron-6 with RTF copper	3.72 (3.6)	0.002	0.37	4
Nelco N4000-13EPSI with RTF copper	3.425 (3.4)	0.008	0.49	2.3

Values from specifications are provided in brackets for comparison

Data from W. Beyene et al., Lessons learned: How to make predictable PCB interconnects for data rates of 50 Gbps and beyond, DesignCon 2014.

Implication of Material Characterization Methods

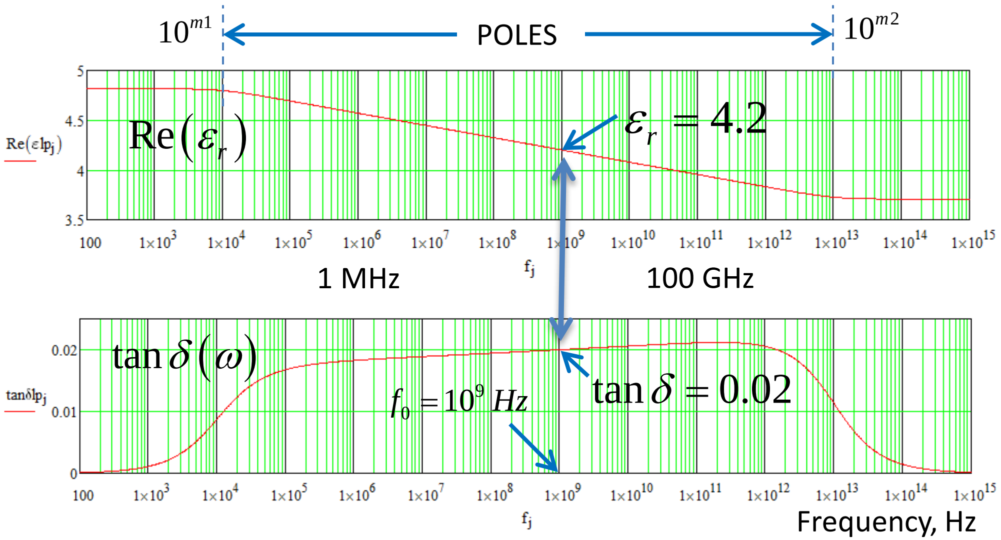


Practical PCB Material Identification Techniques

Presented by Scott McMorrow, Samtec-Teraspeed

Wideband Debye model properties

Dk and LT at one point is sufficient to define the model!



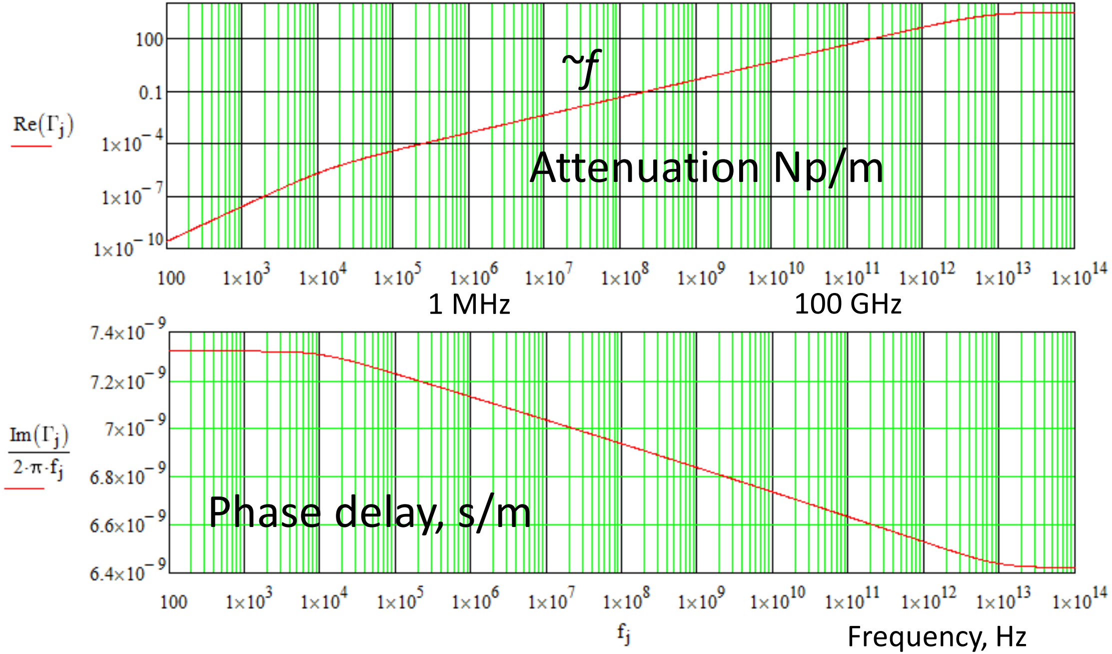
Djordjevic-Sarkar model assumptions

- Dielectric properties represent the behavior of two poles
  - **Low frequency pole (kHz)**
  - **High frequency pole (THz)**
  - **Well outside the frequency band that we want to characterize for data transmission.**

Djordjevic-Sarkar model advantages

- Describes most materials used in PCB/Package/Cable
- Simple to adjust

Plane wave in Wideband Debye dielectric



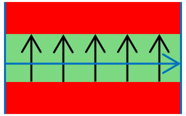
Both attenuation and phase delay provide the same information regarding the dielectric loss.

Slope of the phase delay is dependent upon loss tangent.

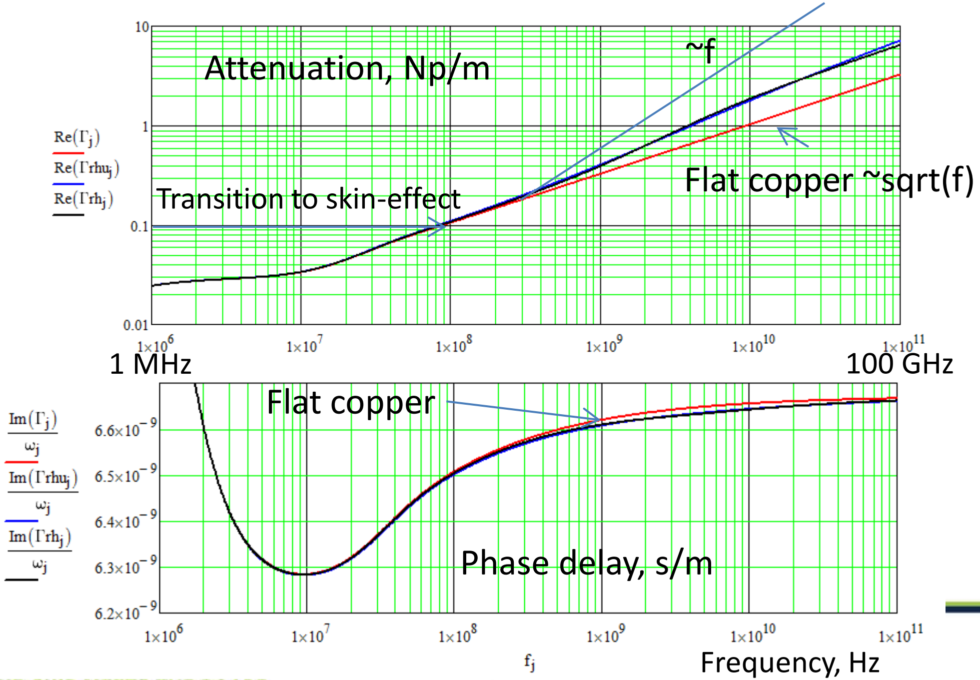
We can use this to identify dielectric, since there is a fairly sensitive slope.

Practical implication of rough conductors

"Oliner's waveguide – ideal to investigate RCCs



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



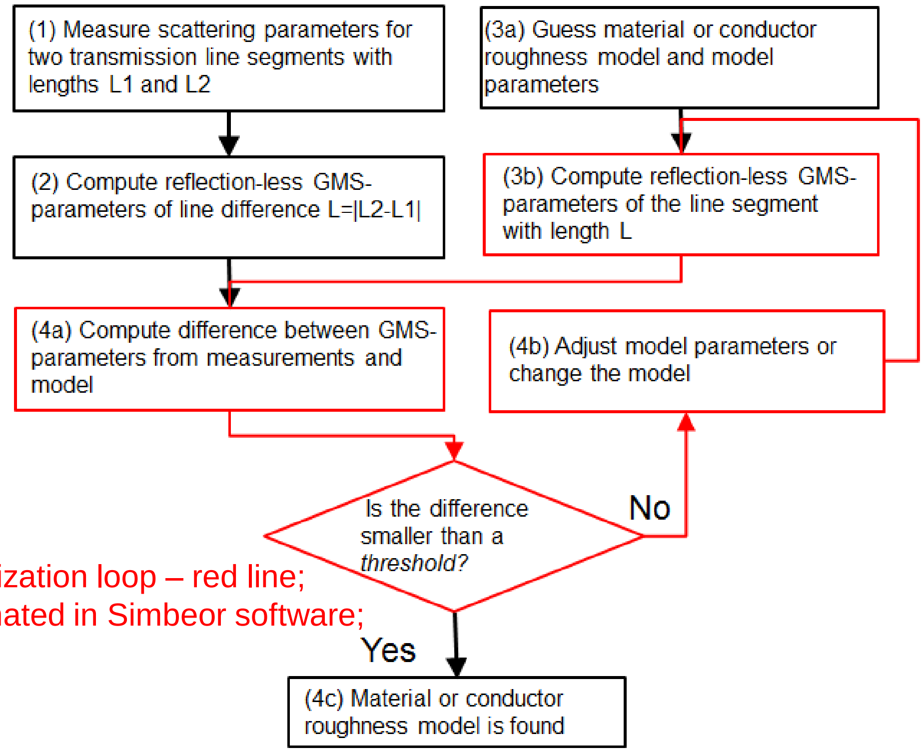
Roughness has a large impact on loss.

Roughness has a very small impact on phase delay.

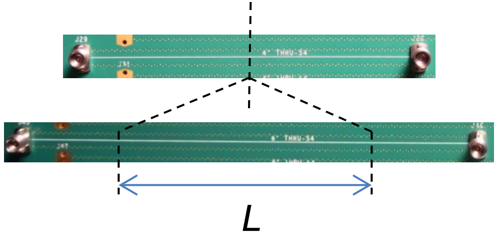
We can use this in the final tuning of overall interconnect loss.

We can neglect roughness for the purpose of identifying Dk and Df.

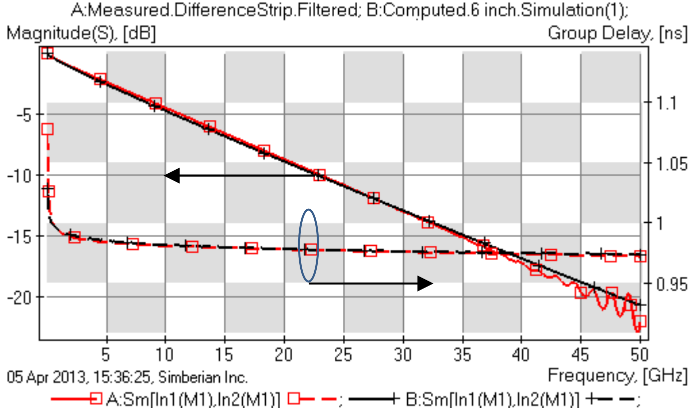
GMS-Parameters



Optimization loop – red line;
Automated in Simbeor software;



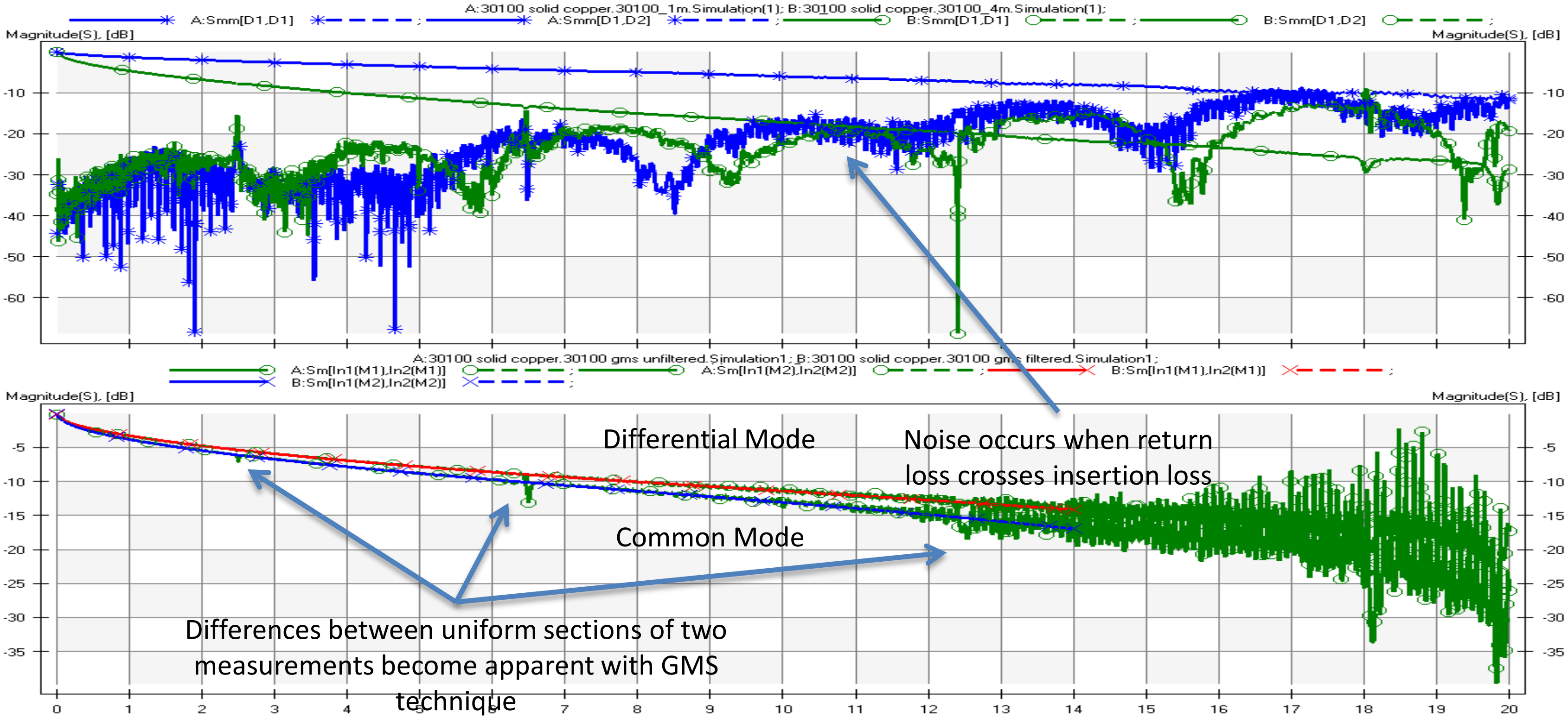
$$GMSc = \begin{bmatrix} 0 & \exp(-\Gamma \cdot L) \\ \exp(-\Gamma \cdot L) & 0 \end{bmatrix}$$



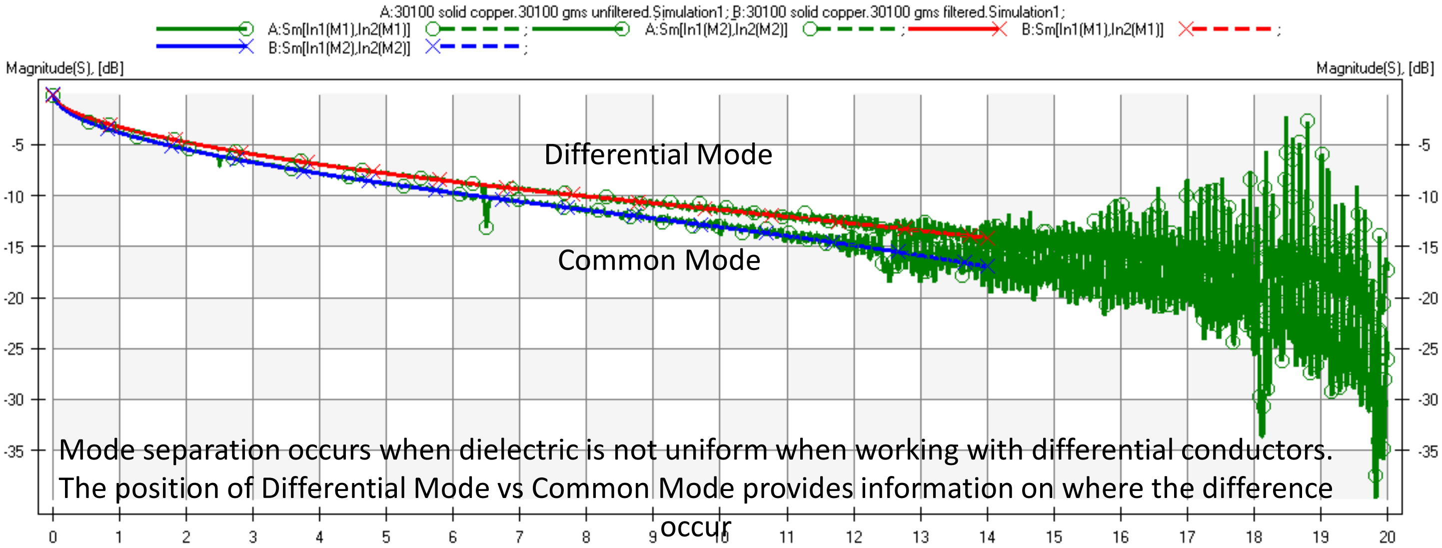
See details at: Y. Shlepnev, A. Neves, T. Dagostino, S. McMorrow, Practical identification of dispersive dielectric models with generalized modal S-parameters for analysis of interconnects in 6-100 Gb/s applications, DesignCon 2009, available at www.simberian.com

Y. Shlepnev, PCB and package design up to 50 GHz: Identifying dielectric and conductor roughness models, The PCB Design Magazine, February 2014, p. 12-28.

Raw vs. GMS

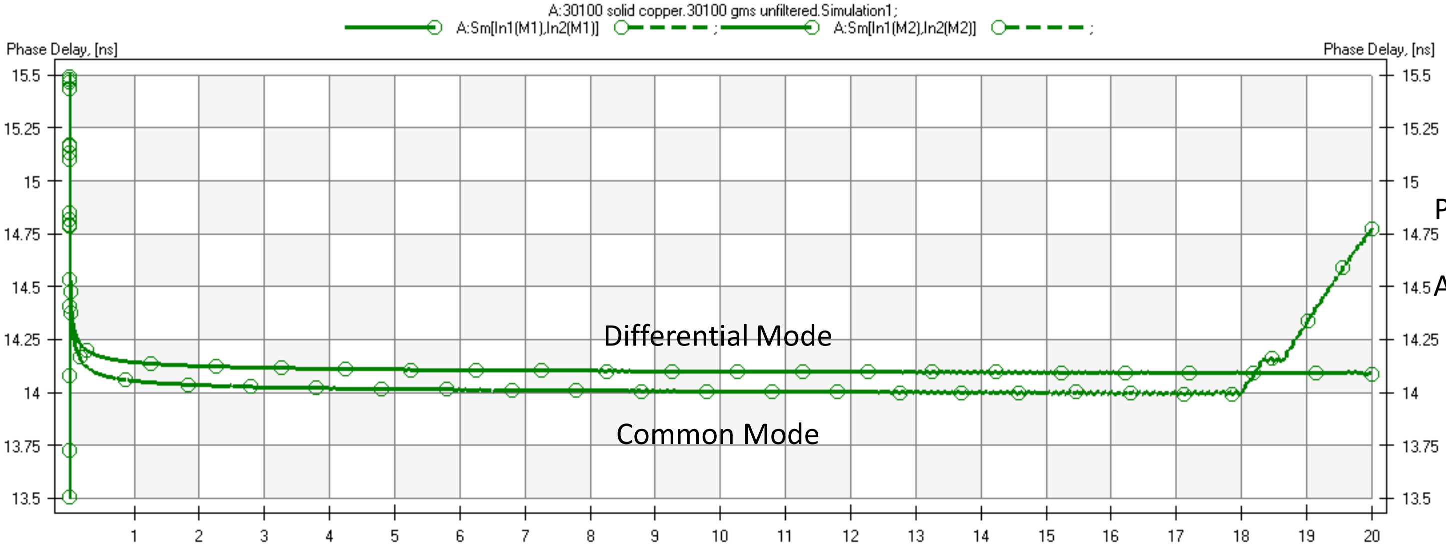

A:30100 solid copper.30100_1m.Simulation(1); B:30100 solid copper.30100_4m.Simulation(1);
A:Smm[D1,D1]
A:Smm[D1,D2]
B:Smm[D1,D1]
B:Smm[D1,D2]
Magnitude(S), [dB]
-10
-20
-30
-40
-50
-60
A:30100 solid copper.30100 gms unfiltered.Simulation1; B:30100 solid copper.30100 gms filtered.Simulation1;
A:Sm[In1(M1),In2(M1)]
A:Sm[In1(M2),In2(M2)]
B:Sm[In1(M1),In2(M1)]
B:Sm[In1(M2),In2(M2)]
Magnitude(S), [dB]
-5
-10
-15
-20
-25
-30
-35
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Differential Mode
Noise occurs when return loss crosses insertion loss
Common Mode
Differences between uniform sections of two measurements become apparent with GMS technique

Filtered vs. Unfiltered Attenuation



Mode separation occurs when dielectric is not uniform when working with differential conductors. The position of Differential Mode vs Common Mode provides information on where the difference occur

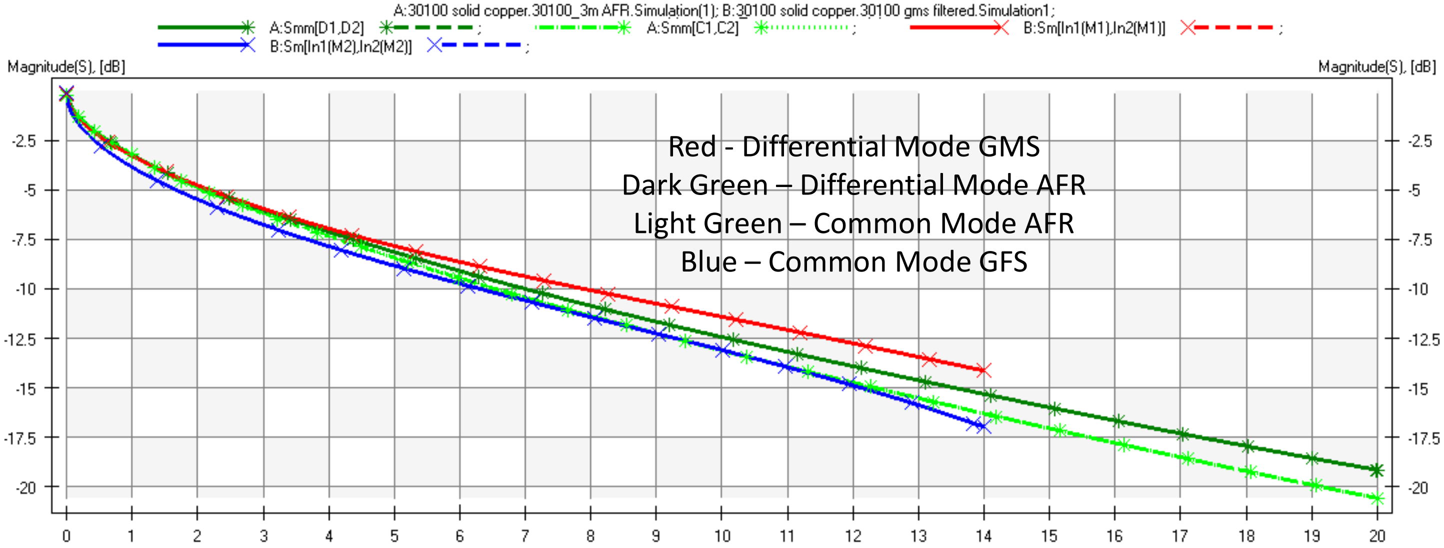
Unfiltered Phase Delay



Phase Delay is always much cleaner than Attenuation or Group Delay

Mode separation occurs when dielectric is not uniform when working with differential conductors. The position of Differential Mode vs Common Mode provides information on where the difference occurs. Faster Common Mode indicates common mode fields are exposed to a lower Dk dielectric.

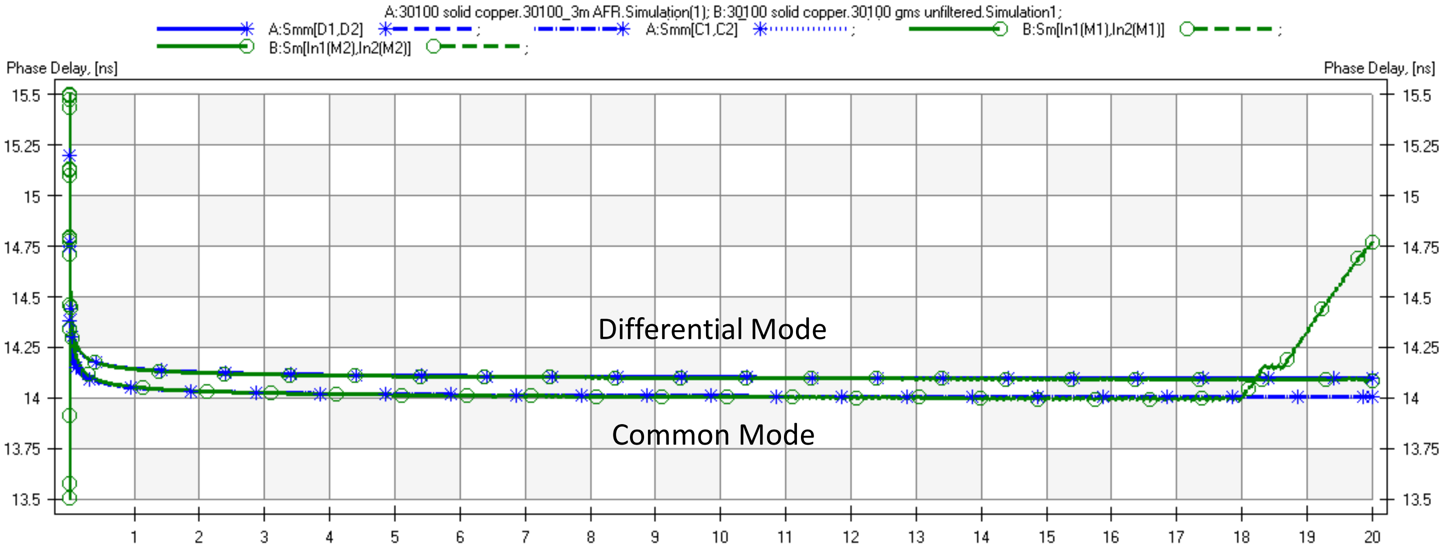
Comparison of GMS and AFR



GMS-parameter method is designed to remove losses due to impedance mismatch by normalizing to a perfectly matched condition at every frequency point.

Other methods are designed to create faithful models of the actual delta-length interconnect. This may introduce additional losses as mismatch increases.

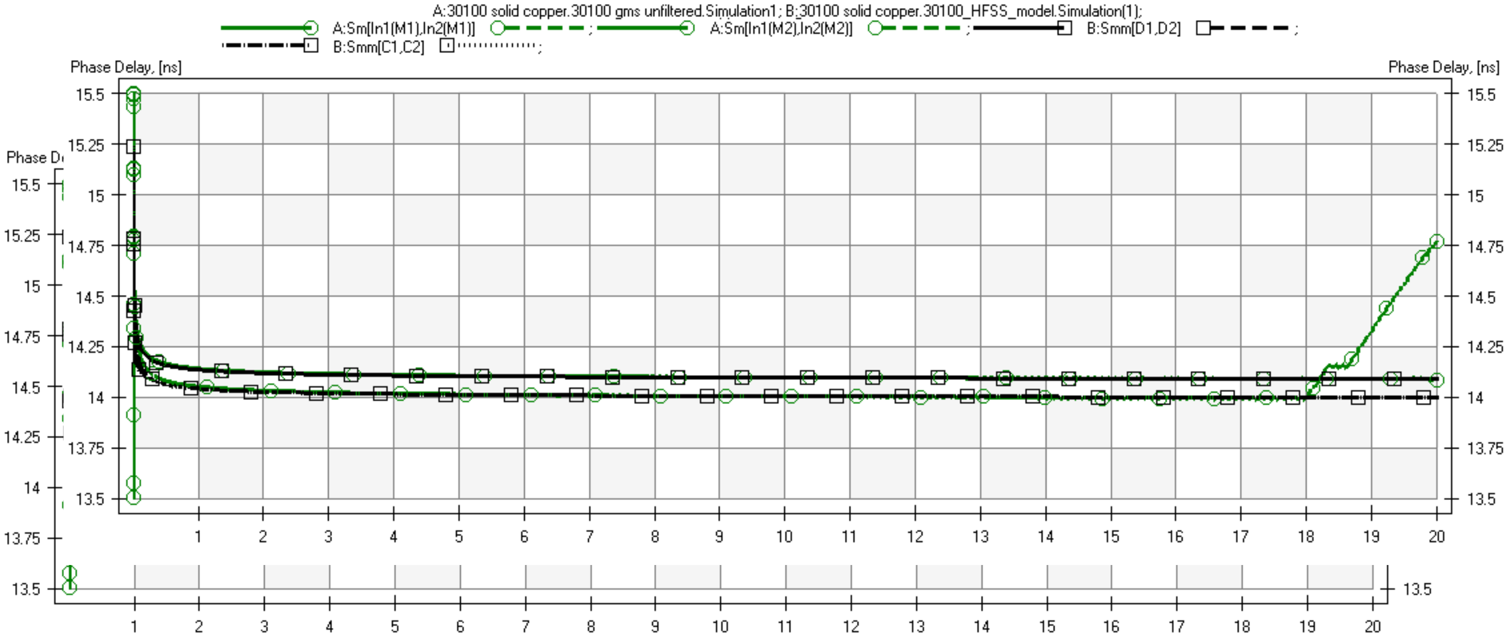
Comparison of GMS and AFR Phase Delay



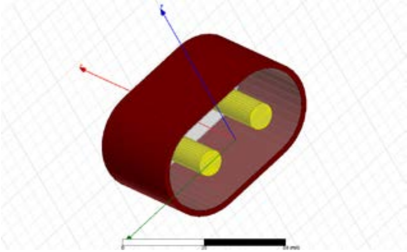
Essentially identical delay between GMS and AFR methods.

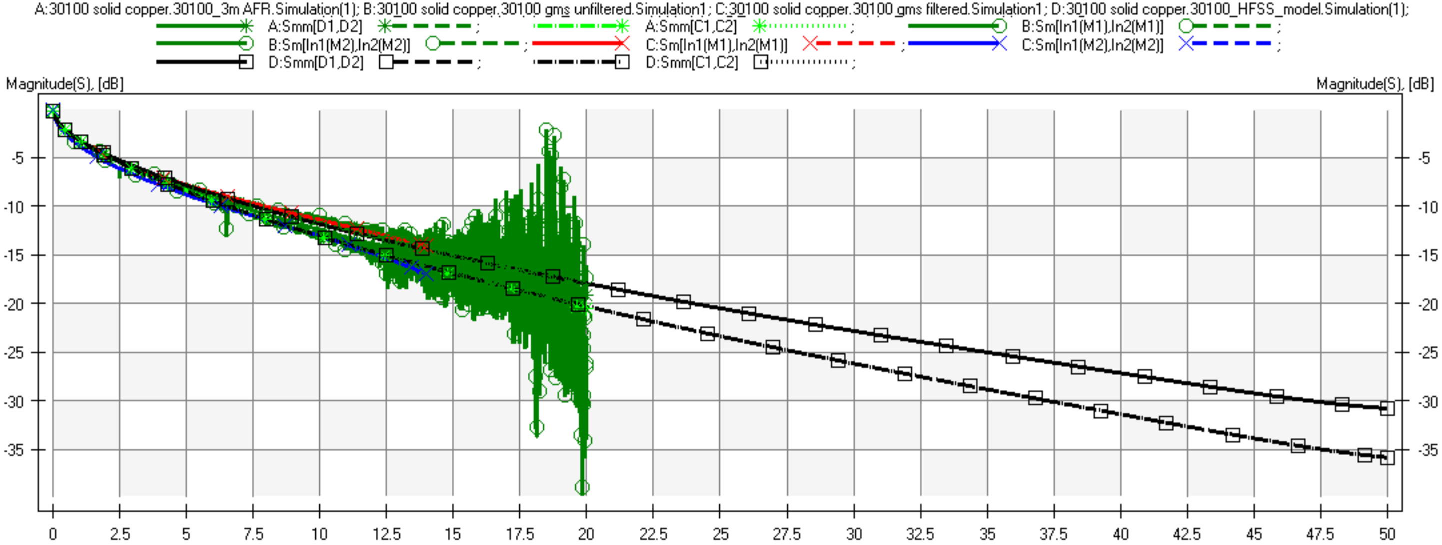
Phase or Phase delay is generally the most stable method for identifying dielectric properties.

Modeled vs. Measured Phase Delay

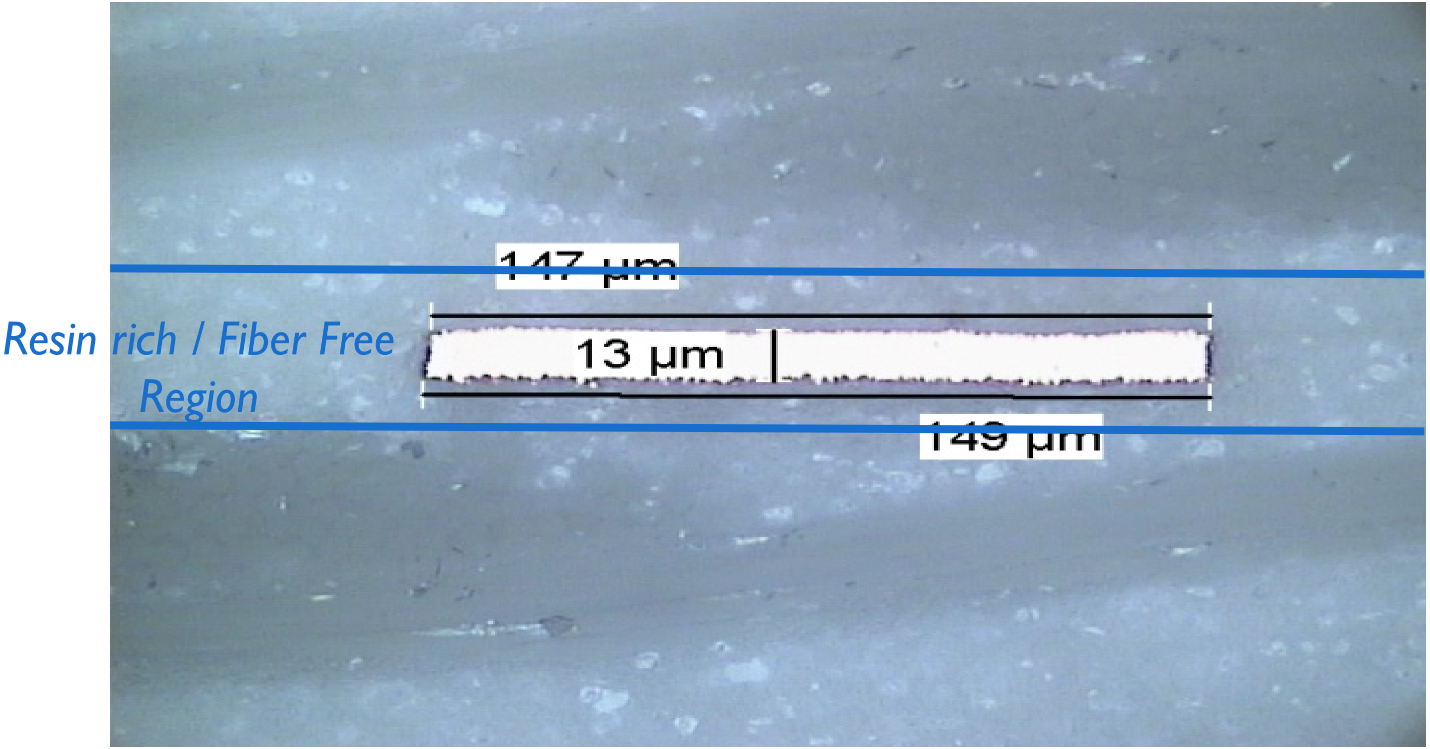


Modeled vs. Measured Attenuation





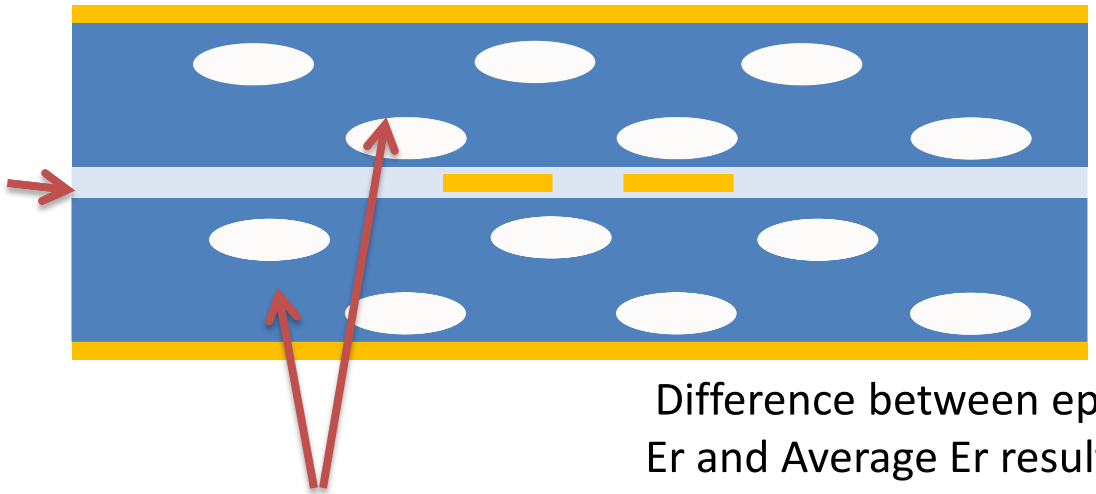
Trace Geometry Cross Section



Differential Pair Geometry

To correctly model differential trace geometries, anisotropic layering must be modeled. Resin/Epoxy/Polymer regions are always lower Dk than mixed dielectric regions. Laminate weave skew is identified and bounded through measurements and then incorporated into channel models as a post process step.

Dielectric Mixture Modeling

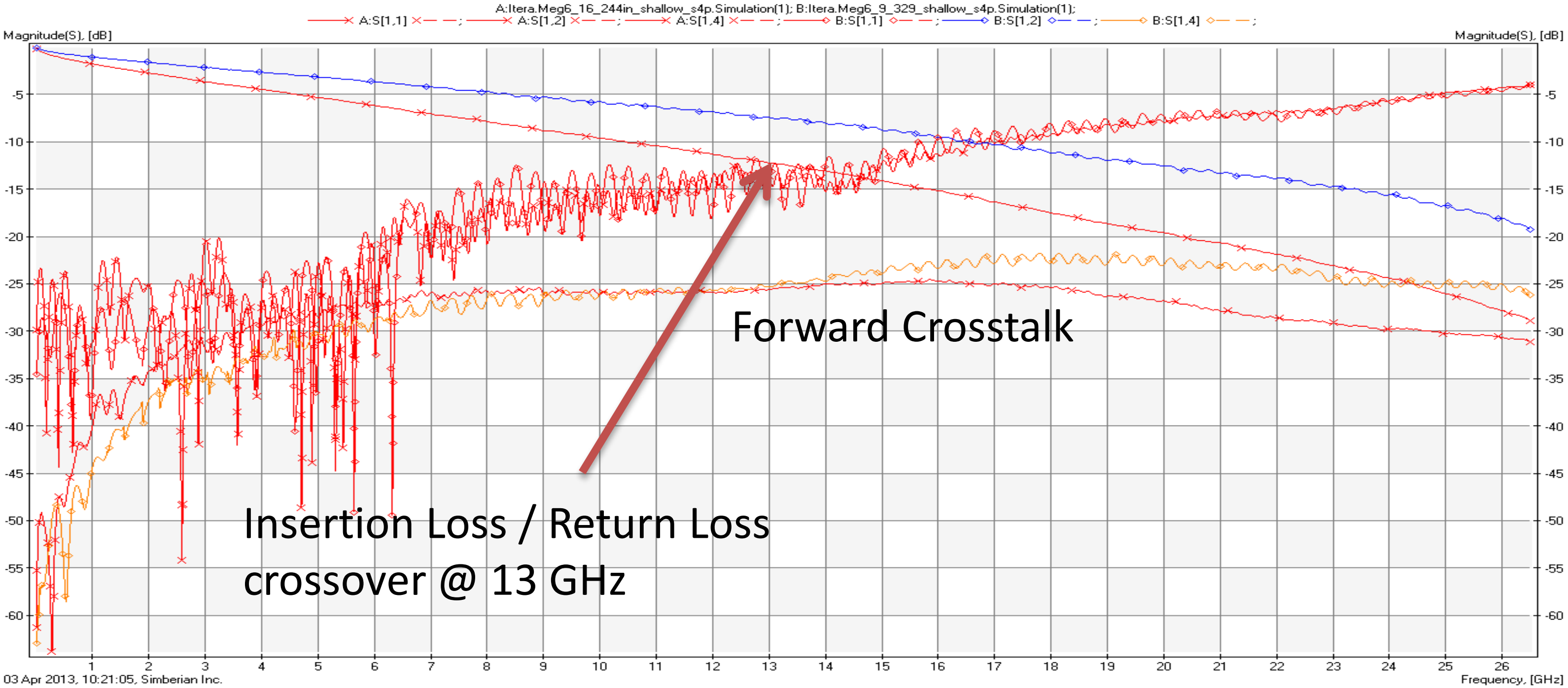


Pure epoxy

Dielectric average of epoxy and glass

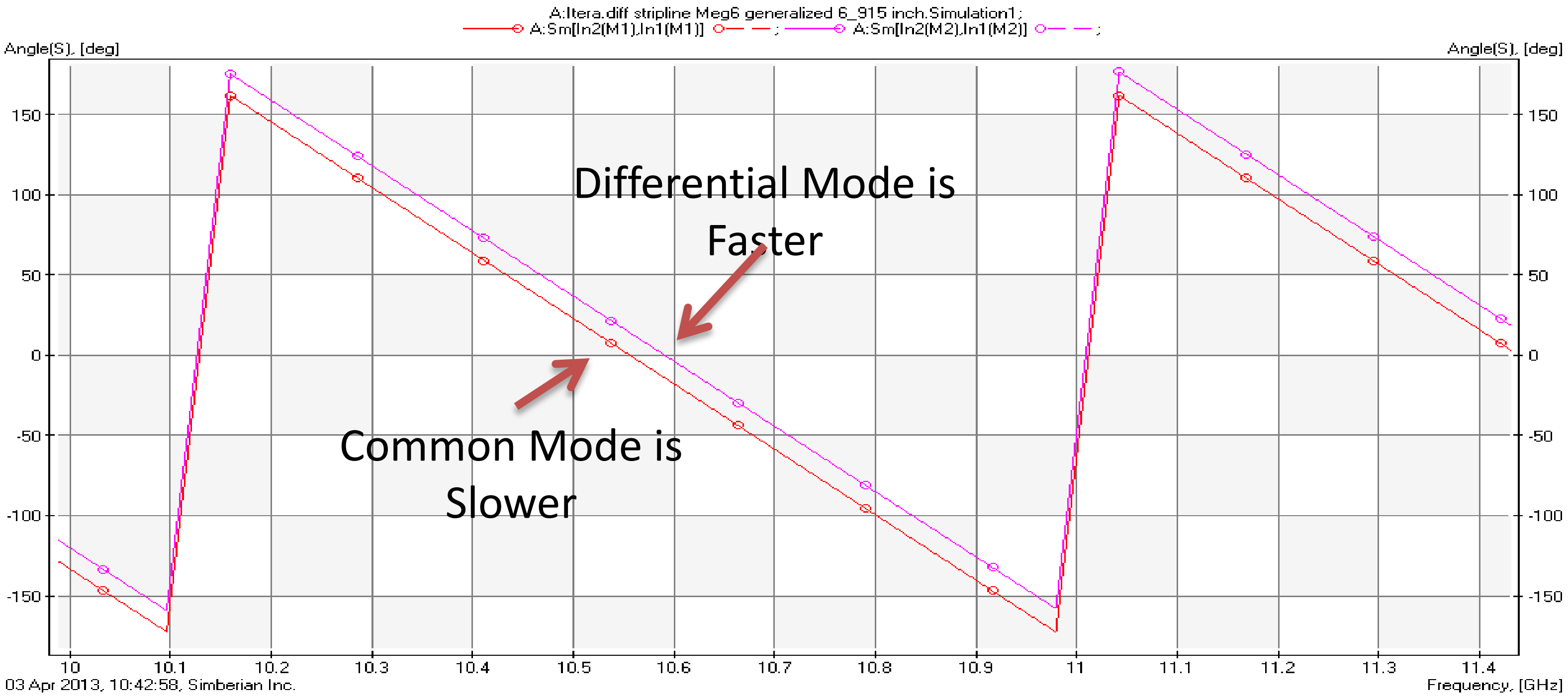
Difference between epoxy Er and Average Er results in separation of common and differential propagation modes.

Measured Meg6 Diff Stripline



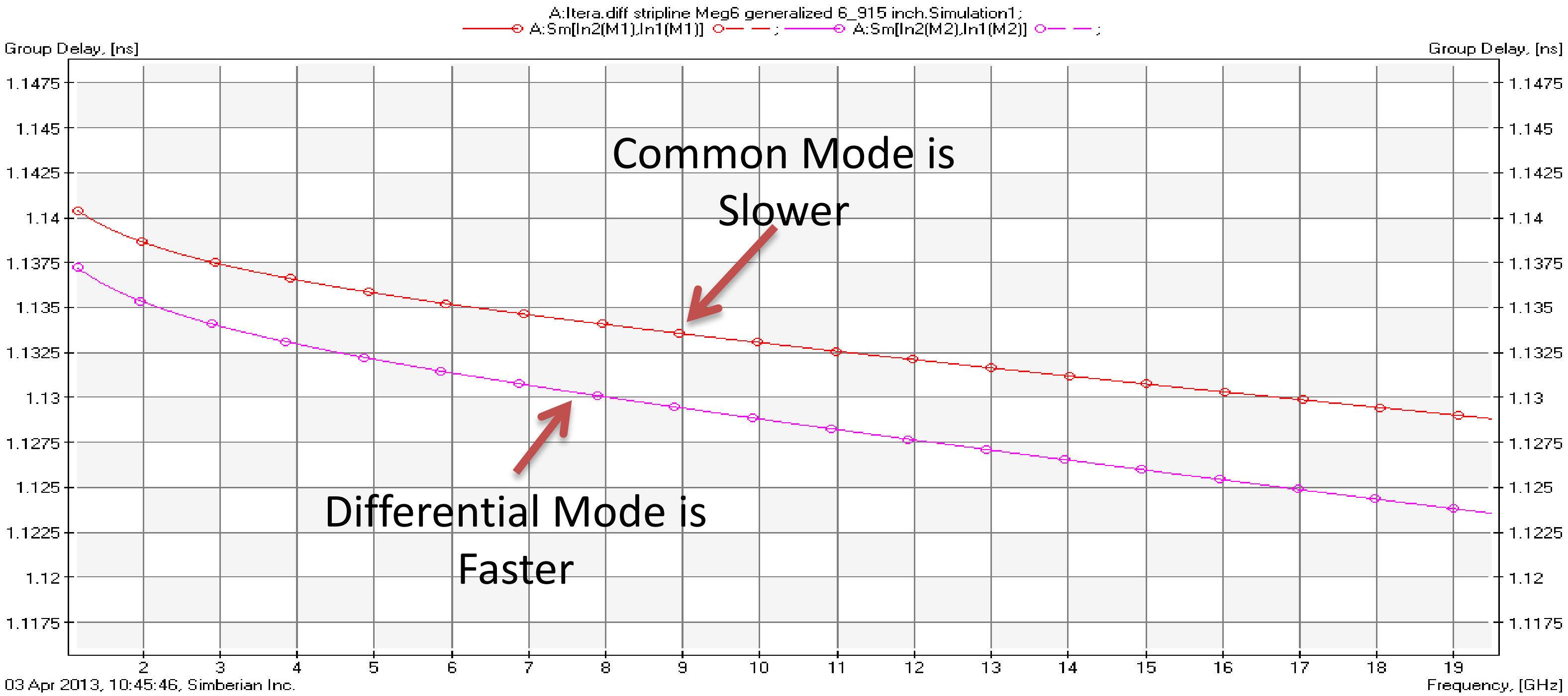
Measured data is often limited by Signal-to-Noise ratio at the insertion loss / return loss crossover point. But even this data can produce good model correlation if parameters are extracted between DC and 13 GHz.

Meg 6 Mode Separation Phase



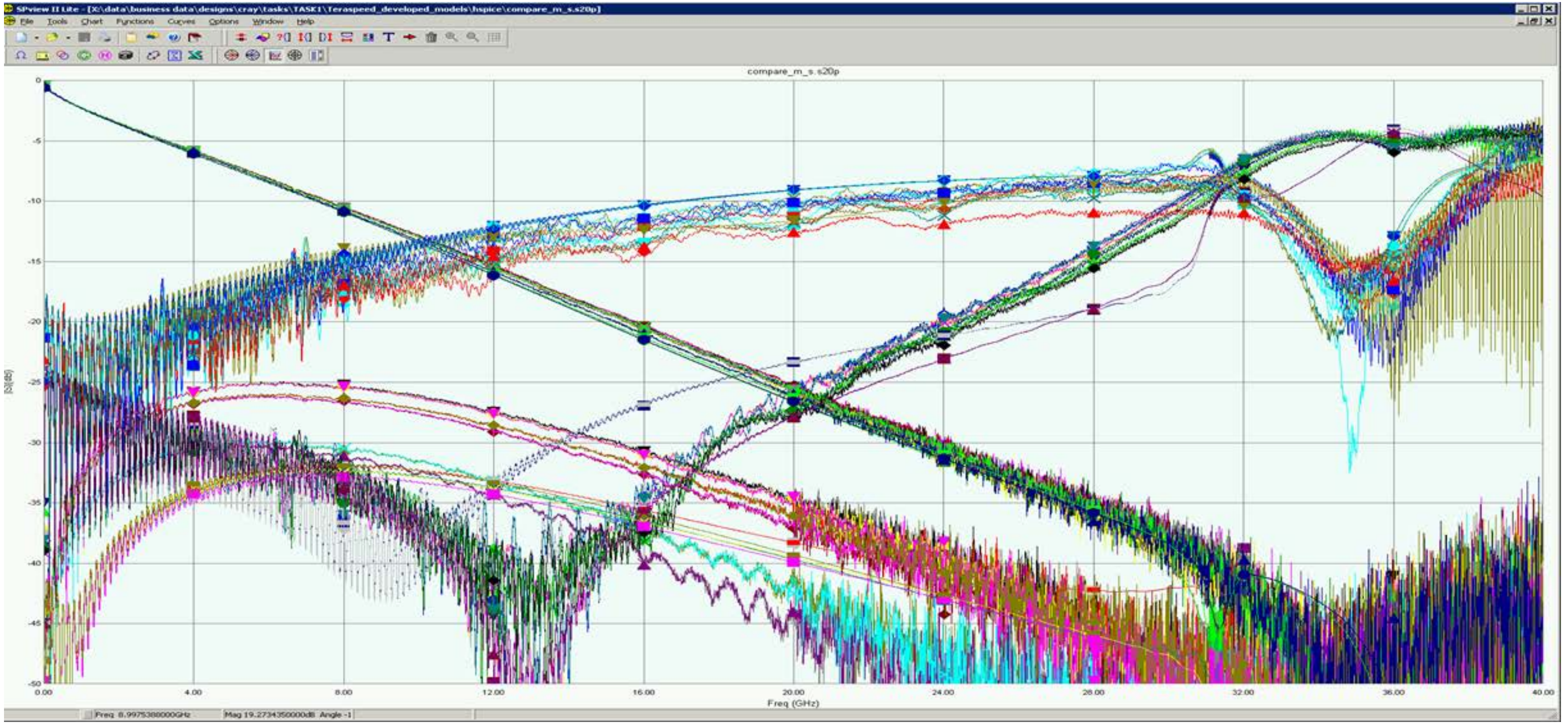
Mode separation due to layered anisotropy of epoxy and fiber rich areas in laminate system

Meg 6 Mode Separation Group Delay



Mode separation due to layered anisotropy of epoy and fiber rich areas in laminate system.

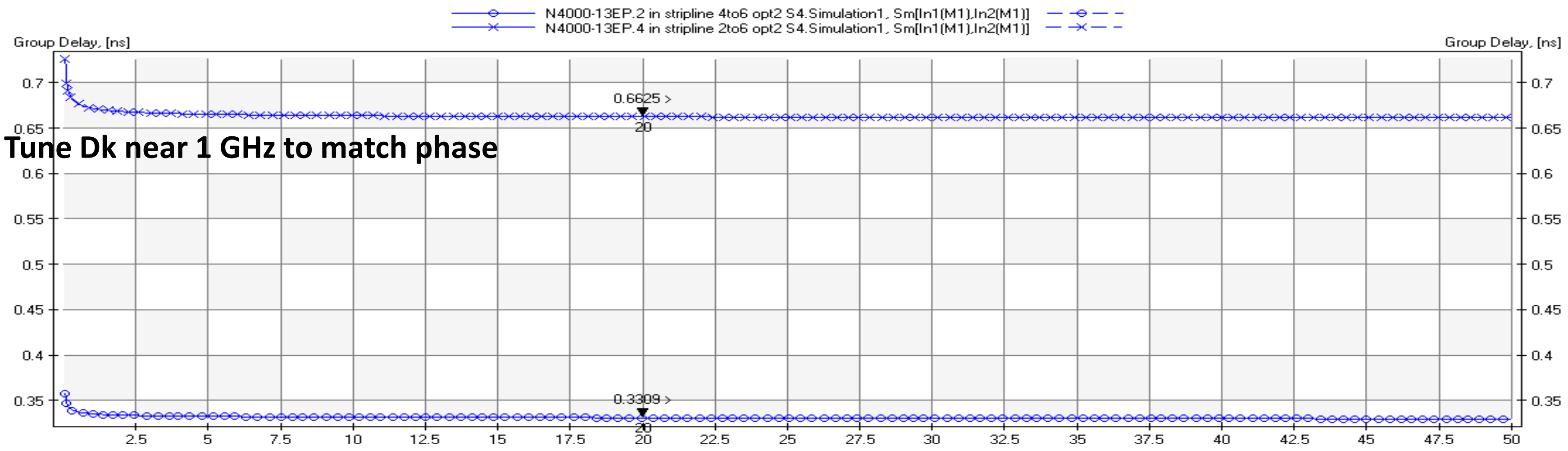
Megtron 6 20” Differential Pair Modeled vs. Measured Single-ended S-parameters



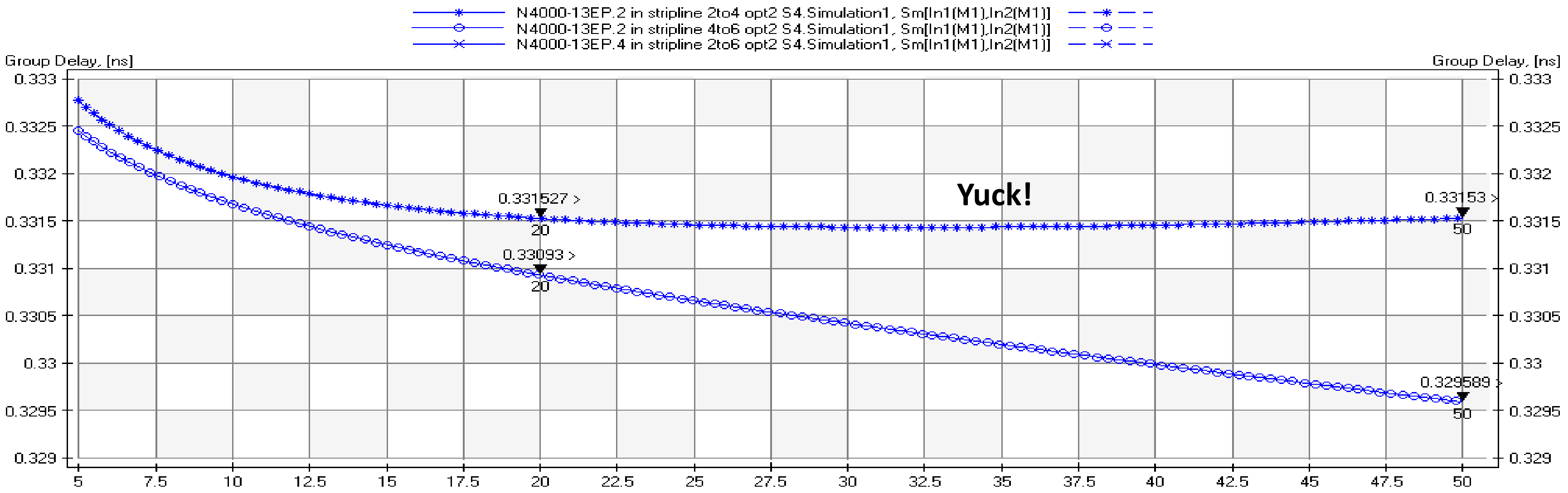
Practical Material Identification

- Step 1 – Use group/phase delay for preliminary Er
- Step 2 – Evaluate potential variation
- Step 3 – Identify low frequency characteristics
- Step 4 – Adjust for dielectric loss
- Step 5 – Final adjustment for conductor roughness
-

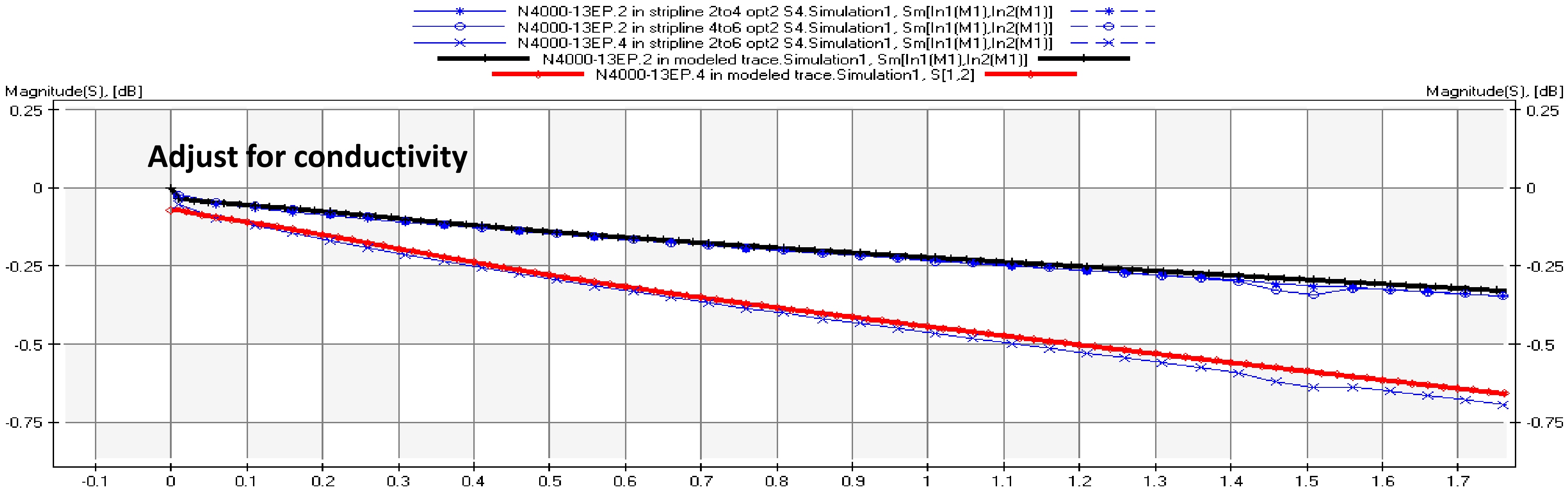
Practical Material Identification
Step 1 – Group Delay Preliminary Er Identification



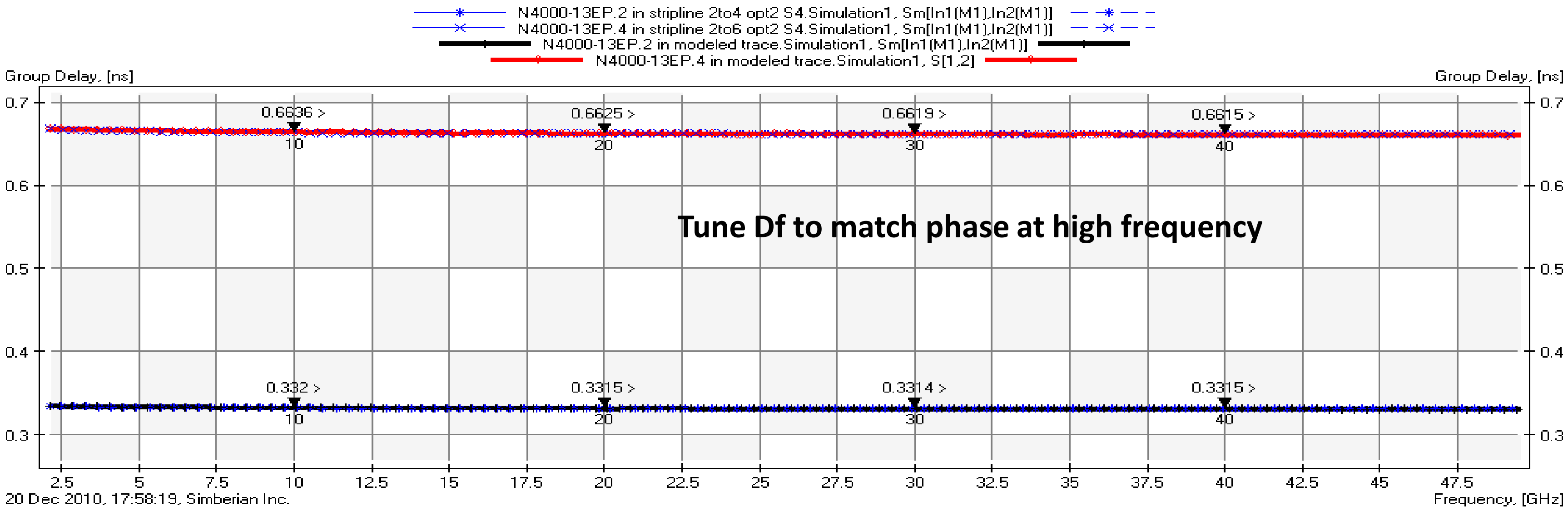
Practical Material Identification
Step 2 – Evaluate variation



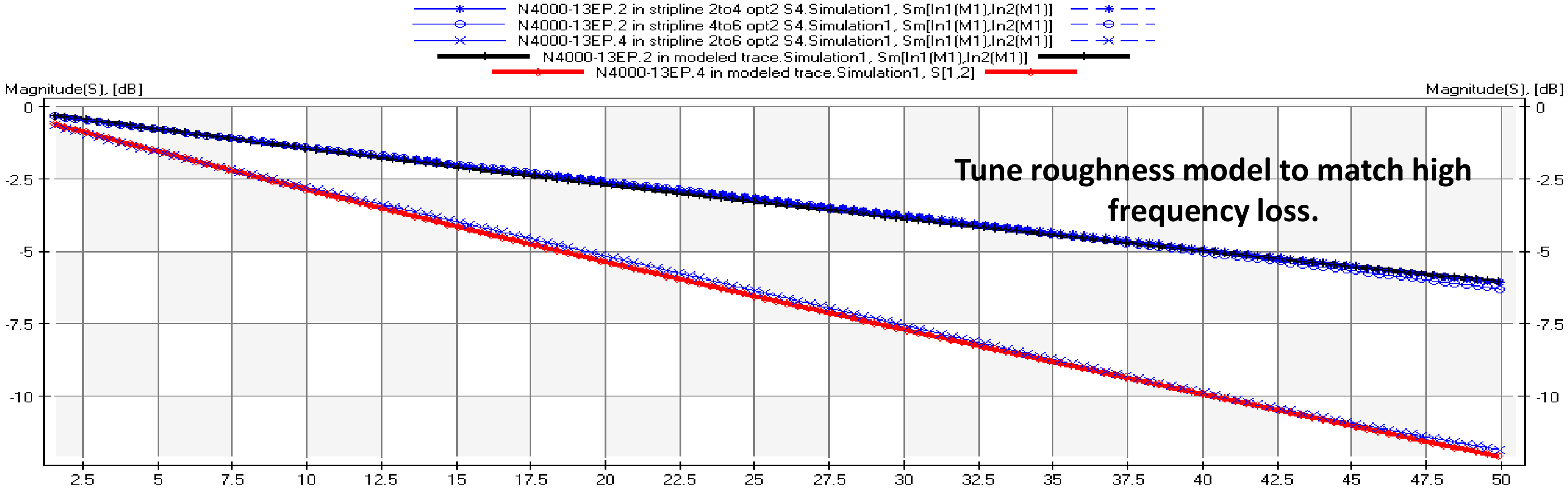
Practical Material Identification
Step 3 – Identify Low Frequency Characteristics



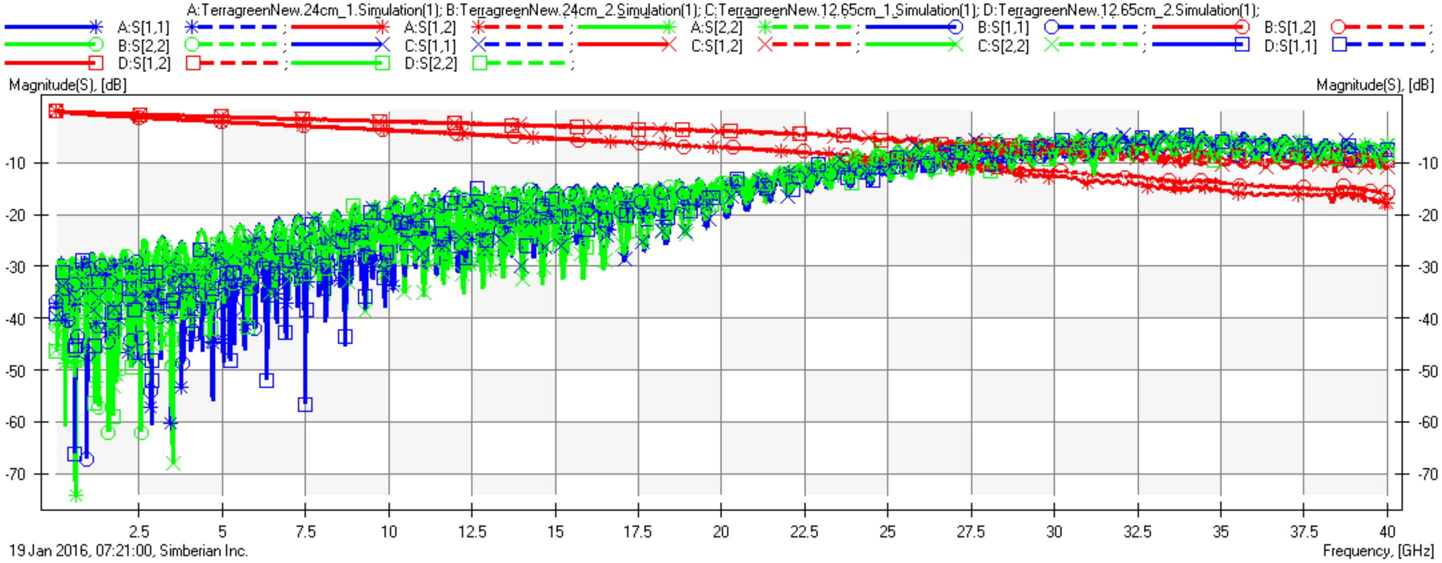
Practical Material Identification
Step 4 – Adjustment for Dielectric Loss



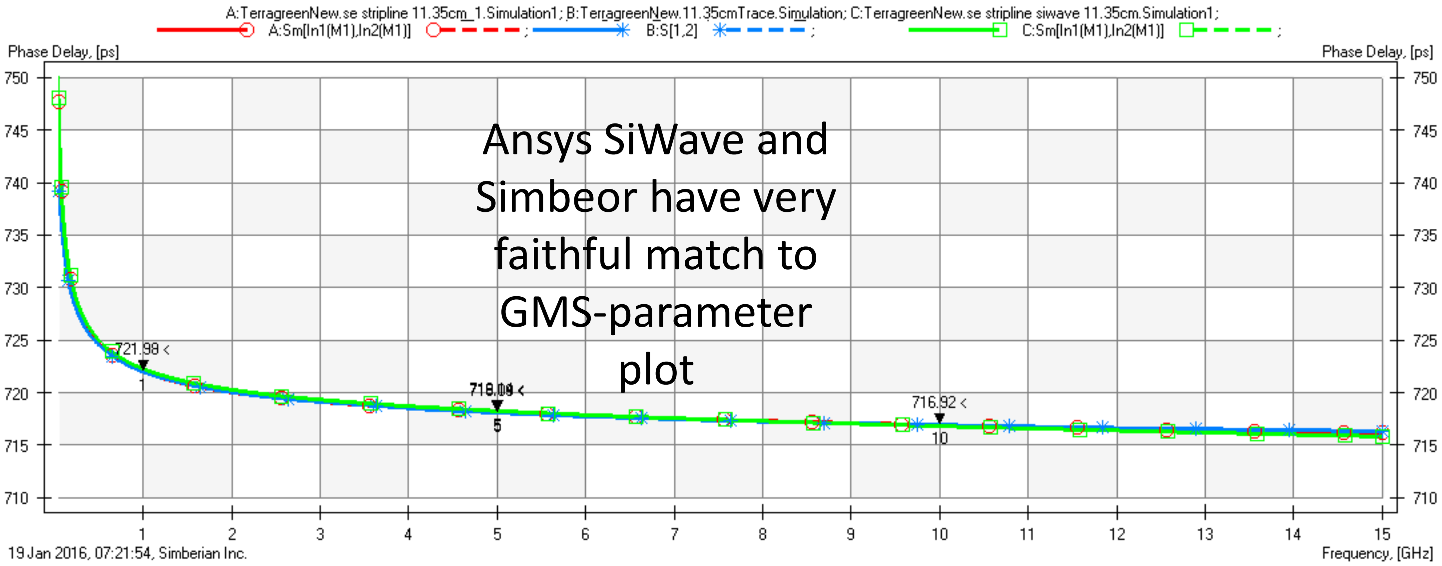
Practical Material Identification
Step 5 – Final Adjustment for Conductor Roughness



Terragreen Raw Measurements

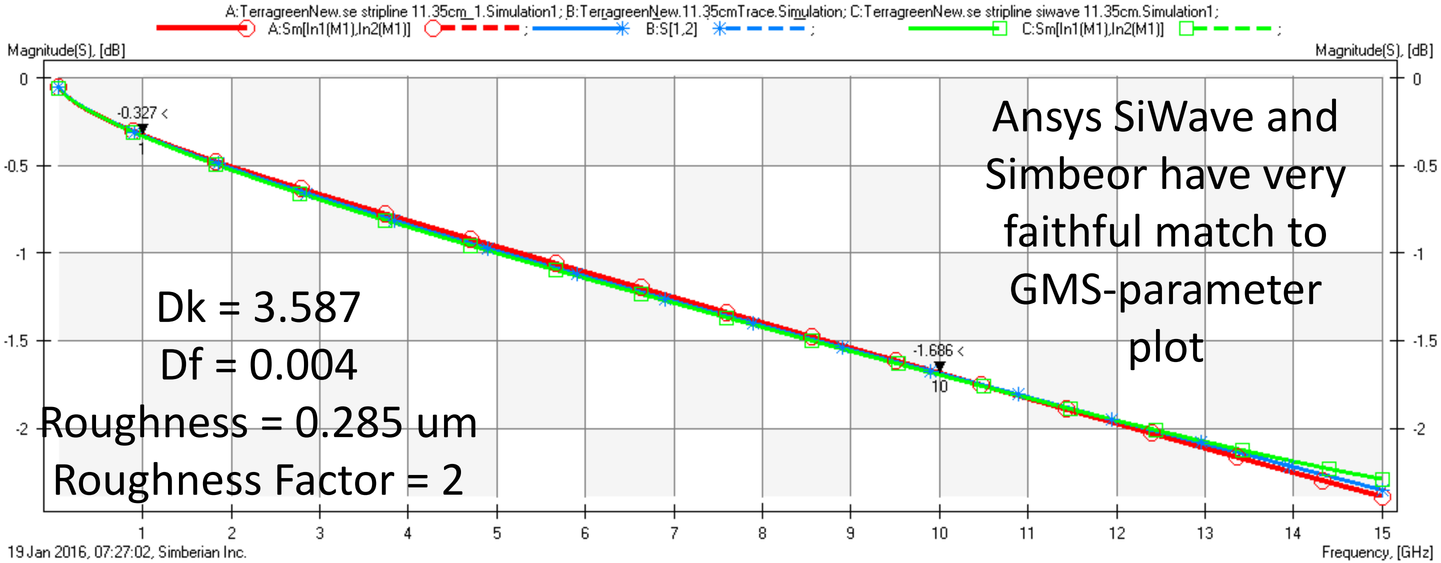


Terragreen Phase Delay
GMS vs Modeled



Ansys SiWave and Simbeor have very faithful match to GMS-parameter plot

Terragreen Attenuation
GMS vs Modeled



Dk = 3.587

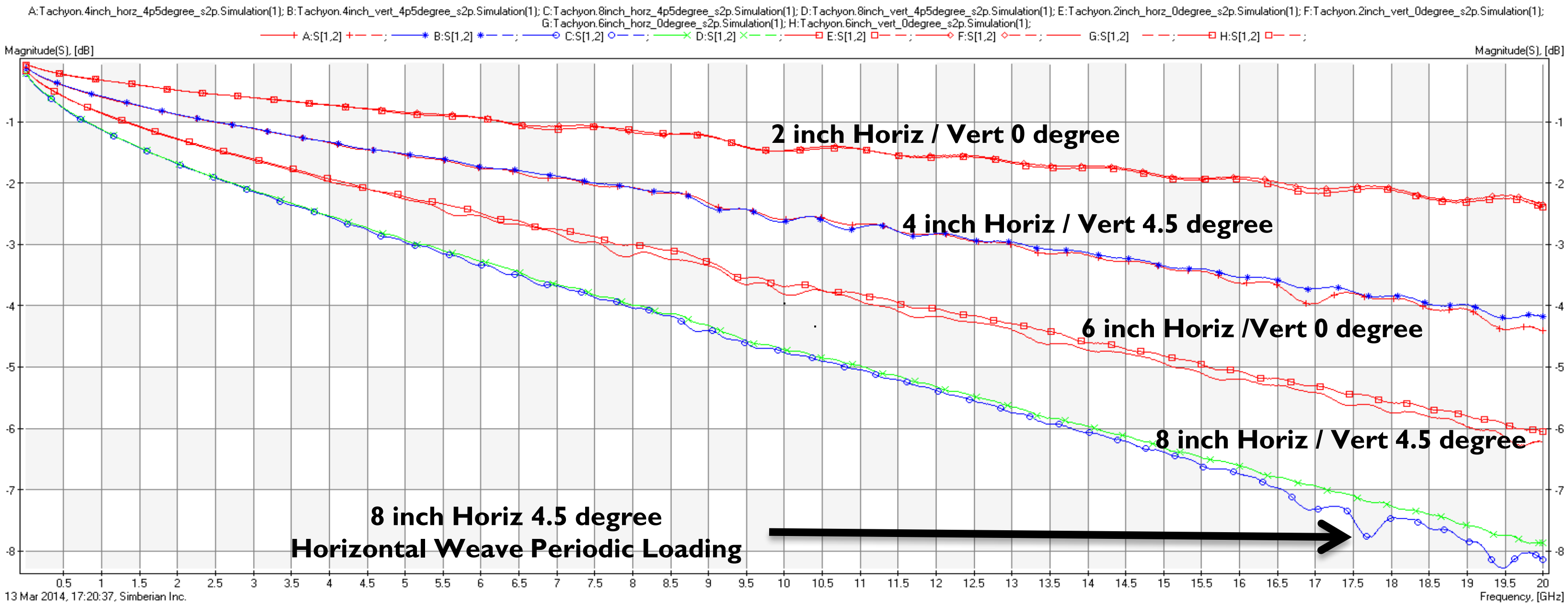
Df = 0.004

Roughness = 0.285 um

Roughness Factor = 2

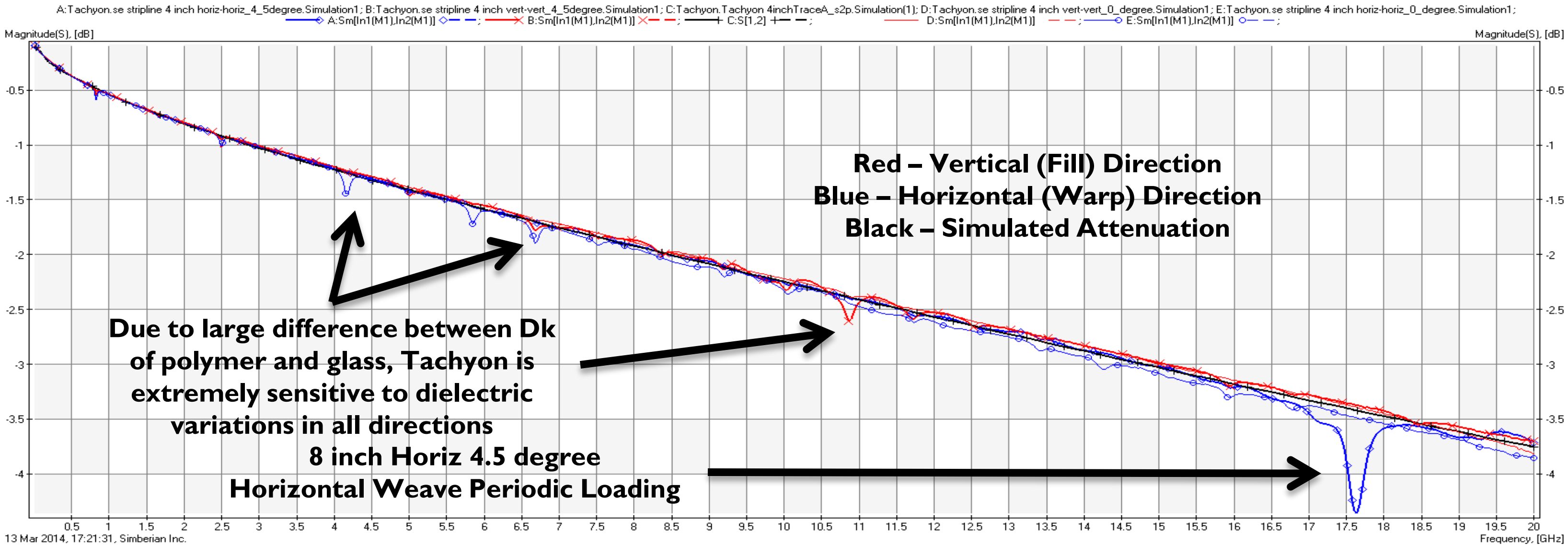
Ansys SiWave and Simbeor have very faithful match to GMS-parameter plot

Tachyon 100G Measured Insertion Loss



Variation of Dk in horizontal weave direction is discerned by 4.5 degree periodic weave loading, which causes a ½ wave resonance at ½ the crossing frequency

Tachyon 100G 4” Generalized De-embedded Attenuation Match



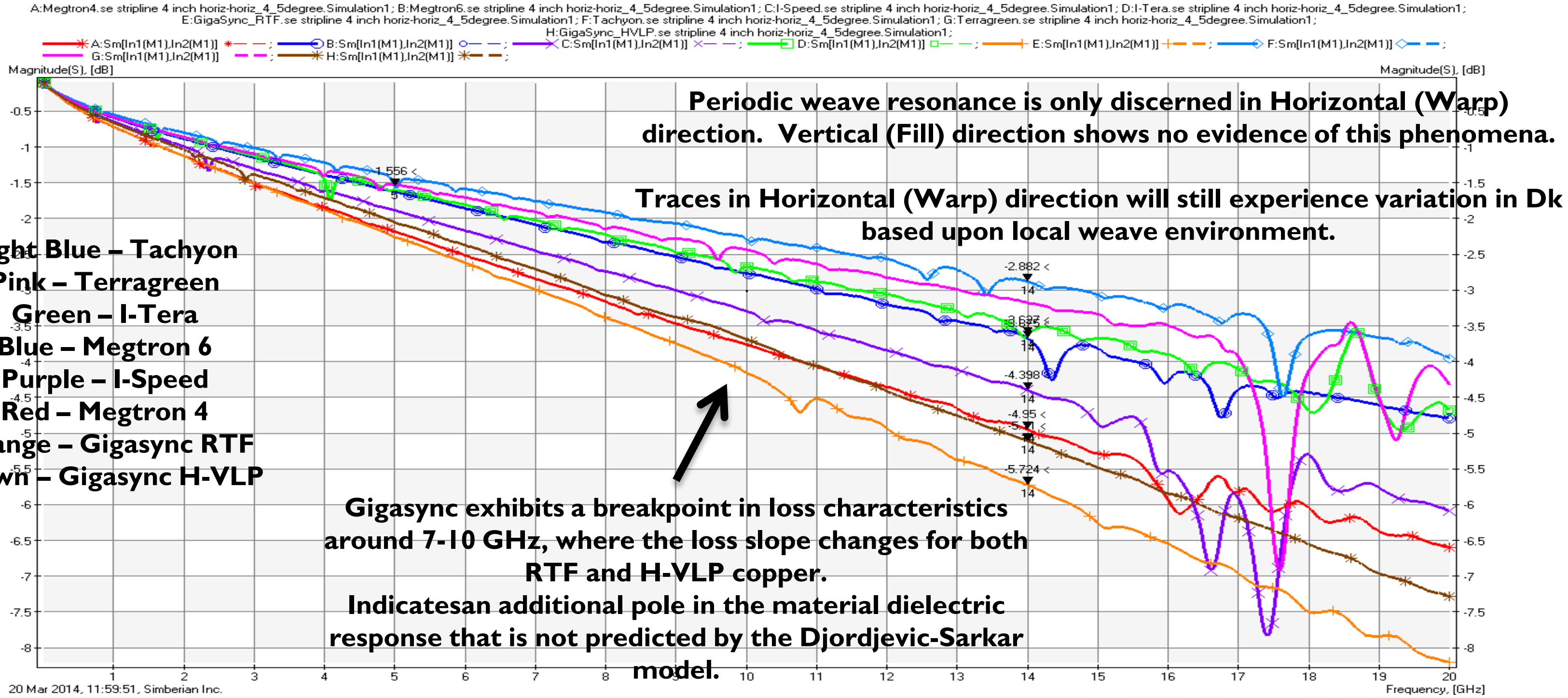
Cu Conductivity – 5.6 e^7 S/M

Cu Roughness – 0.4 micron (Hamerstadt-Jensen)

Dk – 3.06 @ 1 GHz (Djordjevic-Sarkar)

Df - .0025 @ 1 Ghz (Djordjevic-Sarkar)

Material Comparison
De-embedded Periodic Weave Resonance



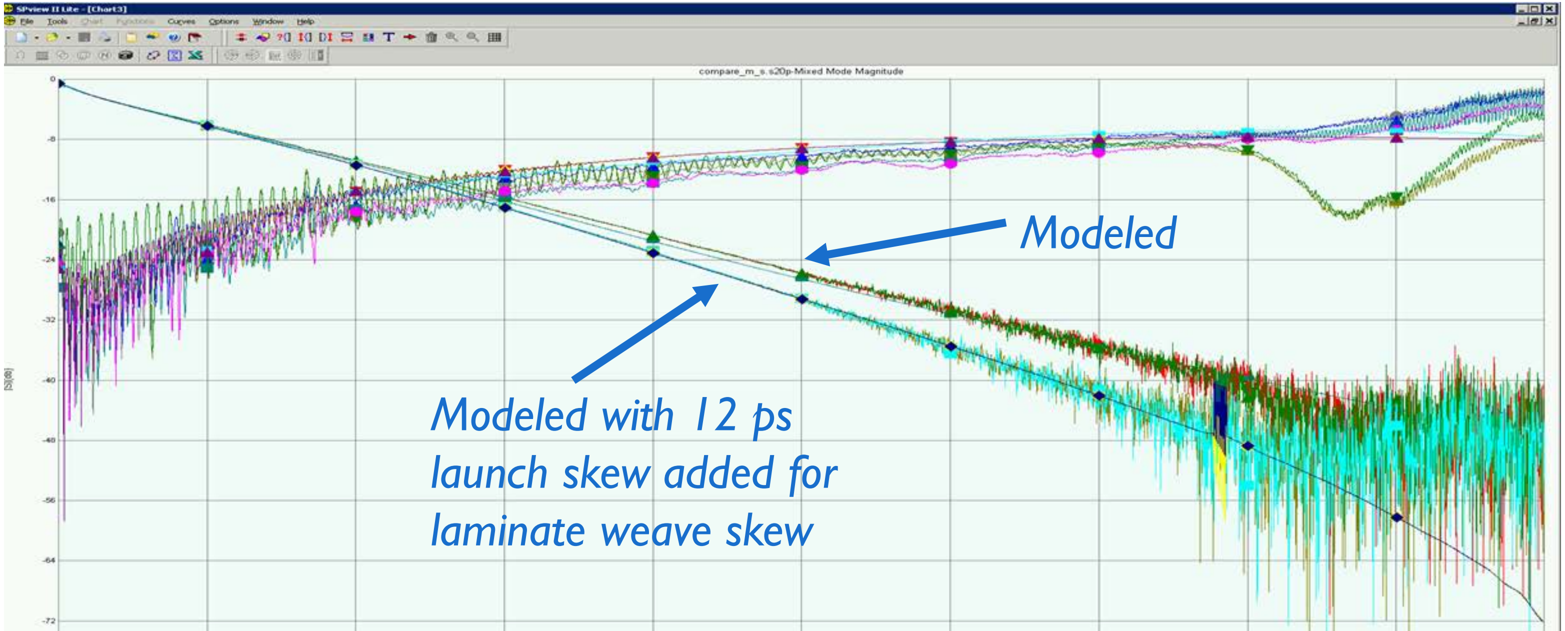
Periodic weave resonance is only discerned in Horizontal (Warp) direction. Vertical (Fill) direction shows no evidence of this phenomena.

Traces in Horizontal (Warp) direction will still experience variation in Dk based upon local weave environment.

Light Blue – Tachyon
Pink – Terragreen
Green – I-Tera
Blue – Megtron 6
Purple – I-Speed
Red – Megtron 4
Orange – Gigasync RTF
Brown – Gigasync H-VLP

Gigasync exhibits a breakpoint in loss characteristics around 7-10 GHz, where the loss slope changes for both RTF and H-VLP copper.
Indicatesan additional pole in the material dielectric response that is not predicted by the Djordjevic-Sarkar model.

Megtron 6 20” Differential Pair Modeled vs. Measured Differential S-parameters



Laminate weave skew introduces an additional factor in the assessment of models. In this case, one measured set of differential pairs had significant P/N skew of 12 ps, identified in group delay and phase plots.

Thank you!

QUESTIONS?

MORE INFORMATION:

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