Roughness Characterization for Interconnect Analysis

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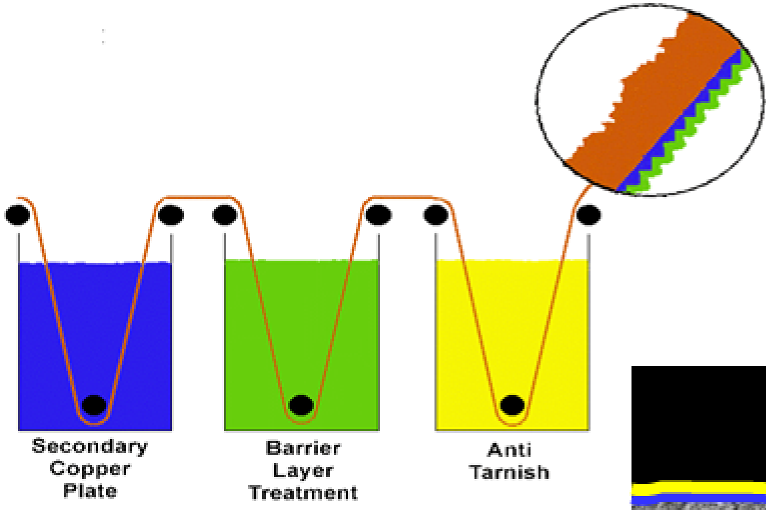
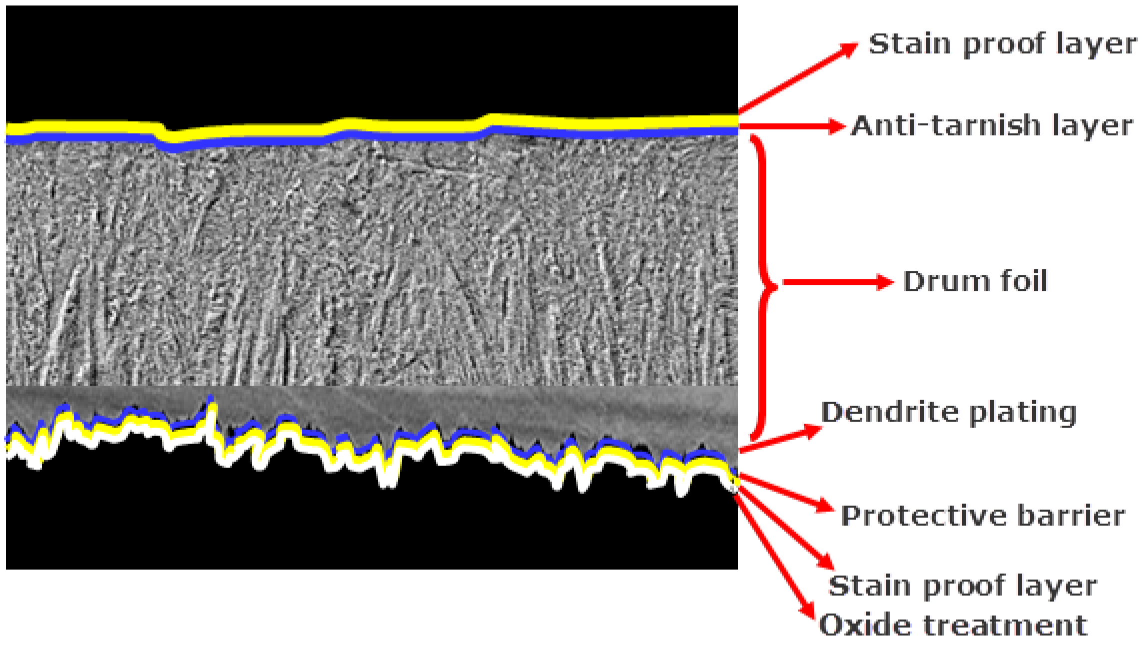
Outline

- Introduction
- Conductor treatment and composition
- Test board
- Roughness characterization overview
- Conductor model with roughness
- Modified Hammerstad correction coefficient
- Roughness parameters identification
- Conclusion

Conductor treatment





Performance specifications

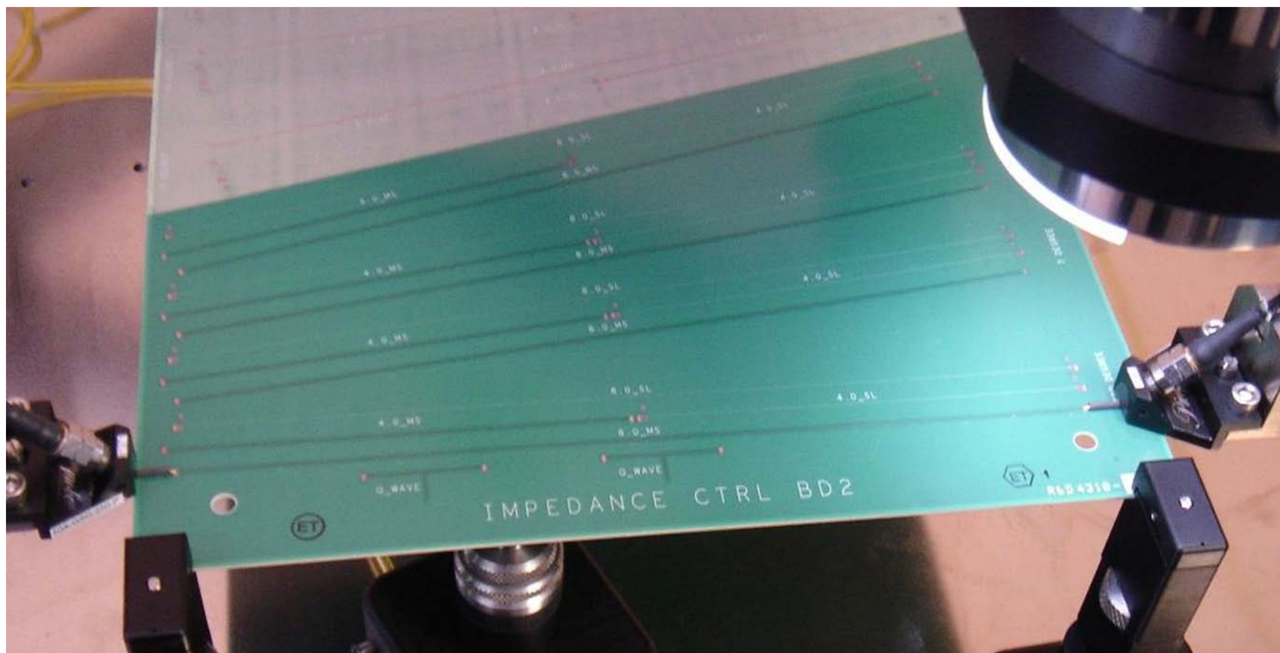
- Standard HTE (high tensile elongation)
  - Rough surface profile results in increased signal attenuation and delay due to increased propagation distance
- RTF (reverse treated foil)
  - Reverse treatment of copper clad laminate allows for improved etching capabilities resulting in smaller variation in Zo
- VLP (very low profile)
  - Smooth surface profile improves signal quality at higher frequencies where skin-depth becomes a limiting factor to signal propagation

Test board

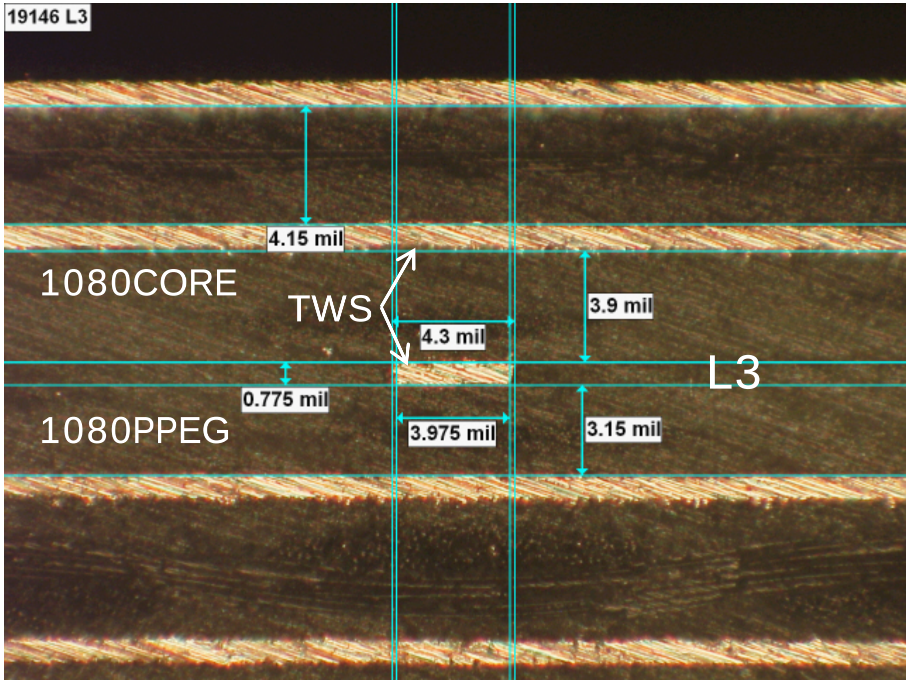
- 8 layer stackup with two microstrip layers (Top and Bottom) and 2 strip-line layers (L3, and L6)
- Microstrip TOP - TWS copper foil, 1080 prepreg, no solder mask
- Strip L3 - TWS copper foil, laminate 1080 core and prepreg
- Strip L6 – LP3 copper foil, laminate 2116 core and prepreg
- Microstrip BOTTOM – LP3 copper foil, laminate 2116 prepreg

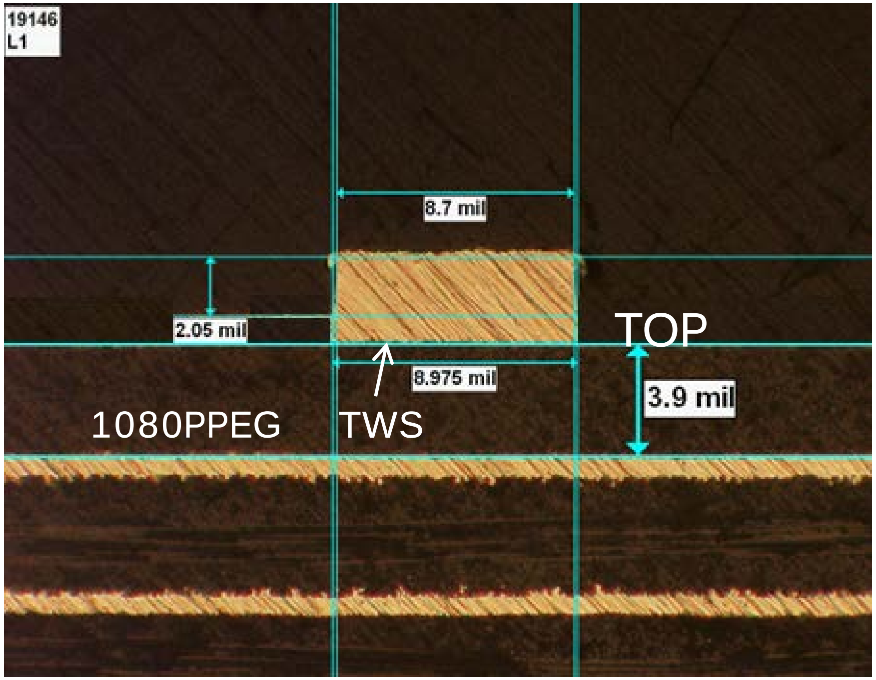
StackUp: LU=[mil], NL=8, T=37.525[mil]
1| Signal: "TOP", T=2.75, Ins="Air", Cond="CondTop"
2| Medium: T=3.9, Ins="1080PPEG", DIE_002
3| Plane: "LAYER_2", Cond="COPPER", T=0.55, Ins="1080CORE"
4| Medium: T=3.9, Ins="1080CORE", DIE_004
5| Signal: "LAYER_3", T=0.775, Ins="1080PPEG", Cond="COPPER"
6| Medium: T=3.15, Ins="1080PPEG", DIE_006
7| Plane: "LAYER_4", Cond="COPPER", T=0.55, Ins="1080CORE"
8| Medium: T=2.5, Ins="1080CORE", DIE_008
9| Plane: "LAYER_5", Cond="COPPER", T=0.55, Ins="1080CORE"
10| Medium: T=5.05, Ins="2116PPEG", DIE_010
11| Signal: "LAYER_6", T=0.775, Ins="2116PPEG", Cond="COPPER"
12| Medium: T=4.9, Ins="2116CORE", DIE_012
13| Plane: "LAYER_7", Cond="COPPER", T=0.55, Ins="2116CORE"
14| Medium: T=5.3, Ins="2116PPEG", DIE_014
15| Signal: "BOTTOM", T=2.325, Ins="Air", Cond="COPPER"

Test structures – 4 and 8 inch line segment with transitions to probe pads

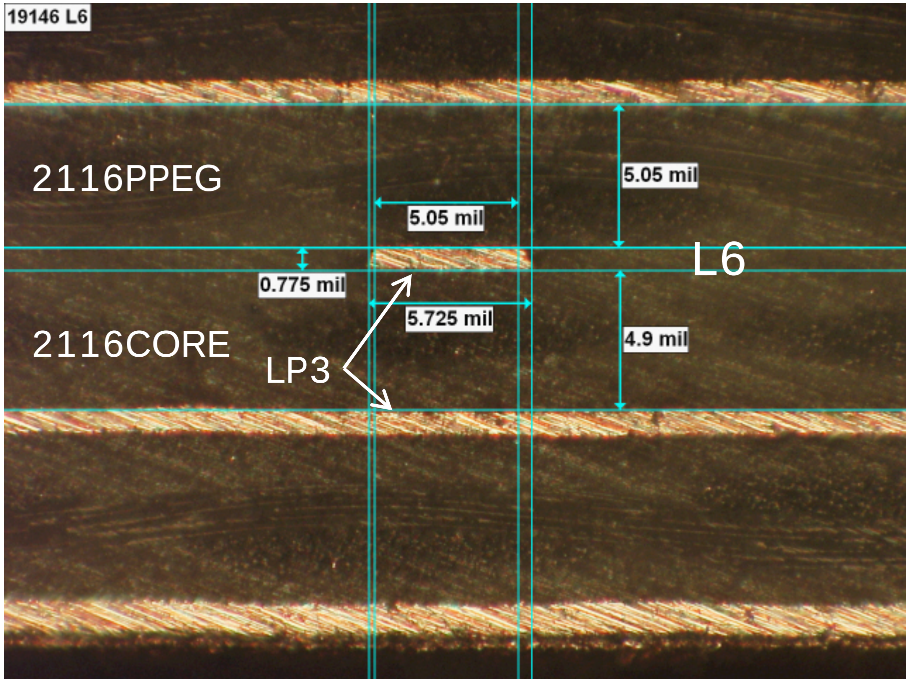


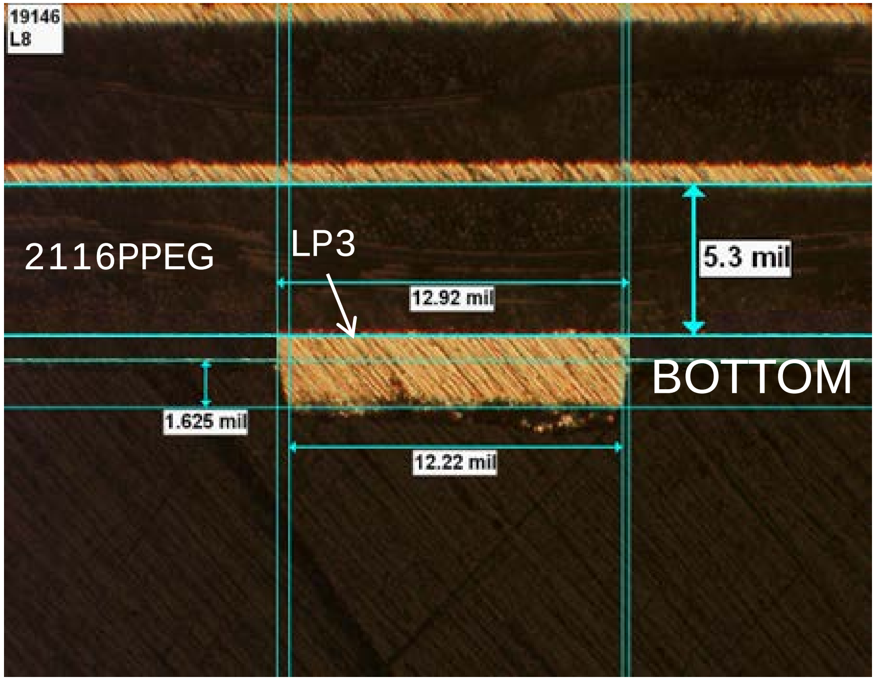
TWS&1080 cross-sections





LP3&2116 cross-sections





Initial data from specifications

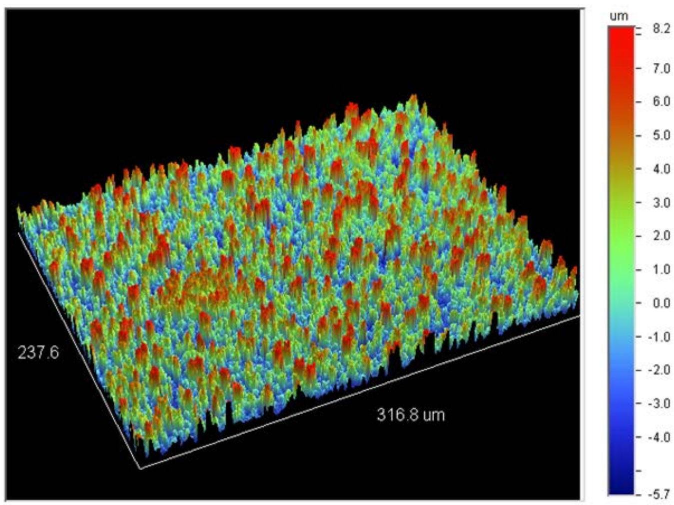
- Dk and LT or Df measured by Berezkin stripline method:

IS680 STANDARD PREPREG OFFERING					
Prepreg Designation	Resin Content (%)	Thickness (in.)	Thickness (mm)	Dk @ 2, 5 and 10 GHz	Df @ 2, 5 and 10 GHz
106	80	0.0030	0.075	2.80	0.0028
1067	80	0.0038	0.095	2.80	0.0028
1080	72	0.0040	0.100	3.00	0.0030
1086	72	0.0047	0.118	3.00	0.0030
3313	60	0.0047	0.118	3.25	0.0032
2116	58	0.0058	0.145	3.30	0.0034

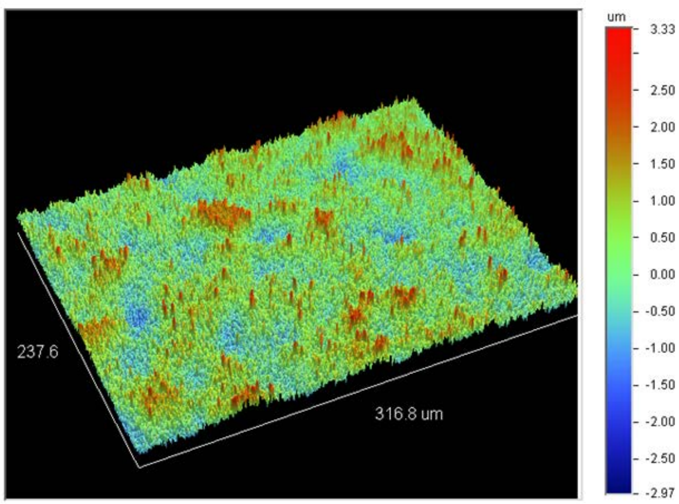
Dk +-0.05
Df +-0.0005

- Roughness parameters are measured with profilometer

TWS: Rq=2.6 um, RF=1.85



LP3: Rq=0.68 um, RF=1.3



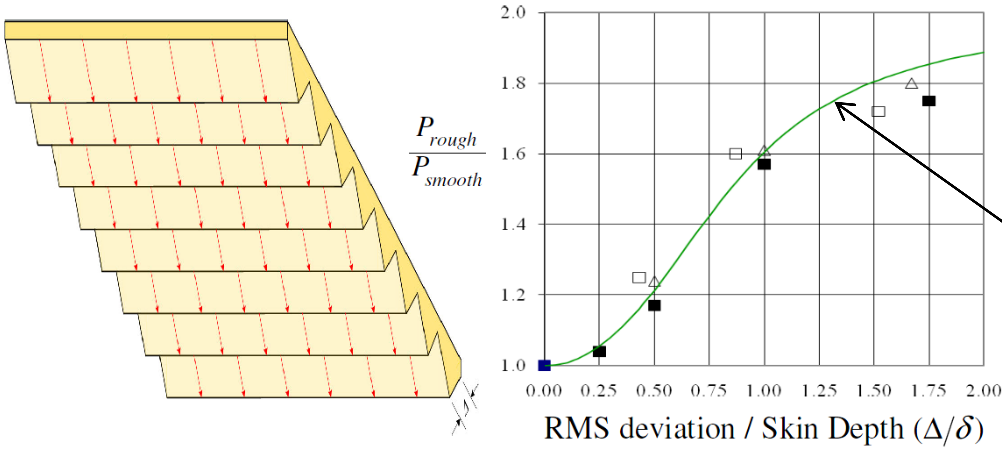
Overview of the roughness characterization

- Attenuation correction coefficients
  - Hammerstad model (Hammerstad, Bekkadal, Jensen)
  - “Snowball” model (Hurray,…)
  - Hemispherical model (Hall, Pytel,…)
  - Stochastic models (Sanderson, Tsang,…)
  - Periodic structures (Lukic,…)
- Conductor and dielectric loss separation by extrapolation
  - Koledintseva, Koul,…
- Equivalent boundary conditions
  - Holloway, Kuester
  - Koledintseva, Koul,…
- Direct electromagnetic analysis

References and details are in the paper and in the appendix to this presentation

Morgan and Hammerstad models

- S.P. Morgan Jr., “Effect of Surface Roughness on Eddy Current Losses at Microwave Frequencies,” *Journal of Applied Physics*, Vol. 20, p. 352-362, April, 1949.
- E. O. Hammerstad, F. Bekkadal *Microstrip Handbook*, 1975 :Univ. Trondheim.
- E. O. Hammerstad, Ø. Jensen, “*Accurate Models for Microstrip Computer Aided Design*”, *IEEE MTT-S Int. Microwave Symp. Dig.*, p. 407-409, May 1980.



Hammerstad’s correction coefficient

$$R_S(\Delta)=R_S(0)\left[1+\frac{2}{\pi}\,\mathrm{Arc\ tan}\ 1.4\left(\frac{\Delta}{\delta}\right)^2\right]$$

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

Figure 1. Samuel Morgan’s 2-D relative power loss calculations for rectangular (□), triangular (Δ), and square (■) grooves that are normal to the direction of current flow in a transmission line Morgan’s equilateral triangular distortion perpendicular to the direction of current flow (arrows) is shown in the graphic on the left.

Illustration is from: P. G. Huray, O. Oluwafemi, J. Loyer, E. Bogatin, X. Ye Impact of Copper Surface Texture on Loss: A Model that Works, DesignCon 2010

Separation of conductive and polarization (dielectric) losses is not possible

- Conductor resistance and corresponding attenuation is not exactly proportional to sqrt(frequency) due to the roughness effect:

$$Z_{sr}(f) = R_{DC} + (1+i)R_s(f) + i2\pi f \cdot L_{ext}(f) \left[\frac{Ohm}{m}\right]$$

- Conductance and corresponding attenuation is not exactly proportional to frequency due to frequency dependency of loss tangent:

$$Y(f) = G_{DC} + 2\pi f \cdot G_d(f) + i2\pi f \cdot C(f) \left[\frac{S}{m}\right]$$

- Thus, we cannot directly separate the losses from insertion losses or complex propagation constant:

$$\Gamma(f) = \sqrt{Z(f) \cdot Y(f)}$$

- Roughness effect should be defined with the data from the physical measurements **or fitted with a heuristic model**
- The rest of the losses can be attributed to dielectric

Use of Generalized Modal S-parameters for roughness identification

Shlepnev at all, DesignCon2010

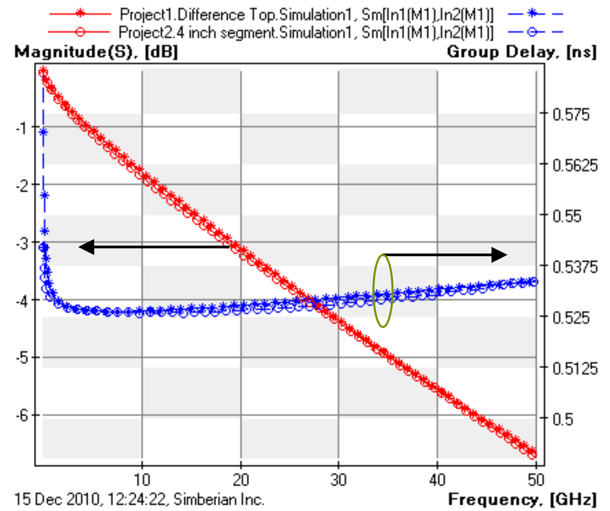
- Solve Maxwell's equations for 1-conductor line:

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

Only 1 complex function!

- Fit measured GMS-parameters (extracted from S-parameters measured for 2 line segments):

$$GMSm = \begin{bmatrix} 0 & T_{11} \\ T_{11} & 0 \end{bmatrix} \qquad dL = L2 - L1$$



- Measured GMS-parameters of the segment can be directly fitted with the calculated GMS-parameters for material parameters identification
- Phase or group delay can be used to identify DK and insertion loss to identify LT or conductor roughness!

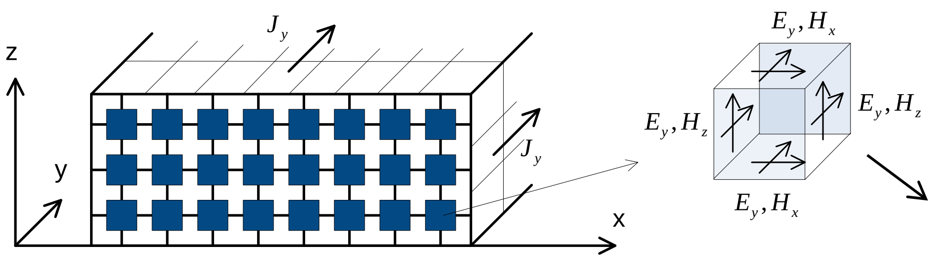
Electromagnetic model

- Hybrid model has been constructed to simulate segment of transmission line
- Method of Lines (MoL) is used for multi-layered dielectric and plane layer – produced grid Green's function (GGF) (*)
- Conductor interior meshed with Trefftz-Nikol'skiy finite elements connected to the GGF (*)
- Method of simultaneous diagonalization is used to extract modal and per unit length parameters of microstrip line (*)

(*) References are in the paper
Model is implemented in electromagnetic signal integrity software Simbeor 2011 – available at www.simberian.com

Conductor differential surface impedance operator

Y.O. Shlepnev, "Trefftz finite elements for electromagnetics", - *IEEE Trans. Microwave Theory Tech.*, vol. MTT-50, pp. 1328-1339, May, 2002.



Differential impedance operator of one Trefftz element:

$$Z_{el} = Z_m \cdot \begin{bmatrix} \frac{\coth(\Gamma \cdot dz)}{dx} & \frac{1}{\Gamma \cdot dx \cdot dz} & \frac{\operatorname{csech}(\Gamma \cdot dz)}{dx} & \frac{1}{\Gamma \cdot dx \cdot dz} \\ \frac{1}{\Gamma \cdot dx \cdot dz} & \frac{\coth(\Gamma \cdot dx)}{dz} & \frac{1}{\Gamma \cdot dx \cdot dz} & \frac{\operatorname{csech}(\Gamma \cdot dx)}{dz} \\ \frac{\operatorname{csech}(\Gamma \cdot dz)}{dx} & \frac{1}{\Gamma \cdot dx \cdot dz} & \frac{\coth(\Gamma \cdot dz)}{dx} & \frac{1}{\Gamma \cdot dx \cdot dz} \\ \frac{1}{\Gamma \cdot dx \cdot dz} & \frac{\operatorname{csech}(\Gamma \cdot dx)}{dz} & \frac{1}{\Gamma \cdot dx \cdot dz} & \frac{\coth(\Gamma \cdot dx)}{dz} \end{bmatrix}$$

$$\delta_s = \sqrt{\frac{2}{2\pi \cdot f \cdot \mu \cdot \sigma}} \quad \Gamma = (1+i)\frac{1}{\delta_s} \quad Z_m = \frac{\Gamma}{\sigma}$$

Built with plane-wave solutions of Maxwell’s equations inside metal as the basis functions
Correct low and high-frequency asymptotes
Skin-effect is automatically included - element size can be much larger than skin-depth!

Impedance matrices of all elements are connected in cross-section to form Zcs with only ports only on the surface of the conductor (surface impedance operator as in (*))

(*) D. De Zutter, L. Knockaert, Skin Effect Modeling Based on a Differential Surface Admittance Operator, IEEE Trans. On MTT, vol. 53, N 8, p. 2526-2538, 2005.

Validation on rectangular conductor impedance

Rectangular PCB-type conductor: 15 mil (381 um) wide, 1.4 mil thick (35.56 um), copper 5.8e7 S/m

Real part of surface impedance p.u.l. , Ohm/m

NxM	100 KHz	10 MHz	100 MHz	1 GHz
1x1	1.27259217	1.34206195	3.31296611	10.0971387
16x2	1.27258674	1.33288663	3.30116248	10.0933573
32x4	1.27258668	1.33212965	3.26813091	10.0836741
64x8	1.27258668	1.33211762	3.25809576	10.0582054
128x16	1.27258669	1.33213473	3.25679451	10.0351867
Wheeler's [1]		**1.2110346**	**3.127071**	**9.9028058**
Ref. [2]: 172x16			**4.848**	

Exact DC resistance is 1.2725805 Ohm/m

Even 1 element produces acceptable accuracy!

Imaginary part of surface impedance p.u.l., Ohm/m

NxM	100 KHz	10 MHz	100 MHz	1 GHz
1x1	0.00608775359	0.585960864	3.18465209	9.90728659
16x2	0.00586611426	0.577135581	3.19108406	9.91039538
32x4	0.00580523237	0.570934552	3.18488433	9.91878448
64x8	0.00578649443	0.568992786	3.17196905	9.92839377
128x16	0.00578152584	0.568478369	3.16720912	9.91582185
Wheeler's [1]		**0.5943148**	**3.1686575**	**9.9028058**
Ref. [2]: 172x16			**4.0287**	

Computed by summing up surface currents, assuming identical voltage drop on the conductor surface (approximation)

1) H.A. Wheeler, Transmission line properties of parallel strips separated by a dielectric sheet, IEEE Trans. on MTT, vol. 13, p. 172-185, March 1965

2) G. Antonini, A. Orlandi, C. R. Paul, Internal impedance of conductors of rectangular cross section, *IEEE Trans. Microwave Theory and Techniques,* vol. 47, N 7, 1999, p. 979-985.

Roughness simulation options

- Use layer of Trefftz elements with effective permittivity and permeability (Holloway-Kuester)
- Use Trefftz elements with effective permittivity, permeability and conductivity for entire conductor interior
- Adjust differential conductor impedance operator with the correction coefficient

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

Z_{cs} - conductor surface impedance operator
K_{sr} – diagonal matrix with correction coefficients on diagonal

  - Any roughness correction coefficient can be used with this formulation
  - Real and imaginary parts are adjusted simultaneously – causal solution

Roughness correction coefficients

- Modified Hammerstad-Jensen(*) model:

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

(*) Original model from: E. Hammerstad, O. Jensen, "Accurate Models of Computer Aided Microstrip Design", *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 407-409, May 1980.

$$\delta_s = \sqrt{\frac{2}{2\pi \cdot f \cdot \mu \cdot \sigma}}$$

skin-depth at frequency *f* in conductor with permeability *mu* and with conductivity *sigma*

Δ - root mean square peak-to-valley distance

RF - roughness factor, defines maximal growth of losses due to metal roughness

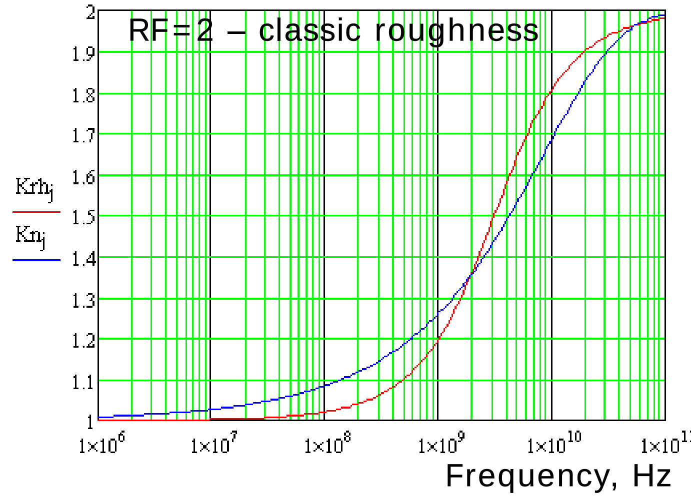
RF=2 gives classical H-J model extensively used in microwave applications

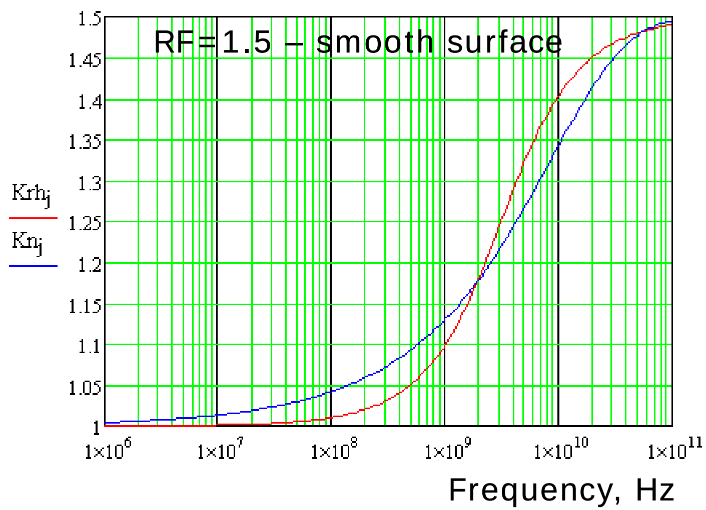
- Similar fitted correction coefficient is used in Simbeor software
- Technically, any correction coefficient can be used to adjust conductor surface impedance computed with TFE

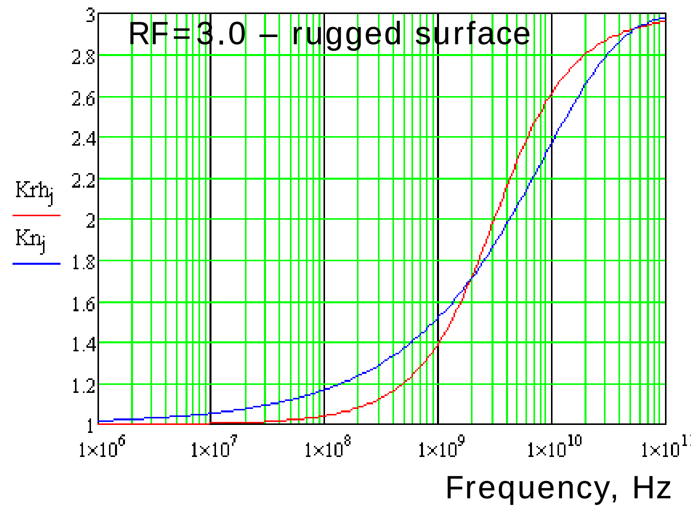
Roughness correction coefficients

With roughness factor we can adjust expected maximal possible attenuation due to rough surface

Computed for copper with Δ=1 um
Red lines – modified Hammerstad-Jensen model
Blue lines – model used in Simbeor software (less then 10% difference)

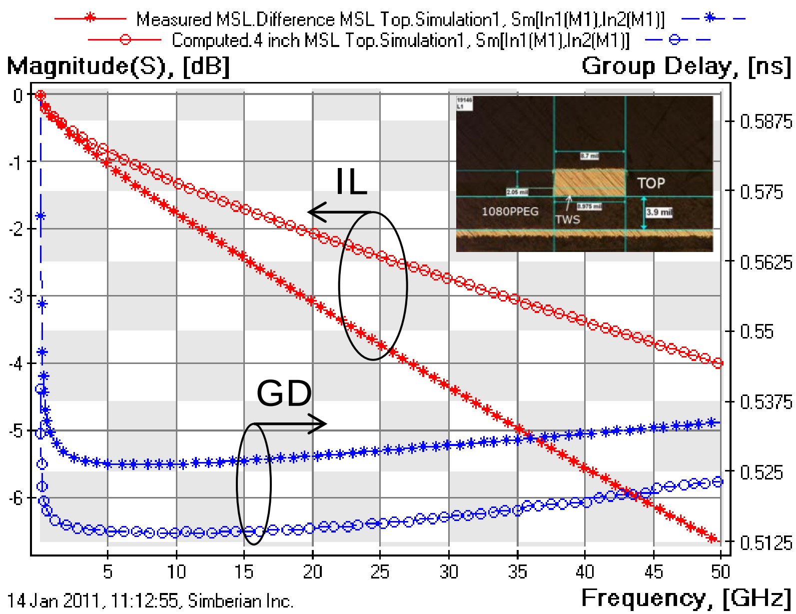


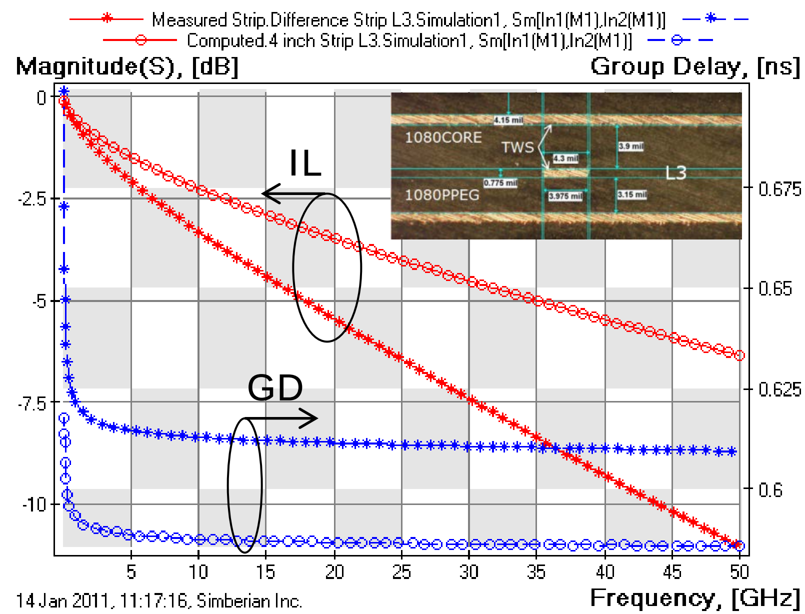




TWS & IS680-1080 – No Roughness

- Huge difference in insertion loss (IL) and in Group Delay both in microstrip and strip-line configurations

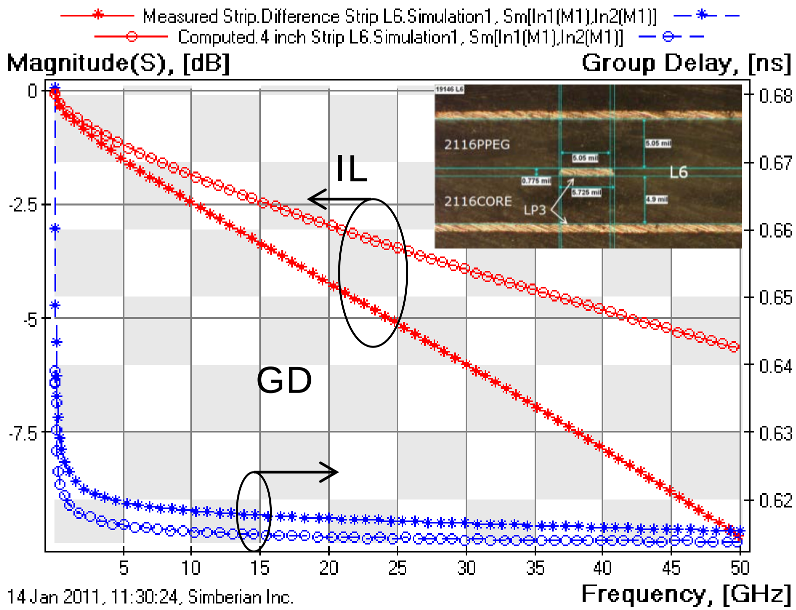


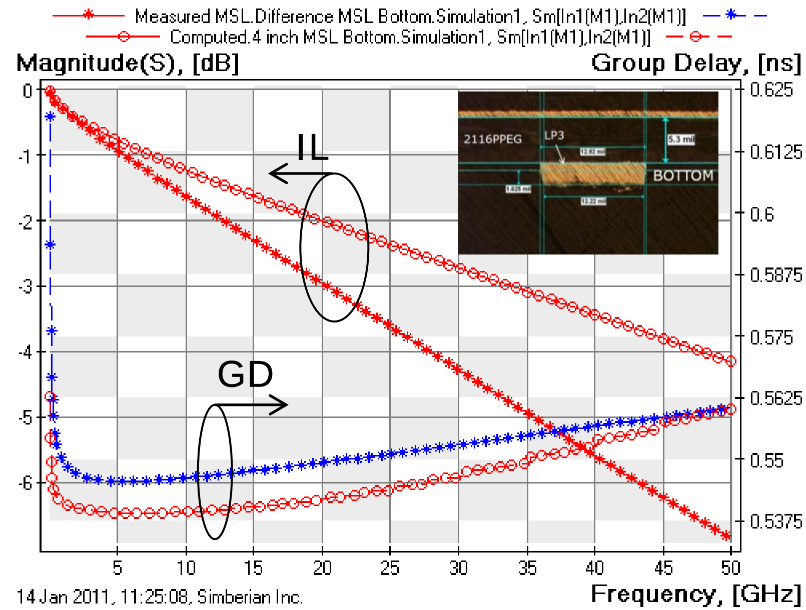


Stars – measured and fitted, Circles - modeled

LP3 & IS680-2116 – No Roughness

- Huge difference in insertion loss (IL) and relatively small in Group Delay both in microstrip and strip-line configurations

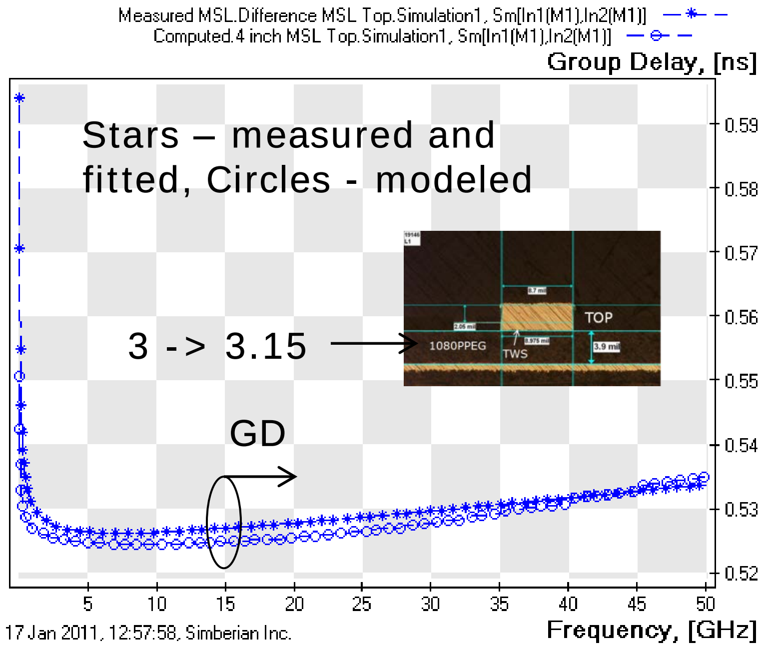


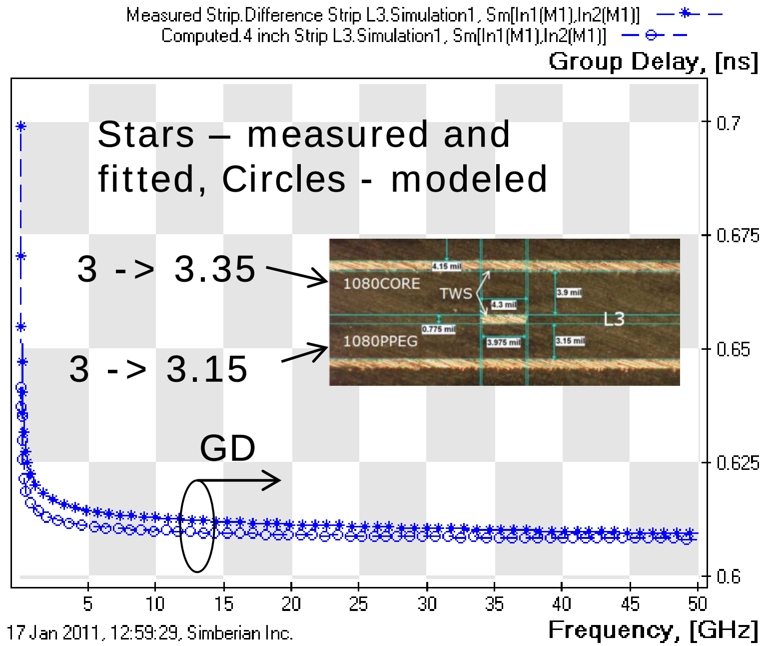


Stars – measured and fitted, Circles - modeled

Roughness effect

- To match group delay dielectric constants are adjusted:
  - 3 -> 3.15 for 1080 prepreg (5%), 3-> 3.35 for 1080 core (>10%)
  - 3.3 -> 3.36 for 2116 prepreg, 3.3 -> 3.25 for 2116 core (within specifications)

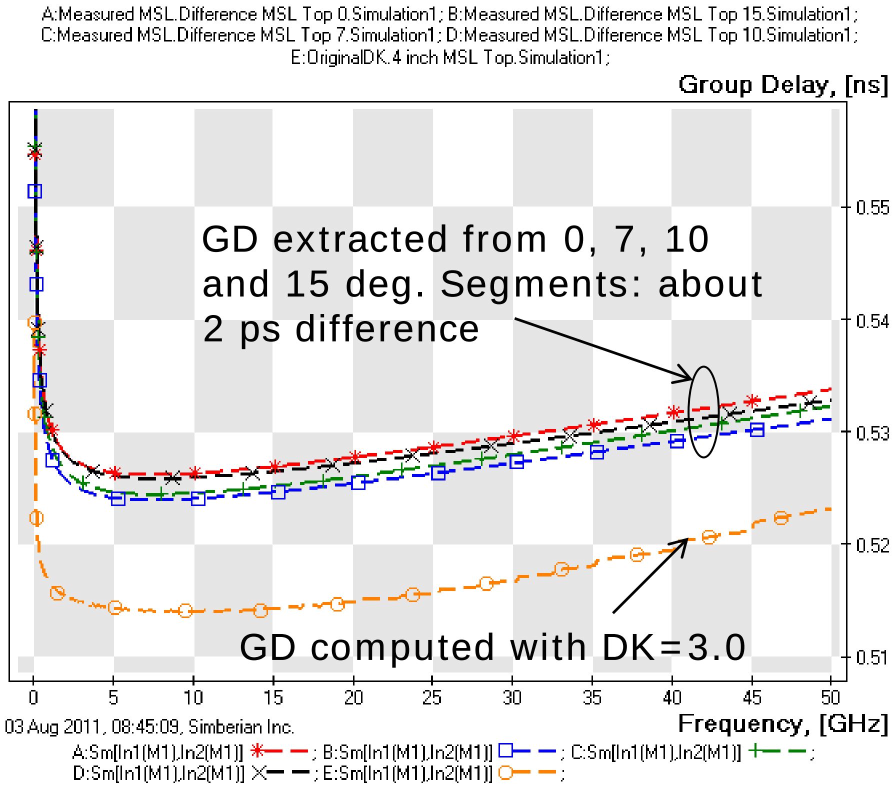


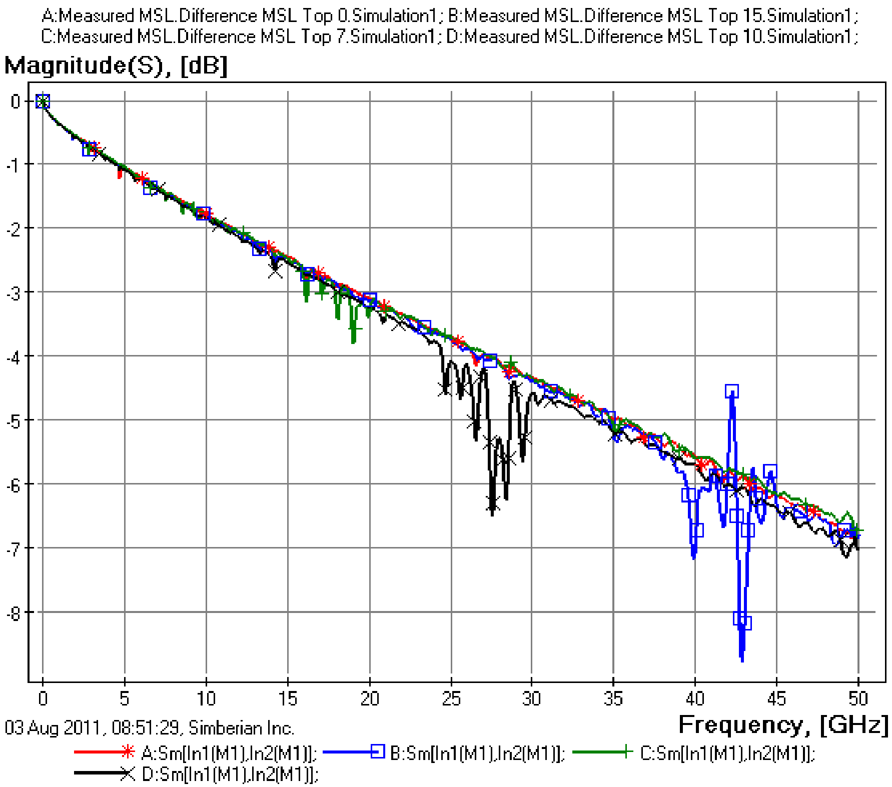


- Is this the effect of roughness?

Definitely not the "weave effect"

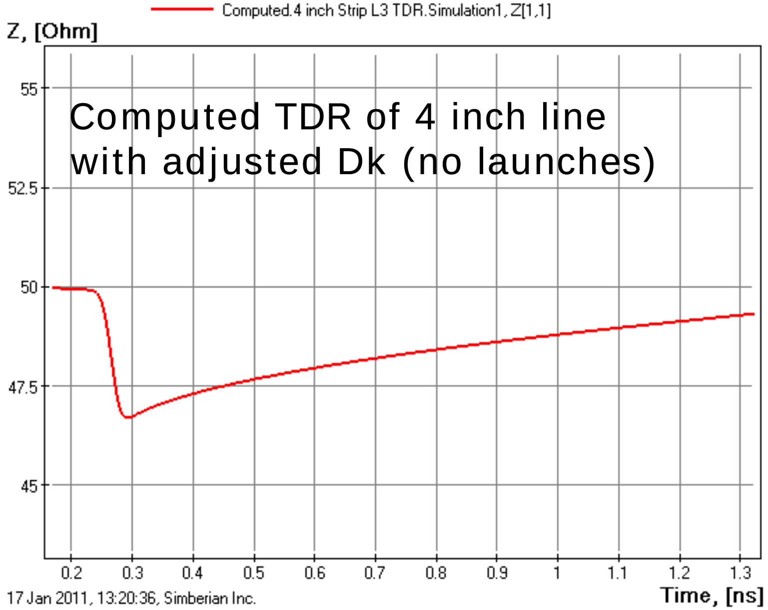
- Traces running at 7, 10 and 15 degrees to the fiber show the same higher group delay!!!

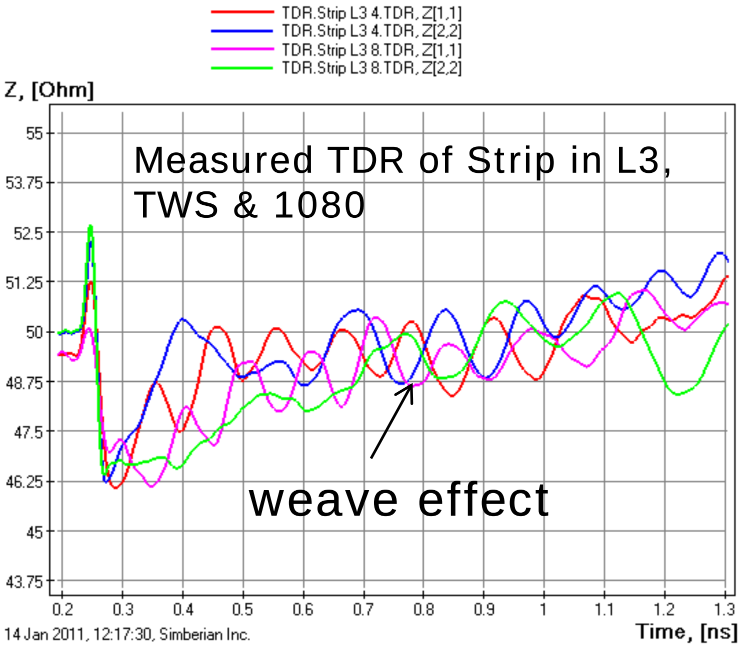




Roughness increases capacitance!!!

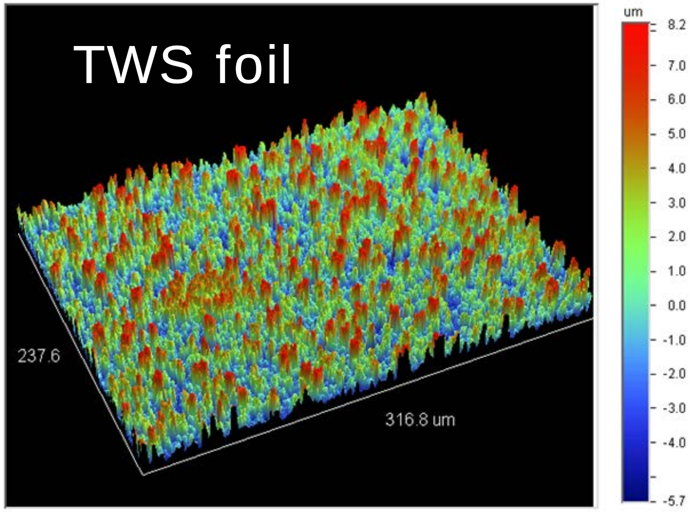
- The effect was first noticed in
  - Deutsch, A. Huber, G.V. Kopcsay, B. J. Rubin, R. Hemedinger, D. Carey, W. Becker, T Winkel, B. Chamberlin, “Accuracy of Dielectric Constant Measurement Using the Full-Sheet-Resonance Technique IPC-T650 2.5.5.6 ” p. 311-314, ., *IEEE Symposium on Electrical Performance of Electronic Packaging, 2002*
- Explained as increase in conductor inductance (no evidence for that)
  - Horn, A.F. Reynolds, J.W. Rautio, J.C. Conductor profile effects on the propagation constant of microstrip transmission lines, 2010 IEEE MTT-S International Microwave Symposium Digest (MTT), p. 868 – 871, May 2010.
- The effect is actually capacitive because of group delay increases and the observed impedance decreases

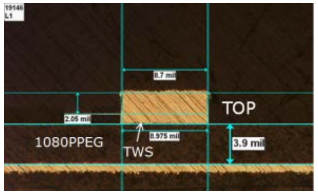


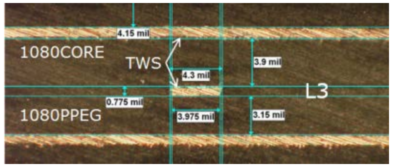


Surface spikes cause increase in capacitance

- Multiple spikes are about 11um from top to bottom
- Electric field is singular on the spikes (similar to strip edges)
- Consistent for 2 line types
  - About 5% increase for MSL with one TWS surface
  - >10% increase for strip line with two TWS surfaces
- Consistent increase in group delay and decrease in characteristic impedance over very wide frequency band

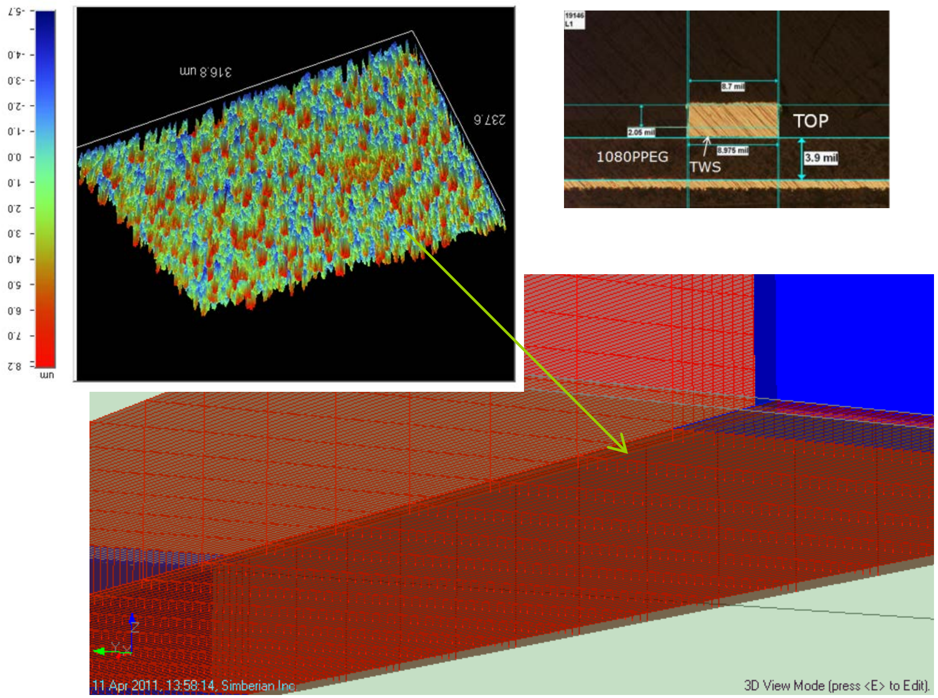


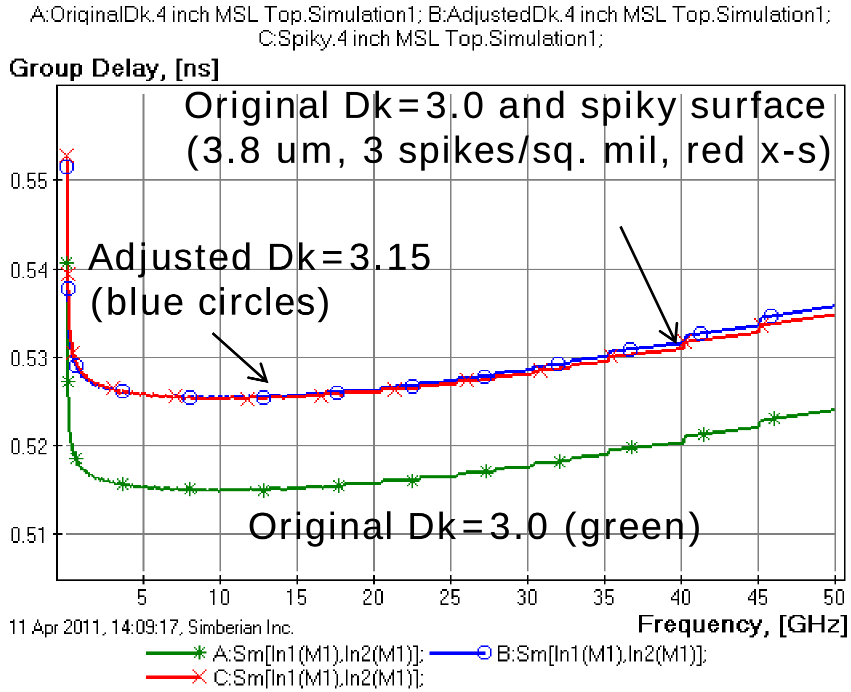




Singular surface roughness model

- Multiple spikes on the surface of conductor are up to 10 um for TWS copper
- Spikes increase capacitance of the surface due to singularity of electric field
- We are dealing with **singular surfaces**

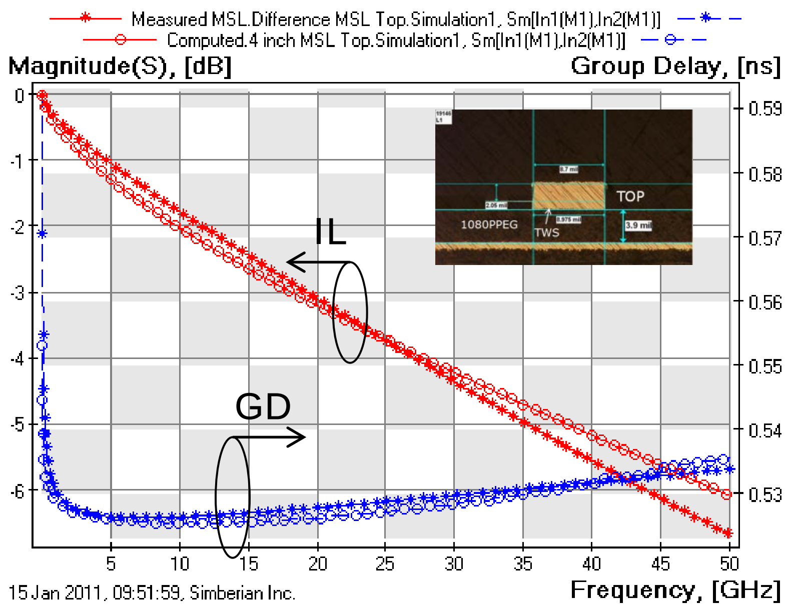


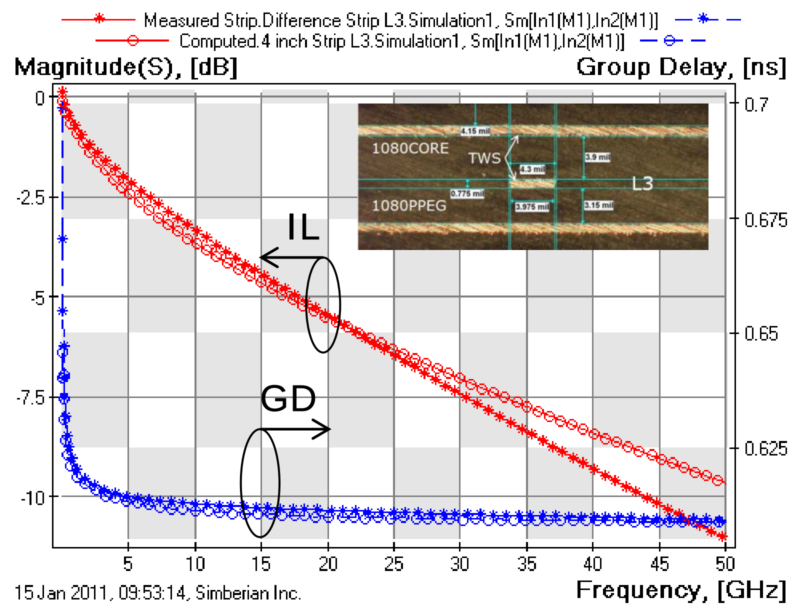


With appropriate spike size and distribution should work for any strip size without Dk adjustment

TWS & IS680-1080 – Roughness from profilometer measurements

- Dielectric constants are adjusted 3 -> 3.15 for 1080 prepreg, 3-> 3.35 for 1080 core
- Roughness parameters from profilometer: Rq=2.6 um, RF=1.85 (25% for shiny)
- Insertion loss still does not match the measurements!

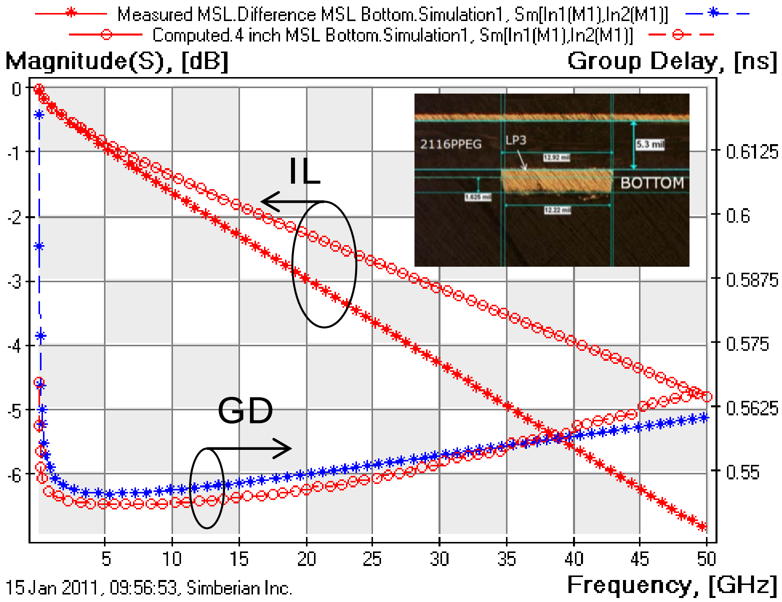


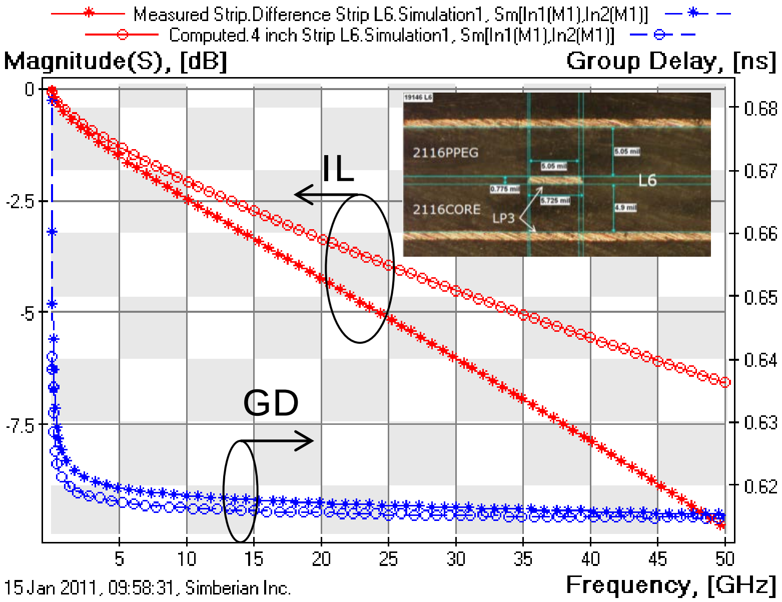


Stars – measured and fitted, Circles - modeled

LP3 & IS680-2116 – Roughness from profilometer measurements

- Dielectric constants are adjusted 3.3 -> 3.36 for 2116 prepreg, 3.3 -> 3.25 for 2116 core
- Roughness parameters from profilometer: Rq=0.68 um, RF=1.3 (25% for shiny)
- Insertion loss is considerably smaller than measured!

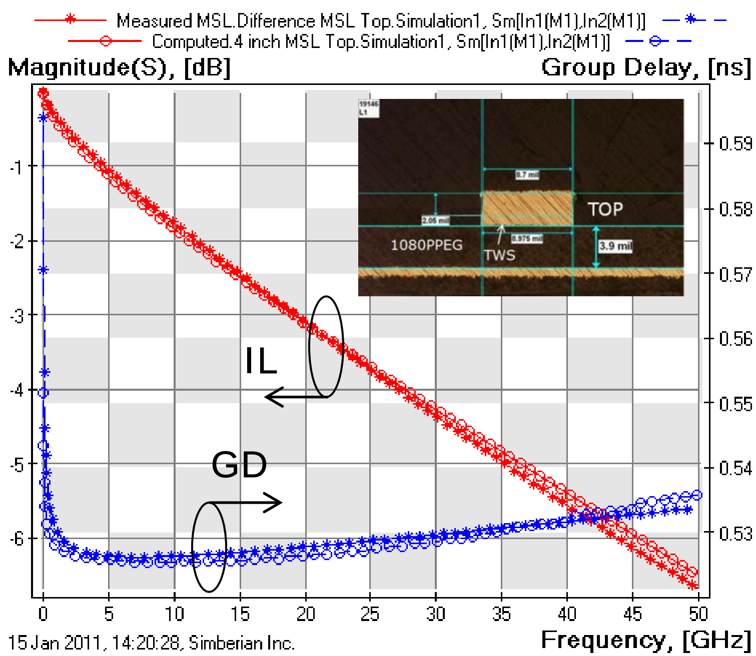


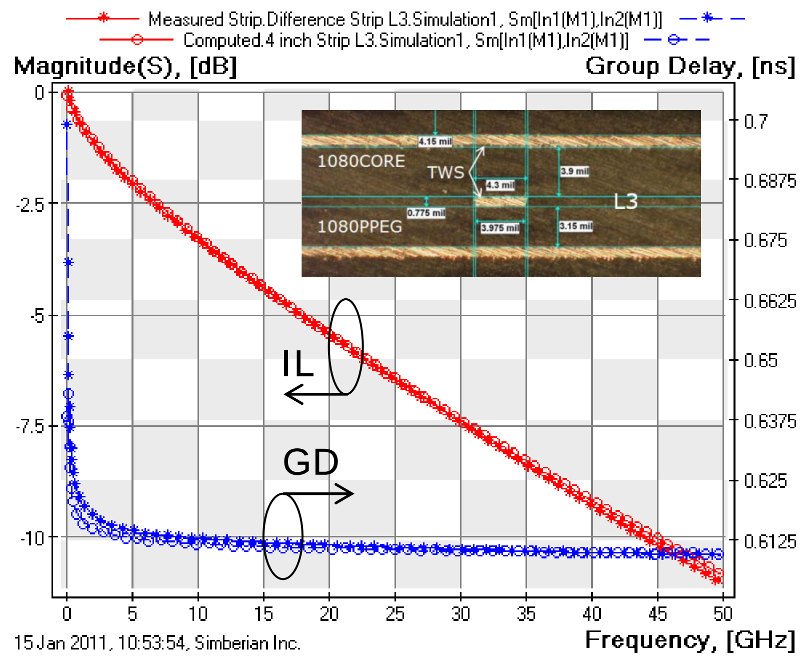


Stars – measured and fitted, Circles - modeled

TWS & IS680-1080 – Adjusted roughness parameters to fit the measurements (Simbeor)

- Dielectric constants are adjusted 3 -> 3.15 for 1080 prepreg, 3-> 3.35 for 1080 core
- Roughness parameters: Rq=0.35 um, RF=2.8 for all surfaces
- Both insertion loss and group delay now match well!

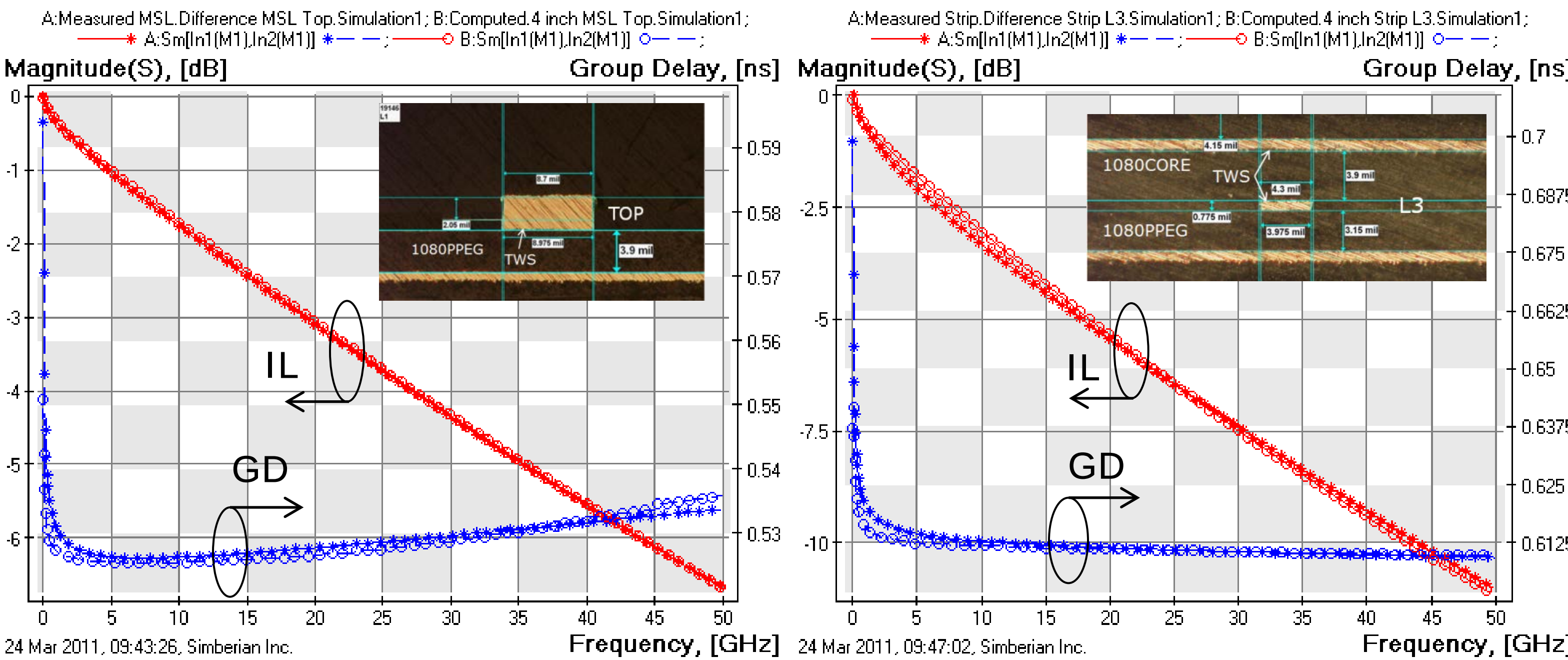




Stars – measured and fitted, Circles - modeled

TWS & IS680-1080 – Adjusted roughness parameters to fit the measurements (MHCC)

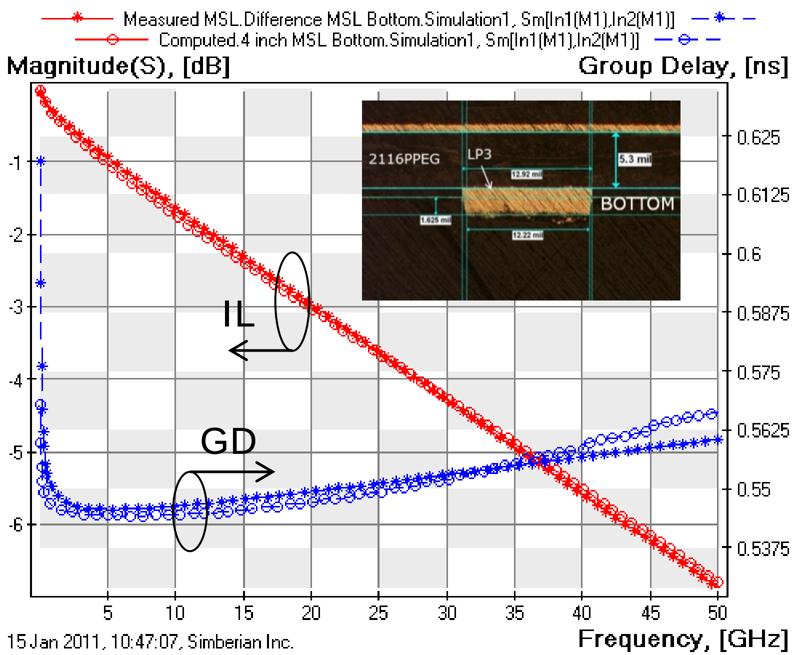
- Dielectric constants are adjusted 3 -> 3.15 for 1080 prepreg, 3-> 3.35 for 1080 core
- Roughness parameters: Rq=0.35 um, RF=2.6 for all surfaces
- Both insertion loss and group delay now match well!

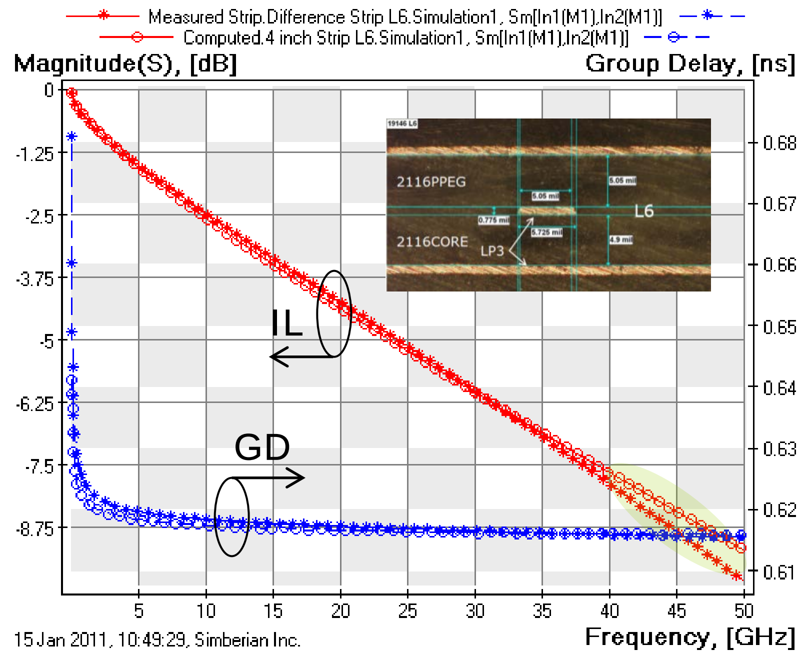


Stars – measured and fitted, Circles - modeled

LP3 & IS680-2116 – Adjusted roughness parameters to fit the measurements

- Dielectric constants are adjusted 3.3 -> 3.36 for 2116 prepreg, 3.3 -> 3.25 for 2116 core
- Roughness parameters: Rq=0.11 um, RF=7 for all surfaces
- Acceptable match for insertion loss and group delay (not perfect for strip)





Stars – measured and fitted, Circles - modeled

Conclusion

- A new practical method for roughness characterization has been proposed
  - Trefftz finite elements used for the conductor impedance operator computation
  - Local differential surface impedance operator adjusted with a roughness correction coefficient
  - Modified Hammerstad correction coefficient has been proposed and used for the adjustment
  - The roughness model parameters are identified with generalized modal S-parameters.
- **Capacitive effect of roughness has been reported and spiky surface model has been proposed**
- A test board has been built and investigated up to 50 GHz
- It was shown that the suggested approach is acceptable for analysis of interconnects on such board within some variation of trace widths at frequencies from DC to 50 GHz or with data rates up to 25-30 Gbps

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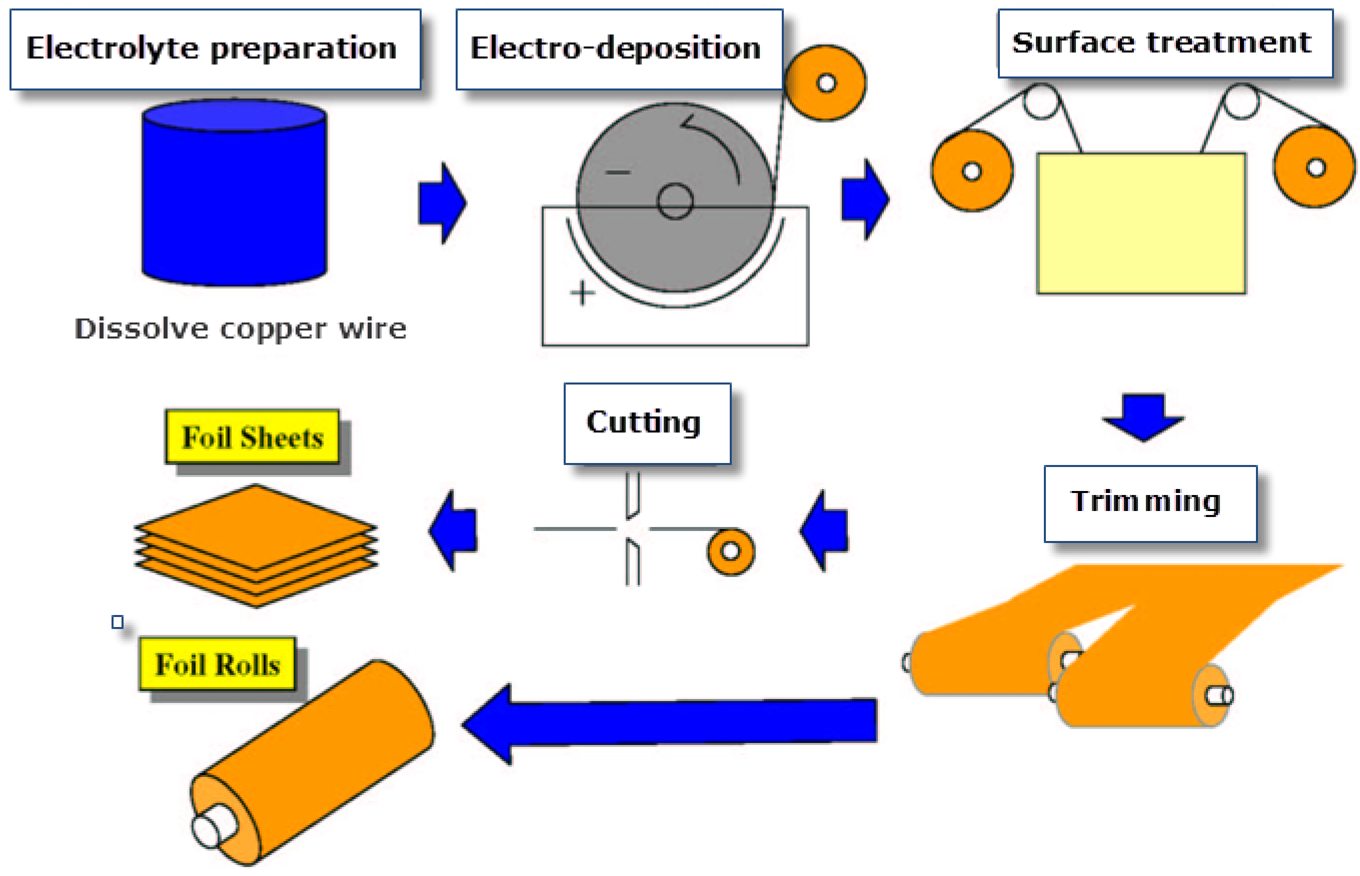
  - www.isola-group.com
- Simberian Inc.
  - www.simberian.com

Appendix: Backup slides

- When to account for roughness
- Roughness characterization methods references
- Test board measurements
- TFE conductor model validation

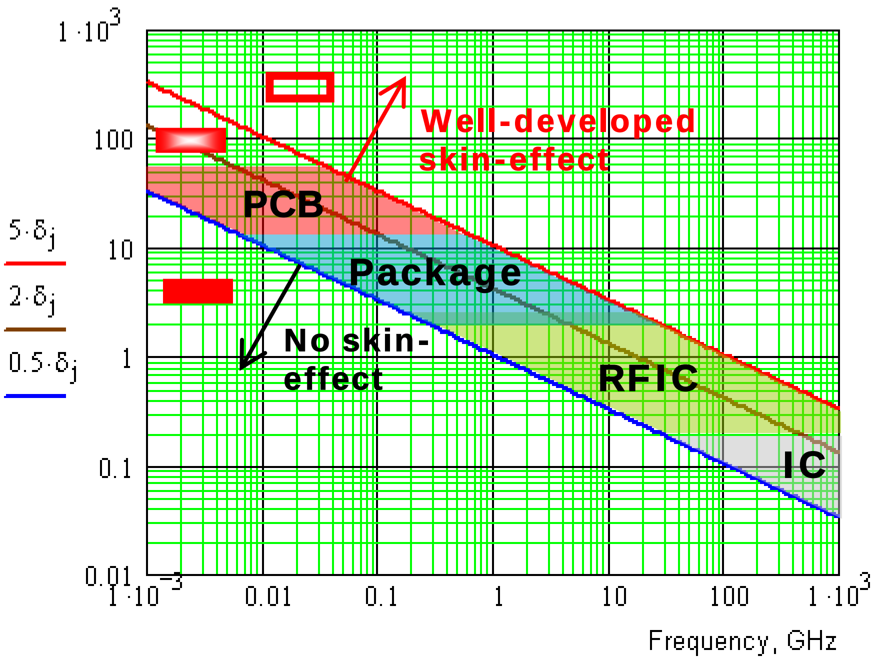
Copper foil manufacturing process

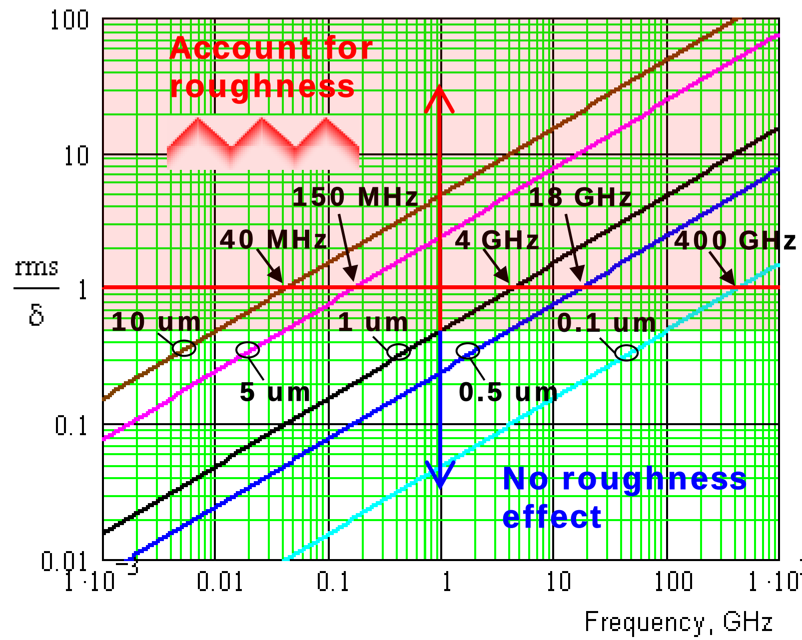


Transition to skin-effect and roughness

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

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





Interconnect or plane thickness 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)

Hammerstad model is not so bad if applied appropriately

- G. Brist, S. Hall, S. Clouser, T Liang, "Non-classical conductor losses due to copper foil roughness and treatment," *2005 IPC Electronic Circuits World Convention,* February 2005
- T. Liang, S. Hall, H. Heck, & G. Brist, "A practical method for modeling PCB transmission lines with conductor roughness and wideband dielectric properties," IEE MTT-S Symposium Digest, p. 1780, November 2006

Applied Hammerstad's correction coefficient to complex conductor resistance (includes internal inductance)

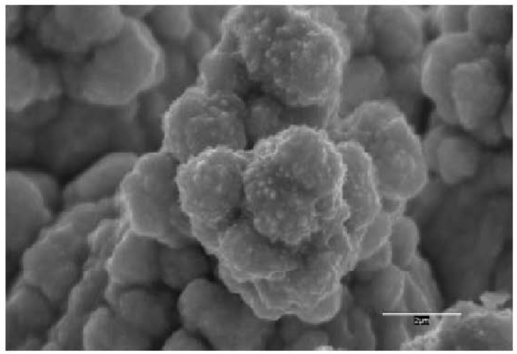
$$K_{sr} = 1 + \mathrm{sgn}(w)\frac{2}{\pi}\arctan[1.4(\frac{\Delta}{\delta})^2]$$

$$\begin{aligned}
L(\omega) &= L_{ref} + R(\omega)/\omega \\
C(\omega) &= C_{ref} \cdot \varepsilon_r(\omega)/\varepsilon_{ref} \\
R(\omega) &= R_{ref} \cdot \sqrt{\omega/\omega_{ref}} \cdot K_{SR} \\
G(\omega) &= G_{ref} \cdot [\varepsilon_r(\omega)/\varepsilon_{ref}](\omega/\omega_{ref}) \cdot [\tan\delta(\omega)/\tan\delta_{ref}]
\end{aligned} \qquad (8)$$

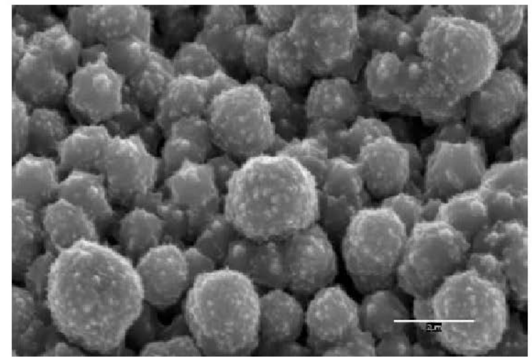
Good agreement in insertion loss and pulse delay for rough copper

“Snowball” model

- P. G. Huray, O. Oluwafemi, J. Loyer, E. Bogatin, X. Ye “Impact of Copper Surface Texture on Loss: A Model that Works”, *DesignCon 2010*



High Profile texture



Low Profile texture

“Snowballs”

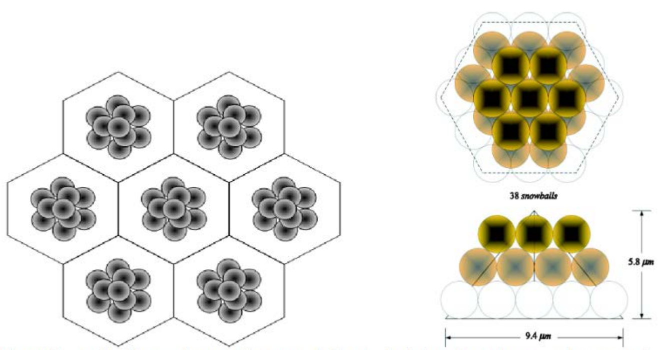


Figure 14. Left- Eleven $1\ \mu m$ radius snowballs stacked into three layers on hexagonal cells with a height of about $5.8\mu m$. Right- Thirty Eight $1\ \mu m$ radius snowballs stacked into three layers on hexagonal cells. Both schemes have a base dimension of $9.4\ \mu m$.

Huray’s correction coefficient

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

Good agreement in insertion loss only

Hemispherical model

- S. Hall, S. G. Pytel, P. G. Huray,D. Hua, A. Moonshiram, G. A. Brist, E. Sijercic, “Multigigahertz Causal Transmission Line Modeling Methodology Using a 3-D Hemispherical Surface Roughness Approach”, *IEEE Trans. On MTT*, vol. 55, No. 12, p. 2614-2623, Dec. 2007

Hemispherical approximation

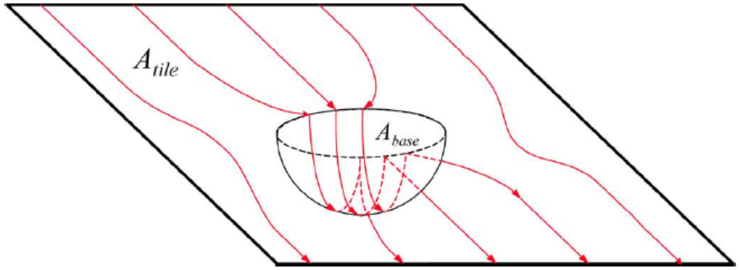


Fig. 13. Current streamlines of flowing over a single protrusion.

“Hemispherical” correction coefficient

$$K_s = \frac{\left|\mathrm{Re}\left[\eta \frac{3\pi}{4k^2}\left(\alpha(1)+\beta(1)\right)\right]\right| + \frac{\mu_o \omega \delta}{4}\left(A_{\mathrm{tile}} - A_{\mathrm{base}}\right)}{\frac{\mu_o \omega \delta}{4} A_{\mathrm{tile}}} \qquad (32)$$

Good agreement in insertion loss and group delay for very rough copper

“If relatively smooth copper is being used, with an rms value of the surface roughness less than 2 um, then Hammerstad’s formula (3) has been shown to adequately approximate the surface roughness losses.”

Small perturbation method

- A.E. Sanderson, Effect of surface roughness on propagation of TEM mode, Advances in Microwaves, vol. 7, 1971.
- S. Sundstroem, "Stripline Models with Conductor Surface Roughness", *Master of Science Thesis*, Helsinki University of Technology, Finland, February 2004.
- S. Hinaga, M., Koledintseva, P. K. Reddy Anmula, & J. L Drewniak, "Effect of conductor surface roughness upon measured loss and extracted values of PCB laminate material dissipation factor," *IPC APEX Expo 2009 Conference*, Las Vegas, March 2009.

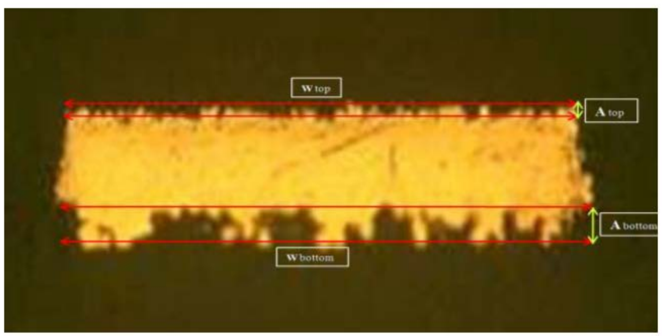


Figure 6.
Trace dimensions and surface roughness of the trace

Sundstroem's correction coefficient

$$\alpha_c = \frac{\beta_o \eta_o}{4 p Z_o}\left[\delta + \frac{1}{\delta}\sum_{n=1}^{\infty} H_n^2 \left(1 - \sqrt{\frac{1}{2}\left(\sqrt{n^4 s^4 \delta^4 + 4} - n^2 s^2 \delta^2\right)}\right)\right]$$

Stochastic approach

- L. Tsang, X. Gu, & H. Braunisch, “Effects of random rough surfaces on absorption by conductors at microwave frequencies, *IEEE Microwave and Wireless Components Letters,* v. 16, n. 4, p. 221, April 2006
- R. Ding, L. Tsang, & H. Braunisch, “Wave propagation in a randomly rough parallel-plate waveguide,” *IEEE Transactions on Microwave Theory and Techniques,* v. 57, n.5, May 2009

Power absorption enhancement function on the base of spatial Power Spectral Density (PSD)

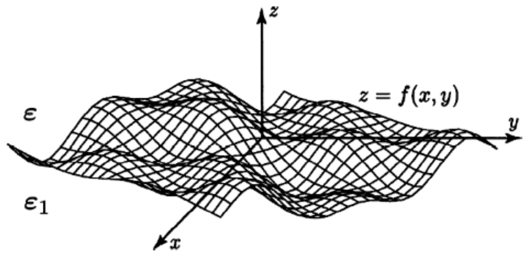


Fig. 1. Random rough interface between dielectric and conductor in a 3-D problem.

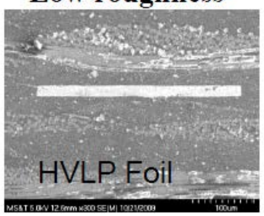
$$\frac{\langle P_{a,\text{rough}} \rangle}{P_{a,\text{smooth}}} = 1 + \frac{2h^2}{\delta^2} - \frac{4}{\delta} \int_0^{\infty} dk_x W(k_x) \operatorname{Re} \sqrt{\frac{2i}{\delta^2} - k_x^2} \, . \tag{38}$$

Difficult to measure, profilometer does not provide enough resolution

Experimental separation of losses

- M. Y. Koledintseva, J. L. Drewniak, S. Hinaga, F. Zhou, A. Koul, A. Gafarov, Experiment-Based Separation of Conductor Loss from Dielectric Loss in PCB Striplines, DesignCon2011

Low roughness



Medium roughness

Differential extrapolation and redistribution method (DERM)

$$\alpha_T^{STD} = K_1^{STD}\sqrt{\omega} + K_2^{STD}\omega + K_3^{STD}\omega^2;$$
$$\alpha_T^{VLP} = K_1^{VLP}\sqrt{\omega} + K_2^{VLP}\omega + K_3^{VLP}\omega^2;$$
$$\alpha_T^{HVLP} = K_1^{HVLP}\sqrt{\omega} + K_2^{HVLP}\omega + K_3^{HVLP}\omega^2.$$

High roughness

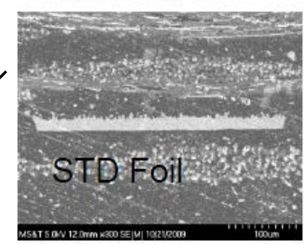


Figure 4. K_1 coefficient as a function of the roughness parameter A_r.

Equivalent boundary conditions

- C. L. Holloway, E. F. Kuester, “Impedance-Type Boundary Conditions for a Periodic Interface Between a Dielectric and a Highly Conducting Medium”, *IEEE Trans. on AP*, vol. 48, N 10, p. 1660-1672, Oct. 2000.

Equivalent Generalized Impedance Boundary Conditions

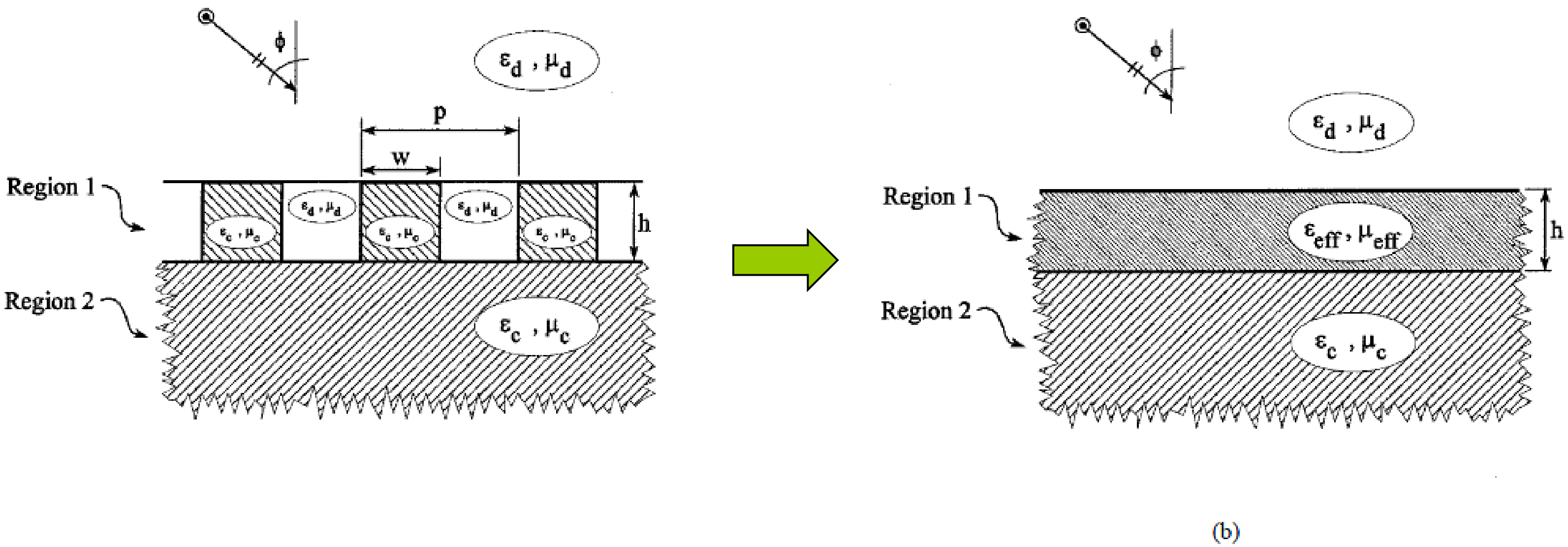


Fig. 9. (a) Two-region representation of the rectangular roughness profile. (b) Representation of region 1 as an effective medium with permittivity ϵ_{eff} and permeability μ_{eff}.

Surface as a periodic structure

- M. V. Lukic´, D. S. Filipovic,“Modeling of 3-D Surface Roughness Effects With Application to -Coaxial Lines”, IEEE Trans. on MTT, vol. 55, No. 3, p. 518-525, 2007.

Rough surface as 2D and 3D periodic structures

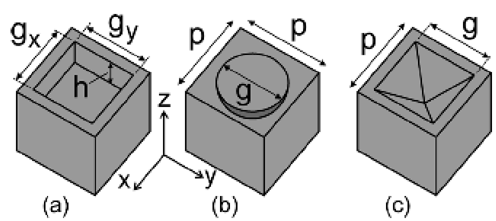


Fig. 8. Unit cells of periodic: (a) cubical, (b) semiellipsoidal, and (c) pyramidal indentations in a conductor surface. The depth for all three shapes is denoted by h and, for clarity, it is shown only for cubical indentations.

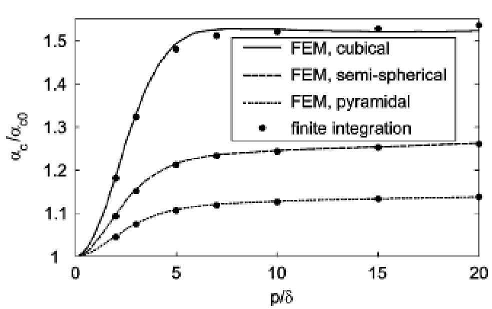


Fig. 9. Comparison between the FEM and finite-integration technique results for relative change of the attenuation constant α_c for cubical, semispherical, and pyramidal indentations in conductor surfaces: $g/p = 0.75$, $h = g/2$.

Lukic’-Filipovic correction coefficient:

$$\frac{\alpha_c}{\alpha_{c0}} = 1 + \frac{2}{\pi} \tan^{-1}\left(\left(\frac{\Delta}{\delta}\right)^2 \left(0.094\left(\frac{\Delta}{\delta}\right)^2 - 0.74\left(\frac{\Delta}{\delta}\right) + 1.87\right)\right). \quad (3)$$

Direct electromagnetic analysis

- X. Chen, “EM modeling of microstrip conductor losses including surface roughness effect,” *IEEE Microwave and Wireless Components Letters,* v. 17, n.2, p. 94, February 2007

Brute force approach – not practical

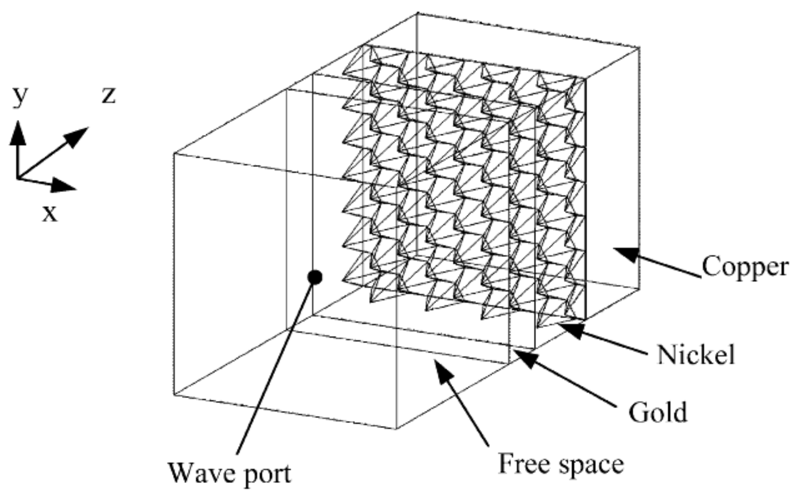


Fig. 2. 3-D HFSS model to obtain effective conductivity of the Au–Ni–Cu metal system. Surface roughness is considered.

Direct electromagnetic analysis

- Deutsch, A. Huber, G.V. Kopcsay, B. J. Rubin, R. Hemedinger, D. Carey, W. Becker, T Winkel, B. Chamberlin, “Accuracy of Dielectric Constant Measurement Using the Full-Sheet-Resonance Technique IPC-T650 2.5.5.6 ” p. 311-314, ., *IEEE Symposium on Electrical Performance of Electronic Packaging, 2002*

Brute force approach – not practical

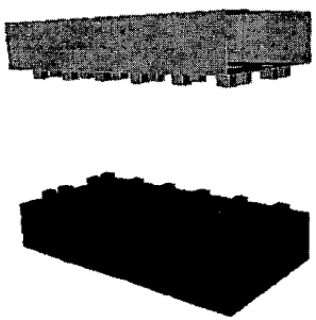
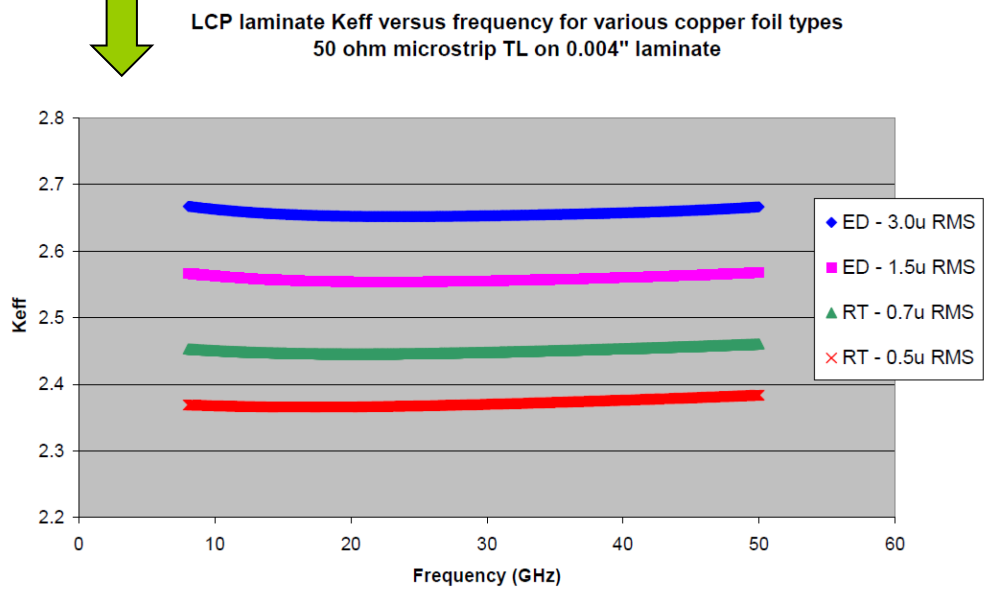


Fig. 5 Model used to include a pseudo-random pattern for the rough ridges.

Observed about 5% increase in effective Dk due to roughness

Effect of roughness on phase constant

- A. Deutsch, at all, “Accuracy of Dielectric Constant Measurement Using the Full-Sheet-Resonance Technique IPC-T650 2.5.5.6 ” p. 311-314, ., *IEEE Symposium on Electrical Performance of Electronic Packaging, 2002*
- A. F. Horn III, J. W. Reynolds, P. A. LaFrance, J. C. Rautio, “Effect of conductor profile on the insertion loss, phase constant, and dispersion in thin high frequency transmission lines”, *DesignCon 2010*.

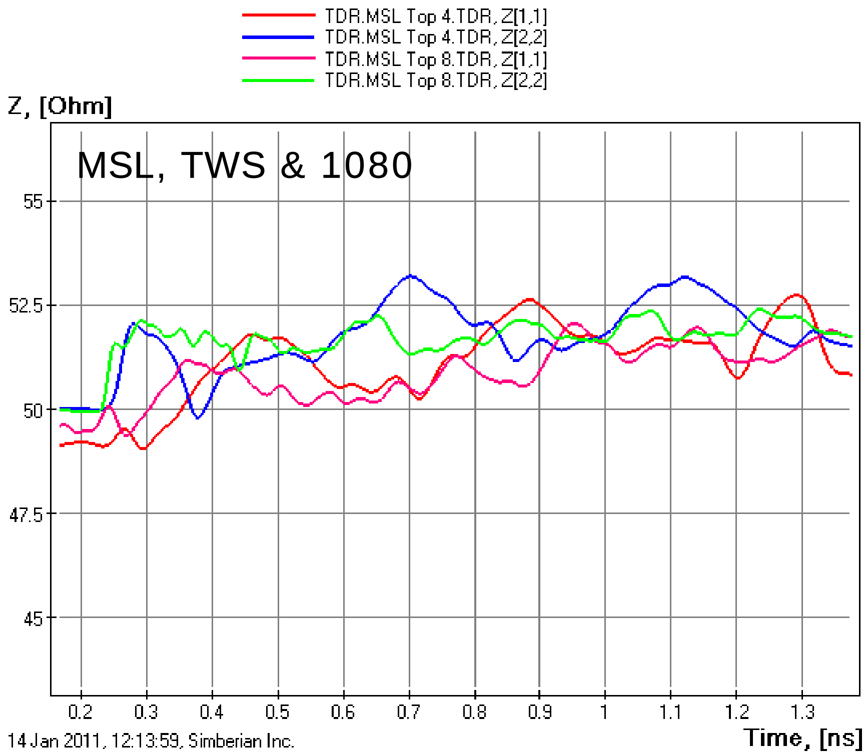


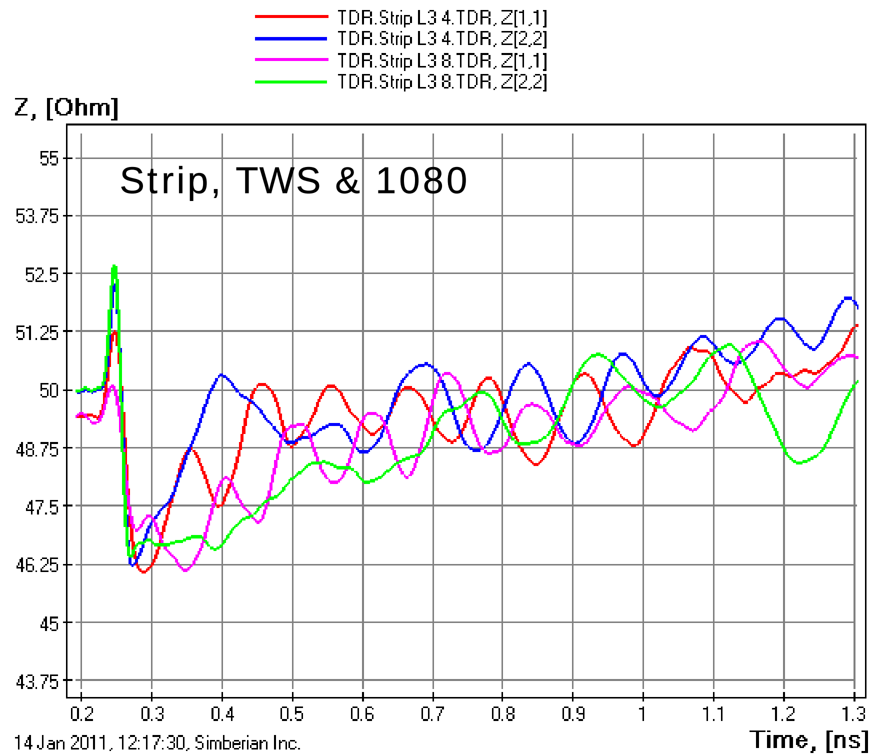
Roughness increases not only attenuation, but also effective dielectric constant or Keff (effective slow down coefficient)

Is this due to excessive capacitance or inductance?

Test board TDR computed from S-parameters

- Large variations (> 3 Ohm) in the impedance
- Weave effect?

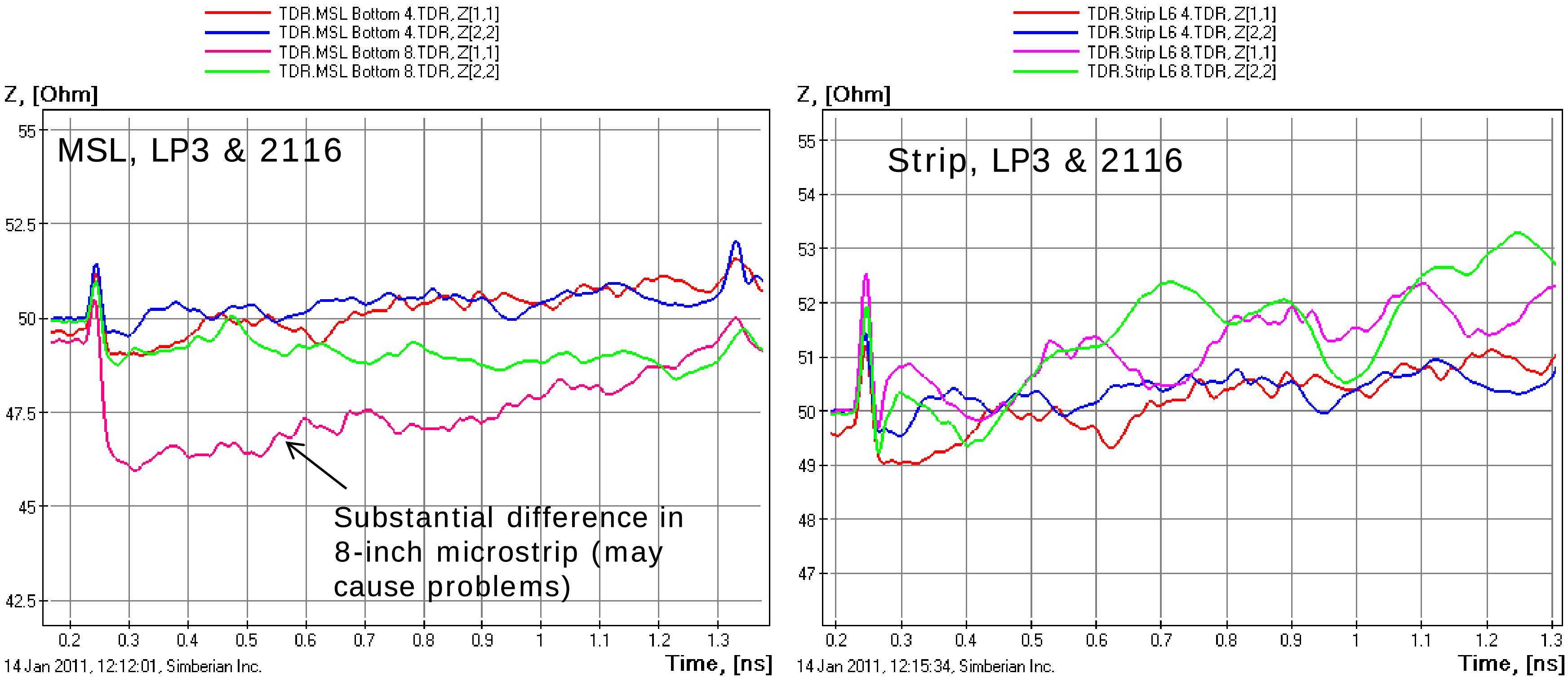




Computed with rational macro-models with RMS Error < 0.065

Test board TDR computed from S-parameters

- Less variations along the line, but large difference between samples

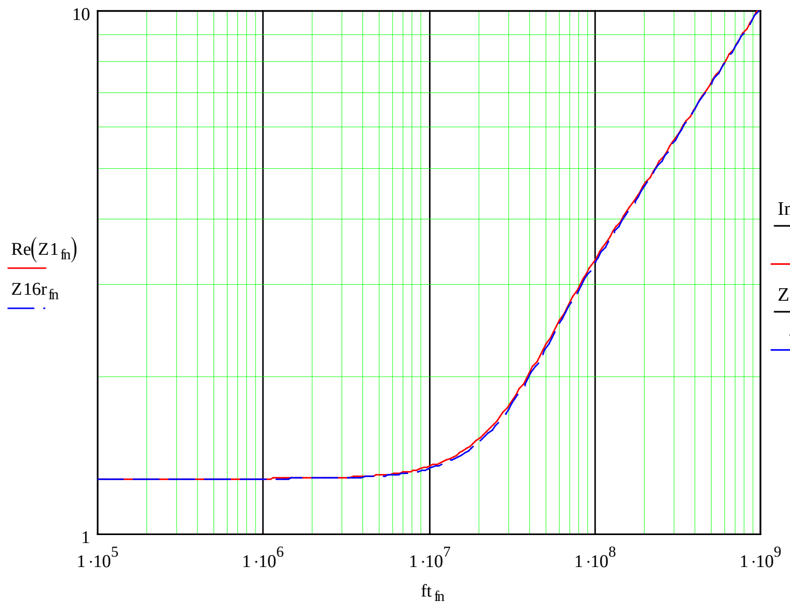


Computed with rational macro-models with RMS Error < 0.065

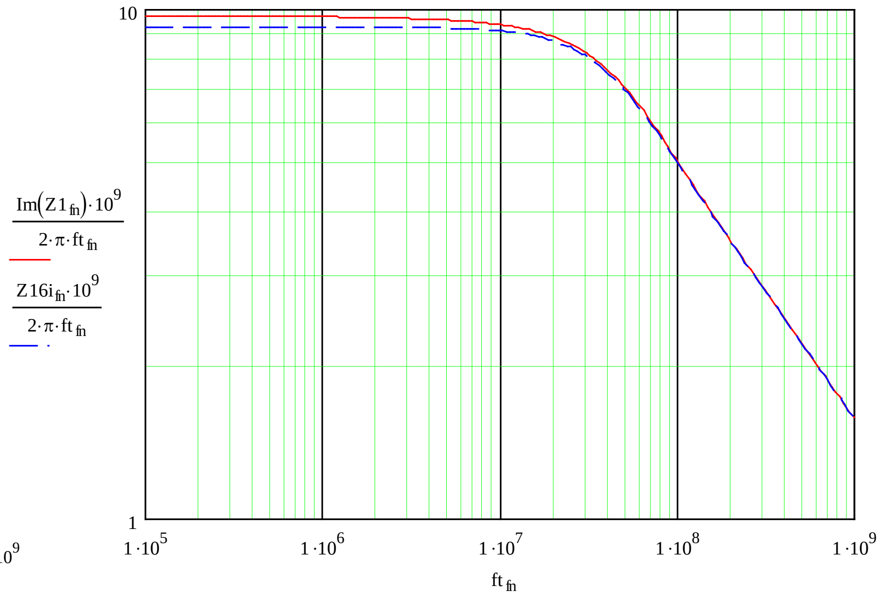
Impedance or 15 mil by 1.4 mil copper conductor computed with TFE

15 mil by 1.4 mil rectangular copper conductor simulated with 1 element (red solid line) and with 128x16 elements (blue dashed line)

Resistance, Ohm/m



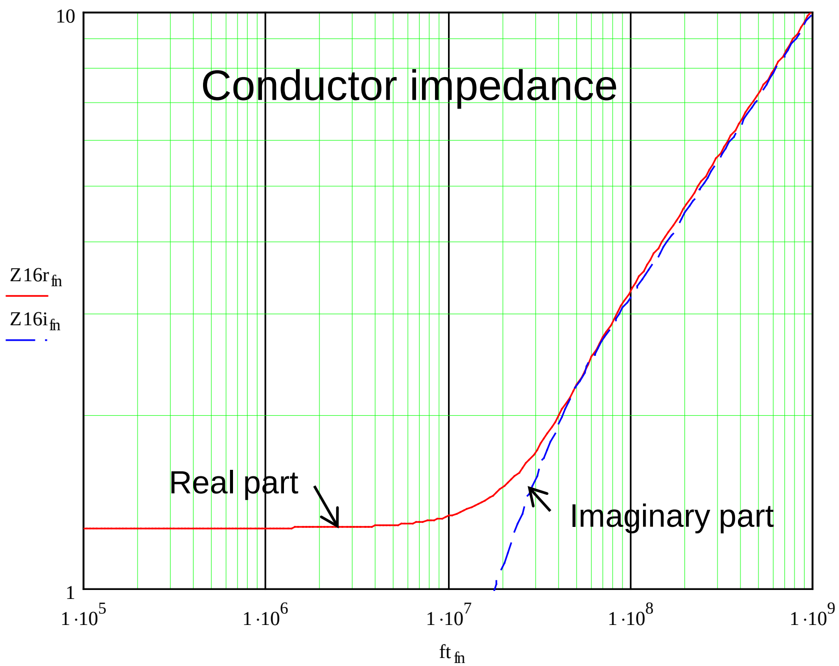
Internal inductance, nH/m

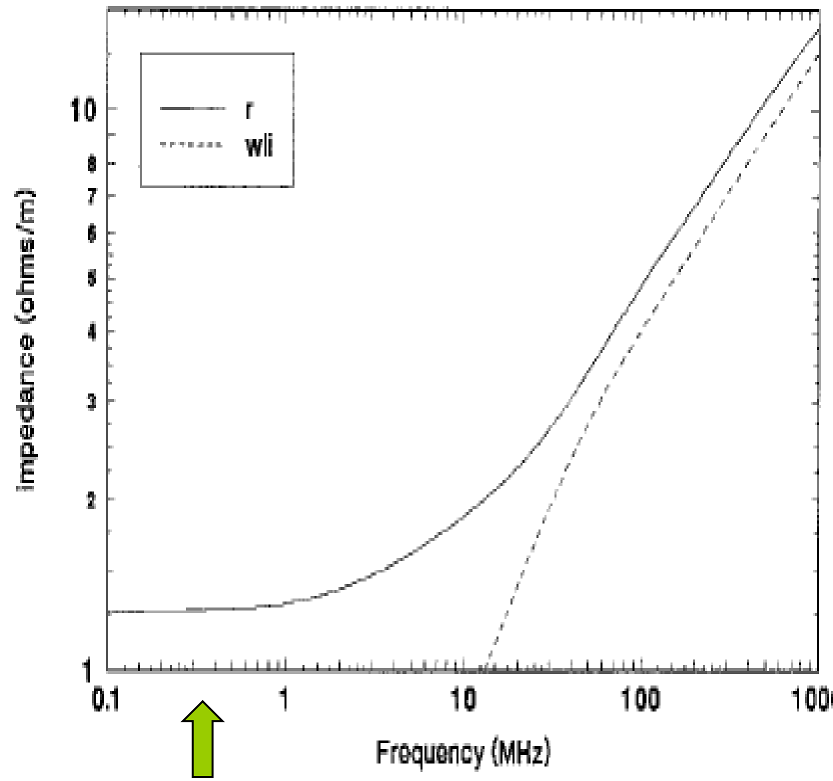


Even 1 element produce accurate conductor model!

Impedance or 15 mil by 1.4 mil copper conductor computed with TFE

- Real and imaginary parts of conductor impedance converge at high frequencies according to Wheeler and Trefftz elements

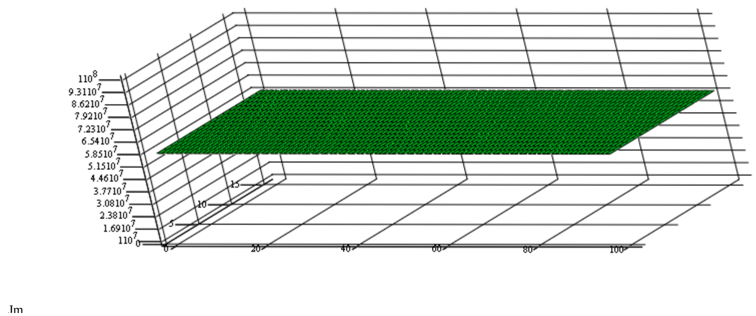




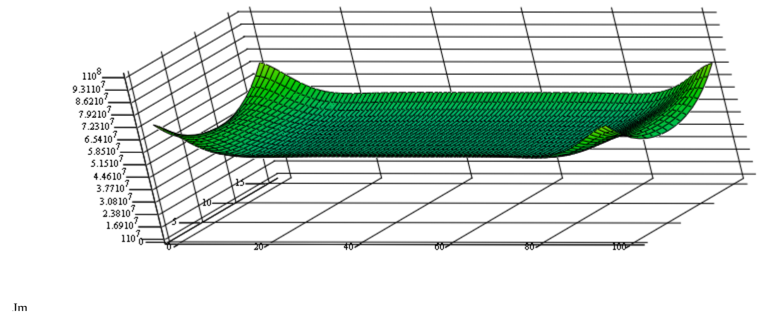
G. Antonini, A. Orlandi, C. R. Paul, Internal impedance of conductors of rectangular cross section, *IEEE Trans. Microwave Theory and Techniques,* vol. 47, N 7, 1999, p. 979-985.

Current distribution in 15 mil by 1.4 mil copper conductor computed with TFE

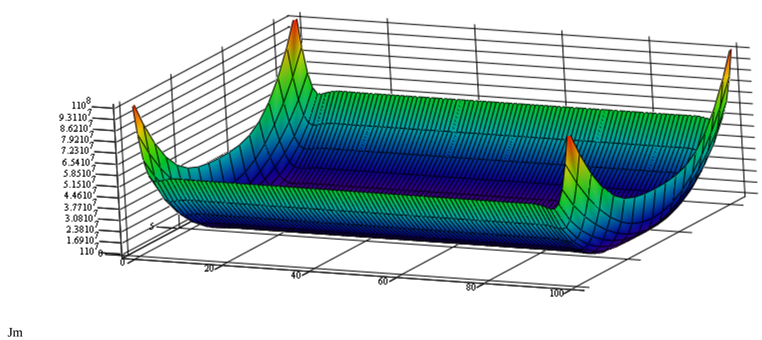
100 KHz (0.05 skin depth)



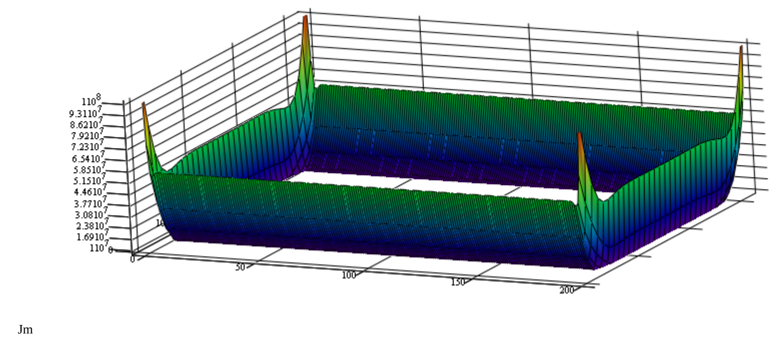
10 MHz (1.7 skin depth)



100 MHz (5.4 skin depth)



1 GHz (17 skin depth)



1 or multiple elements predict almost identical current distribution!