DesignCon® 2013

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SANTA CLARA CONVENTION CENTER

Which one is better?
Comparing Options to Describe Frequency Dependent Losses

Dr. Eric Bogatin, Bogatin Enterprises and University of Colorado
Dr. Don DeGroot, CCN & Andrews University
Dr. Paul Huray, University of S. Carolina
Dr. Yuriy Shlepnev, Simberian Software Corp.

UBM Electronics

Overview

- Eric:
  - Introduction: the challenge
  - A practical process
  - Causal smooth copper and dielectric loss models
- Paul:
  - Copper surface texture first principles model and measurements
- Yuriy:
  - Copper surface texture approximations and measurements
- Don:
  - Summary: so what? closing the design – manufacturing – design feedback loop

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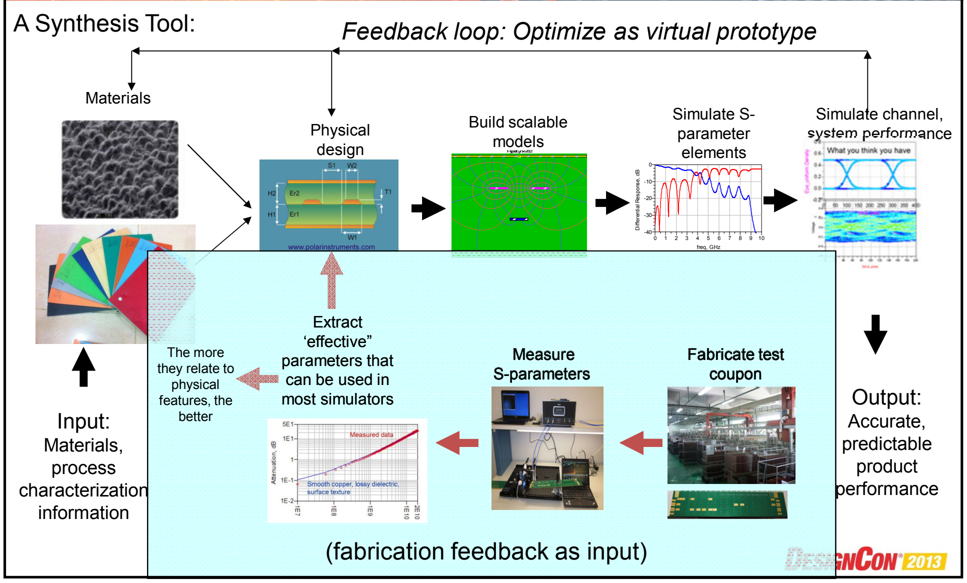
Final Goal: Accurate Prediction of System Performance from 1st Principles Input



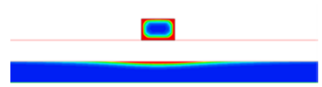
Extract "Effective" Parameters Based on Models Available in Most Simulators

- Wideband Debye model: 4 dielectric properties parameters
  - Dk @ f0
  - Df @ f0
  - f1
  - f2

$$Dk(f) = Dk_2 + \frac{\Delta Dk}{\log(f_2) - \log(f_1)}(\log(f_2) - \log(f))$$

$$Df(f) = \frac{\varepsilon''(f)}{Dk(f)} = \frac{0.682}{Dk(f)} \frac{\Delta Dk}{\log(f_2) - \log(f_1)} = \frac{-0.682}{Dk(f)} slope$$

- Smooth copper conductor loss
  - Conductor line width (w)
  - Bulk conductivity of the copper (σ)



- Surface texture power loss
  - Modified Hammerstad approximation: RMS, Surface Factor (SF)
  - Huray Snowball Model: a_i, N_i, A_{matte}/A_{flat}

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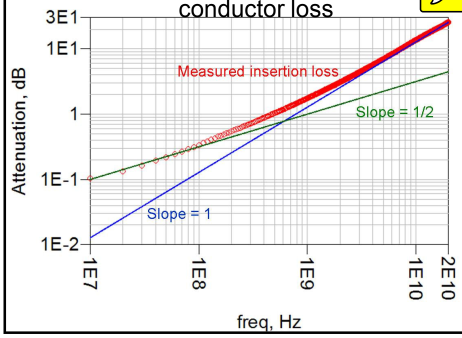
Analysis of Insertion Loss

with self-normalized port Z_0 to minimize return loss (< ~ -20 dB)

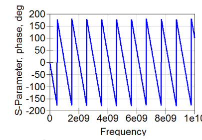
$$S21[dB/in] = 4.34\left(\frac{R_L}{Z_0} + G_L Z_0\right)$$

$$S21[dB/in] \propto \sqrt{f} + f$$

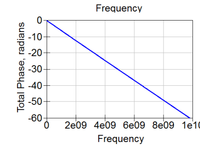
Plot of magnitude of S21, in dB, on Log-Log scale shows dominance of dielectric or conductor loss



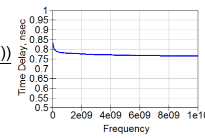
Phase of S21



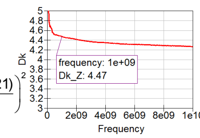
Unwrapped phase of S21



$$TD(f) = \frac{\text{unwrapped(phase(S21(f)))}}{\text{frequency}}$$



$$Dk\_eff(f) = \left(\frac{c}{v(f)}\right)^2 = \left(\frac{11.8}{Len}TD(f)\right)^2 = \left(\frac{11.8}{Len}\frac{\text{unwrapped(phase(S21))}}{\text{frequency}}\right)^2$$



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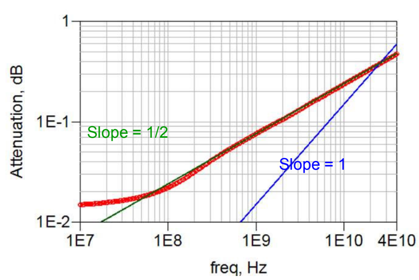
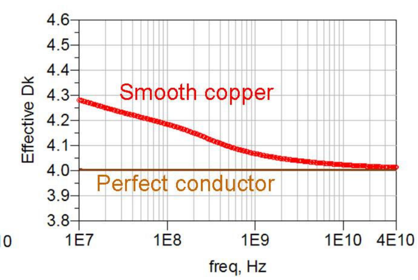
Impact on Insertion Loss from Smooth Copper: a casual model

For 50 Ohm line, no dielectric loss, copper conductivity, ½ oz, w = 7 mils





- Sqrt(f) insertion loss
- Note dispersion at low frequency from freq dependent inductance

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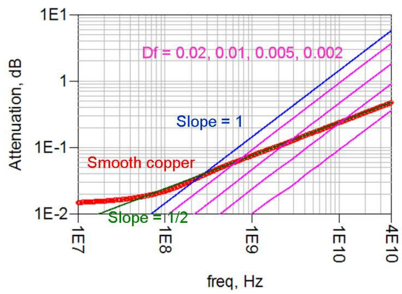
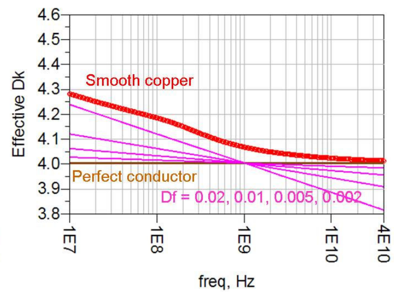
Wide Band Debye Dielectric Loss

$$Df(f) = \frac{\varepsilon''(f)}{Dk(f)} = \frac{0.682}{Dk(f)} \frac{\Delta Dk}{\log(f_2) - \log(f_1)} = \frac{-0.682}{Dk(f)} \text{slope} \qquad Dk(f) = Dk_2 + \frac{\Delta Dk}{\log(f_2) - \log(f_1)} \left(\log(f_2) - \log(f)\right)$$



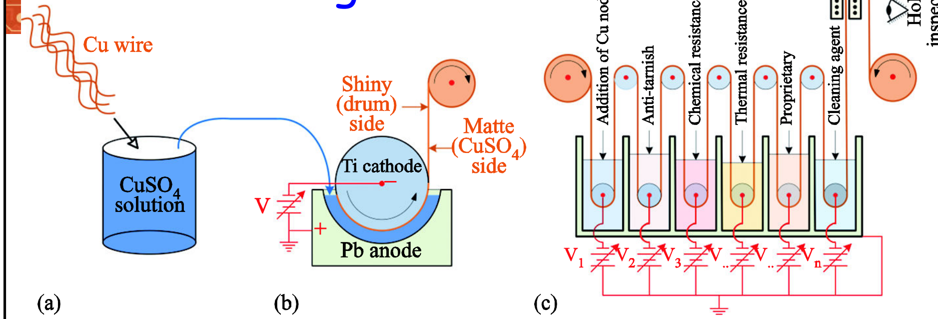


- Insertion loss is very close to slope of 1
- Df relates to value of insertion loss and slope of Dk with frequency
- Lower loss → less dielectric dispersion
- At low loss, conductor loss and dispersion may dominate

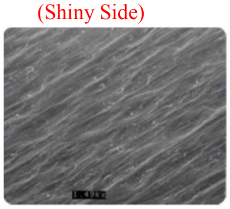
Professor Paul Huray

University of S. Carolina

Typical Copper Foil Manufacturing Process



Before Treatment (Shiny Side)



After Treatment (Shiny Side)

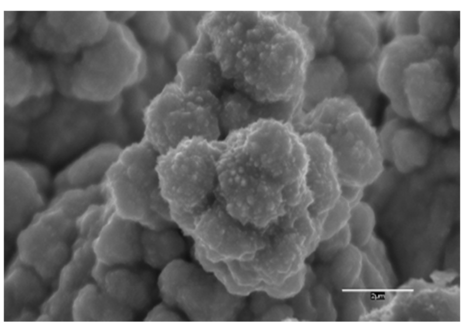
Before Treatment (Matte Side)

After Treatment (Matte Side)

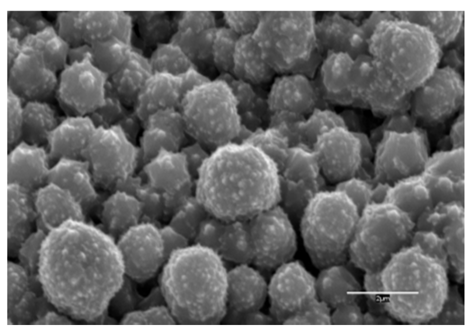
SEM Photos of some rough Copper Foils

SEM pictures are consistent with the following textures:

- High profile samples are made up of copper snowballs arranged on a *Matte* finish surface.
- Low profile samples are made up of copper snowballs randomly scattered on a *Flat* plane.

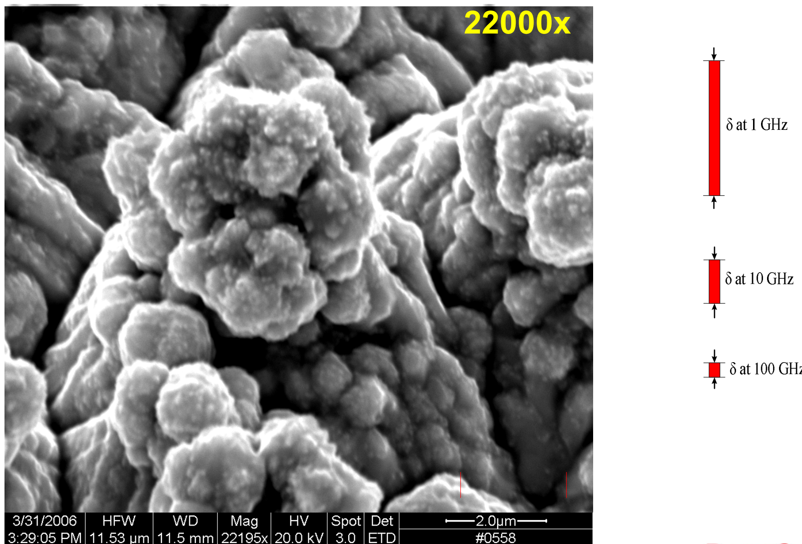


High Profile texture

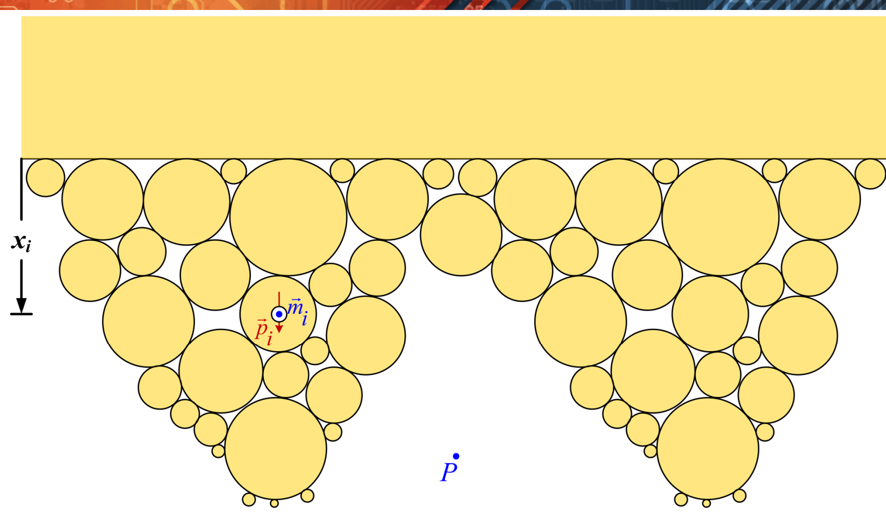


Low Profile texture

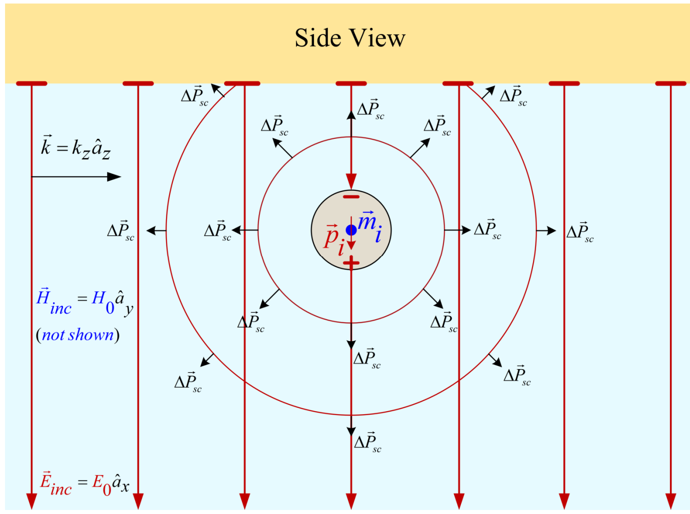
SEM photo of a high profile surface relative to skin depth at 1, 10 and 100 GHz



Non-uniform Snowball Model

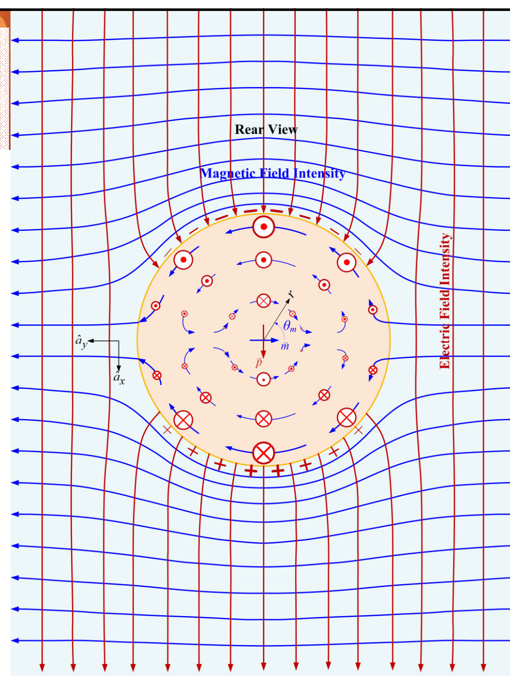


Electromagnetic power scattered from one good conducting sphere by an incident TEM wave



Rear View

snapshot of the Electric & Magnetic Field Intensity of an incident TEM wave as it interacts with one *good* conducting sphere



Good Conductor Cross Sections

- For a good conducting sphere the respective cross-sections, σ, consistent with conductor surface impedance (neglecting quadrupole and higher multipole terms) are:

$$\sigma_{absorbed}(\omega) \approx 3\pi k_2 a_i^2 \delta \Big/ \left[1 + \frac{\delta}{a_i} + \frac{\delta^2}{2a_i^2}\right]$$

$$\sigma_{scattered}(\omega) \approx \frac{10\pi}{3} k_2^4 a_i^6 \left[1 + \frac{2}{5}\left(\frac{\delta}{a_i}\right)\right]$$

- $k_2 = \omega/c_2 = \sqrt{\varepsilon_{r,2}}\,\omega/c$ is the wave number in the propagating medium so the scattered power is in the form of Rayleigh scattering ($\omega^4 a_i^6$) which is large at optical frequencies.
- For a 1 µm radius sphere and frequencies below 9 THz, the absorption cross section is larger than the scattering cross section so that below 100 GHz power lost to scattering may be neglected.
- At 100 GHz, the skin depth, δ, is small compared to radius, a_i =0.5 µm, so copper spheres of that radius absorb incident power with cross-section $\sigma_{i,abs} \approx 3\pi k_2 a_i^2 \delta$

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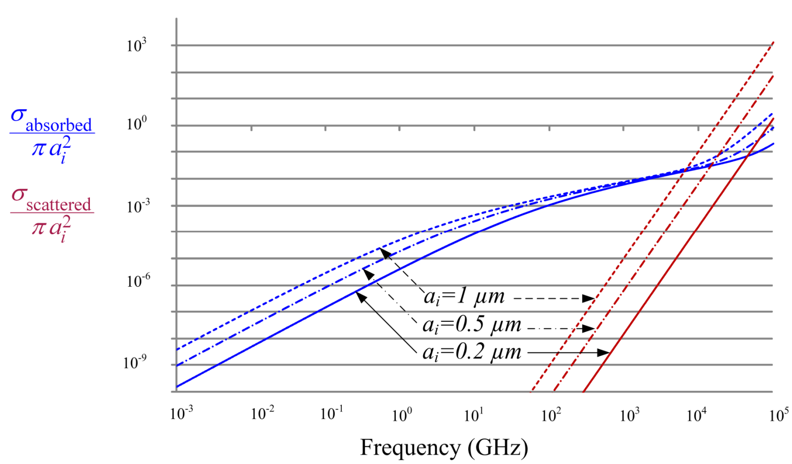
Absorbed and scattered cross sections relative to geometric cross sectional area



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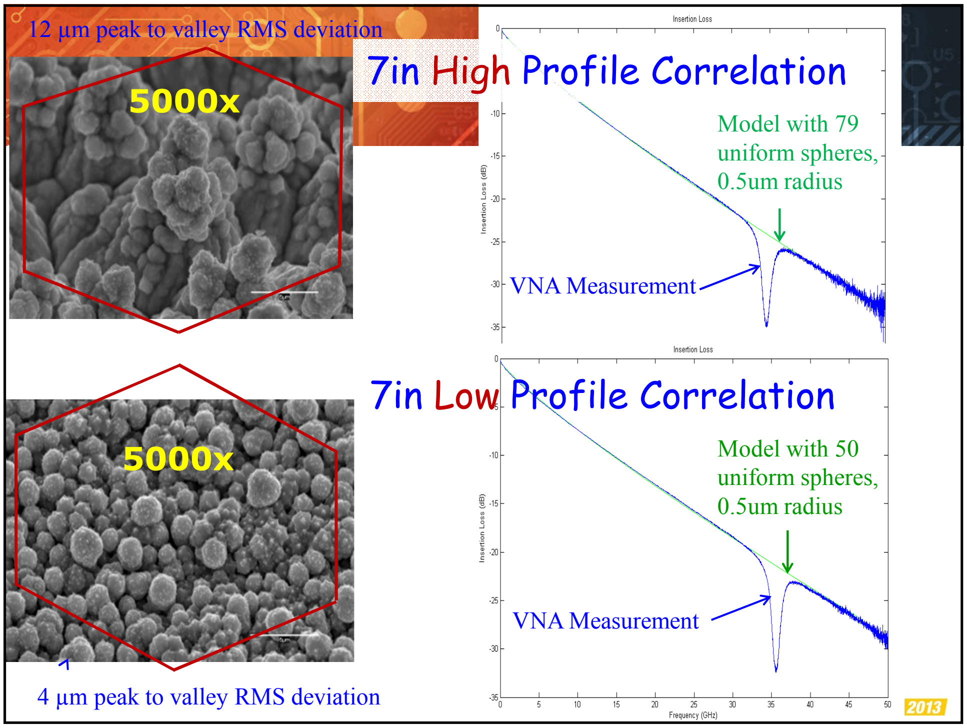

Takeaways for Surface Roughness loss

- The relative power loss produced by a copper surface (as a function of frequency) for a PCB that is roughened by electrodepositing anchor nodules on a *Matte* surface is larger than the power loss of a *Flat* surface by:

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

Conclusions:

- The relative power loss for a stack-up of anchor nodules on a *Matte* surface is independent of the RMS deviation, Δ.

- The relative power loss depends only on:
  - A_{Matte} / A_{Flat},
  - The number, N_i, per unit area, A_{Flat}, of the various additional anchor nodules of radius, a_i,
  - The **sum** of the additional areas of the N_i anchor nodules of radius a_i relative to a *flat* area according to the factor $\left(\frac{3}{2}\right)\left(\frac{N_i 4\pi a_i^2}{A_{Flat}}\right)\Big/\left[1+\frac{\delta}{a_i}+\frac{\delta^2}{2a_i^2}\right]$ where $\delta(\omega)$ is the skin depth at frequency ω not an arctangent function.

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Dr. Yuriy Shlepnev

Simberian Software Corp

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Impedance roughness correction coefficients

- Huray snowball model correction coefficient (HSCC, simplified)

$$K_{rhu} = 1 + \left(\frac{N \cdot 4\pi \cdot r^2}{A_{hex}} \right) \Big/ \left(1 + \frac{\delta}{r} + \frac{\delta^2}{2 \cdot r^2} \right)$$

- Modified Hammerstadt correction coefficient (MHCC)

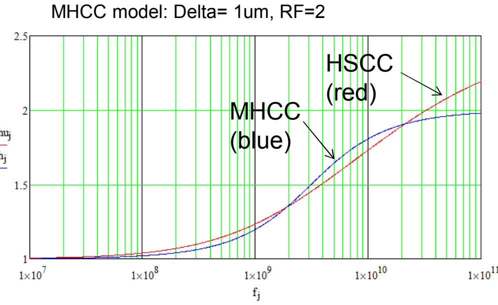
$$K_{rh} = 1 + \left(\frac{2}{\pi} \cdot \arctan\left[1.4 \left(\frac{\Delta}{\delta} \right)^2 \right] \right) \cdot (RF - 1)$$

- Correction coefficients are applied to conductor surface impedance operator (causal correction)

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

Regular treated copper
Huray model: r=0.85 um, At=65 um^2, N=11

MHCC model: Delta= 1um, RF=2



Do we need these models?
If yes, were to get model parameters?

Details in Y. Shlepnev, C. Nwachukwu, Roughness characterization for interconnect analysis. - Proc. of the 2011 IEEE International Symposium on EMC, Long Beach, CA, USA, August, 2011, p. 518-523
See also our DesignCon 2012 paper – available at www.simberian.com

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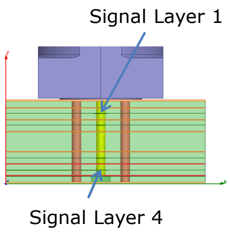
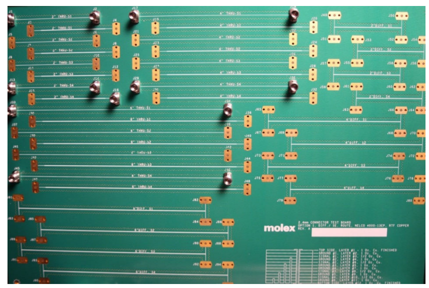
Material identification board

- 12-layer board made with Panasonic Megtron 6 dielectric, VLP copper

6 test fixtures with 2, 4 and 6 inch strip line segments in Layer 1 (S1) and Layer 4 (S4)



Board made by Molex and measured by David Dunham, Molex
Scott McMorrow from Teraspeed Consulting Group designed launches for 2.4mm Molex connectors,



Similar board made with Nelco 4000-EP have been described and investigated up to 50 GHz in:
D. Dunham, J. Lee, S. McMorrow, Y. Shlepnev, 2.4mm Design/Optimization with 50 GHz Material Characterization, DesignCon2011

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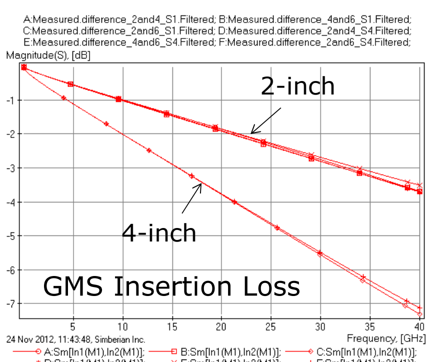
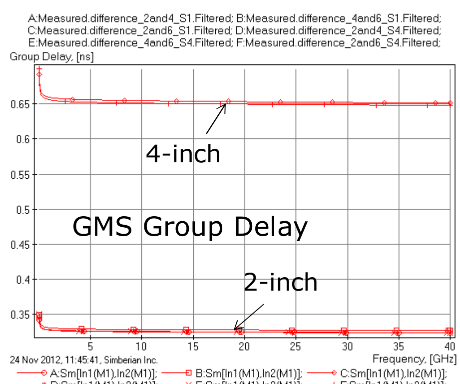
Measured Generalized Modal S-parameters

- Measurements are pre-qualified and GMS-parameters of 2 inch and 4 inch difference segments are extracted from all possible combinations





Details in 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, DesignCon2010, Feb. 2010. See also app notes on material identification with GMS-parameters at www.simberian.com

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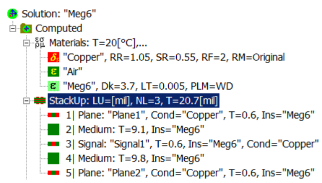
Cross-section and materials for model

- Model to compare with measured GMS-parameters

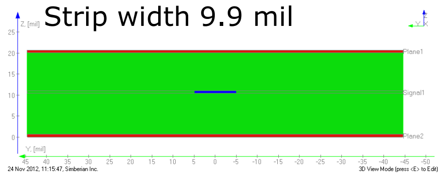


Data from Panasonic Megtron 6 datasheet:

	Test Sample .006" (2-1080 @63%RC)	Dielectric Constant (Dk)	Dississapation Factor (Df)	Test Method Used
FREQUENCY	2 GHz	3.40	0.002	IPC TM 650 2.5.5.5
	4 GHz	3.40	0.003	
	6 GHz	3.40	0.003	
	8 GHz	3.40	0.004	
	10 GHz	3.40	0.004	

Constant Dk and growing LT –
NON CAUSAL (no such models)!

Strip width 9.9 mil



Dk is 3.6-3.7 for 2116 glass style

No data for copper roughness model!

Let's use Dk=3.7 and LT=0.004 from specs…

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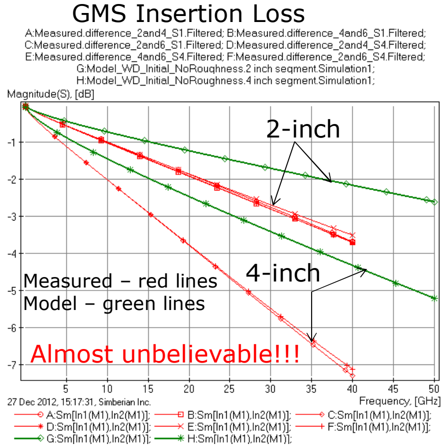
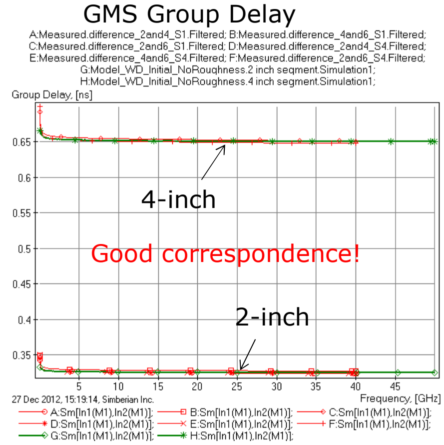
Model with parameters from specs, no roughness (smooth copper)

- Dk=3.7, **LT=0.004**, @ 10 GHz, Wideband Debye model (causal)

GMS Insertion Loss



GMS Group Delay



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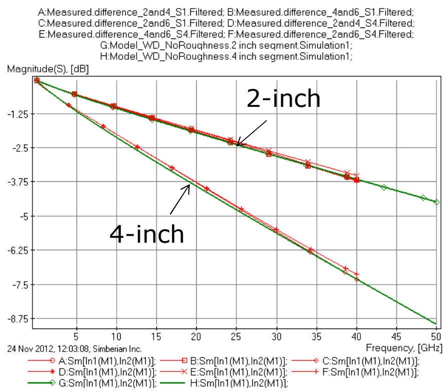
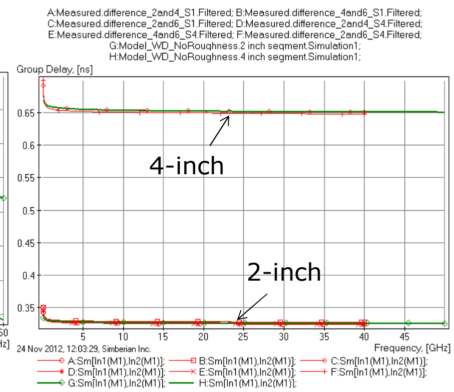
1: Adjusted dielectric model, no roughness

- Wideband Debye model, DK=3.7, **LT=0.0082** at 50 GHz, WD Low frequency is set to 10 GHz – good fit (green lines)

GMS Insertion Loss



GMS Group Delay



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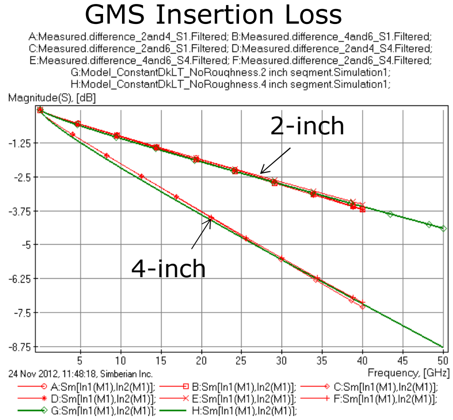
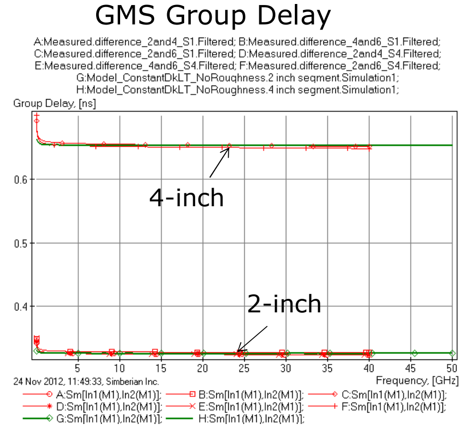
2: Flat non-causal dielectric model, no roughness

- Dk=3.7, LT=0.0082 – acceptable fit (green line)

GMS Insertion Loss



GMS Group Delay



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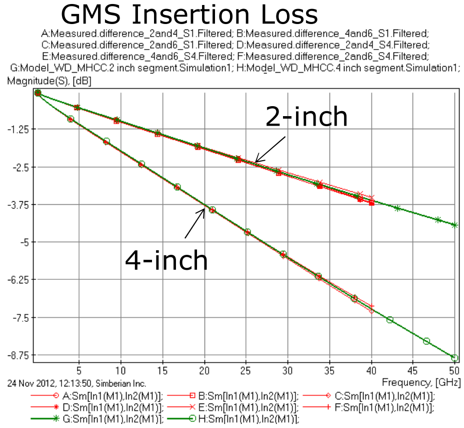
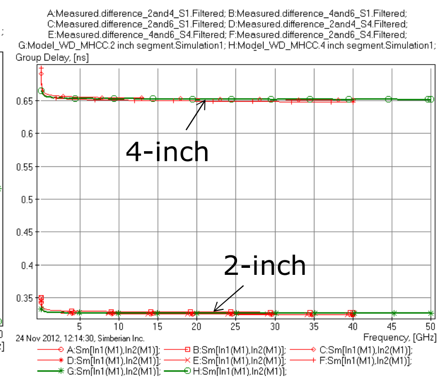
3: WD dielectric model with roughness (MHCC)

- Dielectric: Wideband Debye, DK=3.7, LT=0.004 @ 10 GHz (as in specs)
- Roughness: Modified Hammerstadt Correction Coefficient, SR=0.3 um, RF=5, RR=1.1 – excellent fit (green lines)

GMS Insertion Loss



GMS Group Delay



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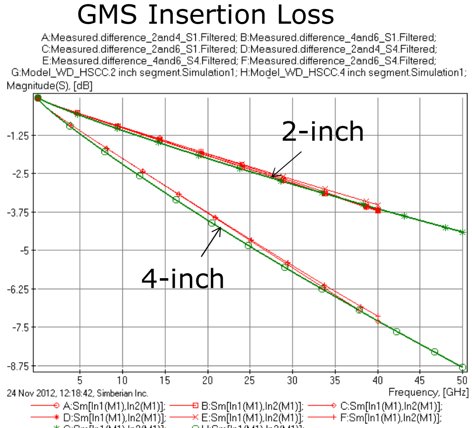
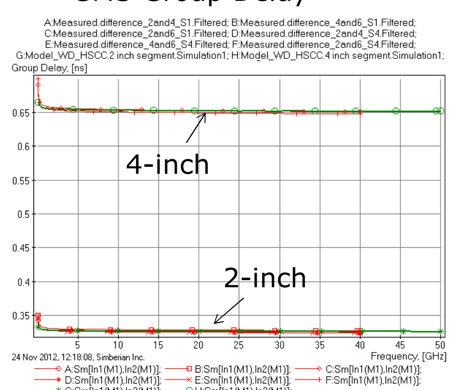
4: WD dielectric model with roughness (HSCC)

- Dielectric: Wideband Debye, DK=3.7, LT=0.004 @ 10 GHz (as in specs)
- Roughness: Huray Snowball Correction Coefficient, BS=10 um, BD=0.7 um, Nb=330, good fit (green lines), multi-ball model may be needed for better fit, RR=1.1

GMS Insertion Loss



GMS Group Delay



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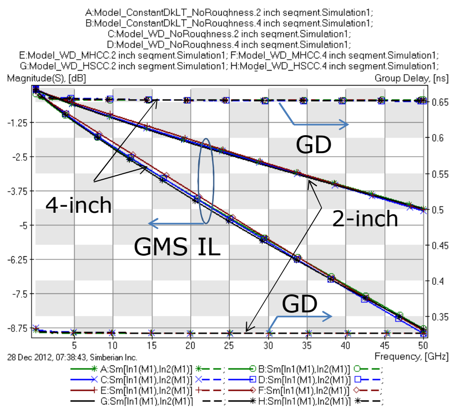
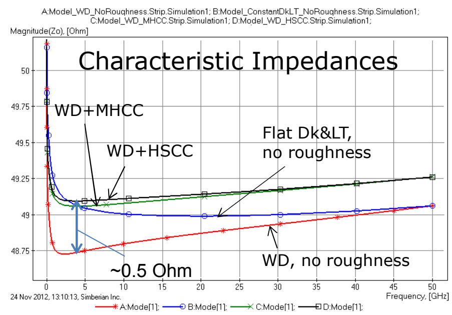
Which one is better?

All 4 identified models look acceptable for 9.9 mil strip-line up to 50 GHz

1: WD, no roughness
2: Flat Dk&LT, no roughness
3: WD+MHCC
4: WD+HSCC





Does it mean that we can safely use any of the constructed models?

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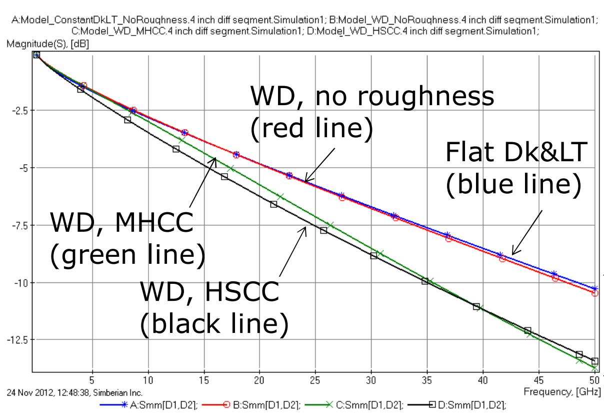
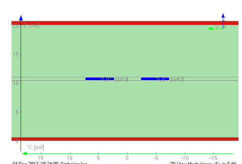
Can we use models for another cross-section?

- Differential 5 mil strips, 4.6 mil distance

GD is close for all models, but the loss is different:





Which one is better?

Over 30% difference in differential IL!!!

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Summary on practical identification

- Material models must be identified and verified on **a set of cross-sections** for a particular board and manufacturer
  - Properly identified models will work on a set of cross-sections without additional adjustments
  - Improperly identified material models will require adjustments if cross-section changed (Whac-A-Mole game literally)
- Roughness model must be identified for low dielectric loss boards to use on a set of cross-sections
  - Without the appropriate roughness models, dielectric models may need adjustment for every cross section!

Similar investigations have been done for Nelco N4000-13EP and Isola FR-408 materials – see app notes at www.simberian.com or visit Simberian's booth #626

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Dr. Don DeGroot

CCN Labs and Andrews University

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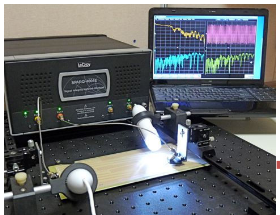
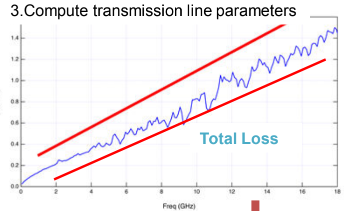
Measurement-Based Feedback



2.Measure & de-embed S-parameters

3.Compute transmission line parameters

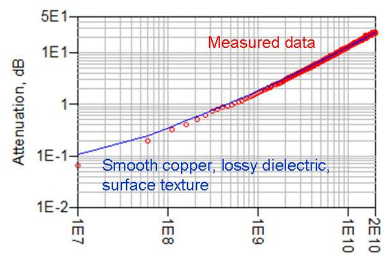


Pass/Fail Tests
Test Coupon Parameters

SnP
Total Propagation Loss
Effective Dk

1.Fabricate test coupons

4.Fit measurements to material models



Scalable Feedback

Copper Parameters
Bulk resistivity
Texture parameters

Dielectric Parameters
Dk (f)
Df (f)

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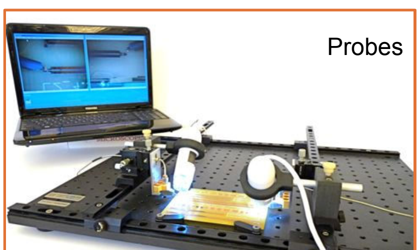
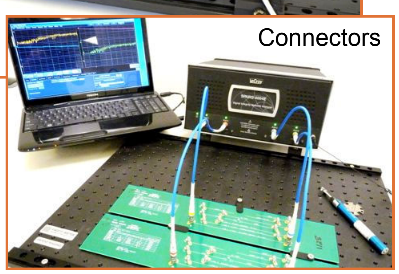
Lab & Factory Floor Tests

OEM & Test Service Labs - Clean





Factory Floor - Difficult

- CCN Coupon Test System
  - Variety of coupon types
  - Fixture de-embedding
  - Pass/Fail tests
  - S-parameter database and statistics as feedback
- SET2DIL Probes
  - Hand-held probes
  - Pass/Fail tests
  - S_{DD21}

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Parameters for Design Feedback

1 Acquire S-parameters from fabricator coupons
   - TDR or VNA Test Coupon Fixture System

2 Apply practical parameterization
   - Low frequency test to get copper bulk resistivity
   - Fit low frequency **S** using model of smooth copper and wideband Debye Dk & Df
   - Fit high freq. **S** by adjusting copper texture parameters
   - *Feed* the conductor and dielectric parameters *back* to CAD tools

Coupons for Design Feedback

- Uniform transmission lines
  - NIST Multiline (CCN's Dk4 Test Coupon)
  - Differential and single-ended of two or more lengths
- IPC TM-650 2.5.5.12 Total Loss
  - SET2DIL
  - Short Pulse Propagation (like Multiline)
- Automatic Coupon Generator
  - Polar Instruments SpeedStack
  - Use correct fixture pads for de-embedding!

Summary

- Measurement-based material parameters can provide feedback from production to design
- Both copper texture approaches provide
  - A surface roughness scale
  - An increased surface area
  - Scalable feedback
- Approaches may not give unique parameters
  - Difficult to know precise geometry of conductors
  - Doesn't matter if used directly in the simulator

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Summary

- Ability to show accurate copper loss-to-dielectric loss fraction is key to manufacturing multigigabit channels.

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