Unified form for conductor roughness correction coefficients

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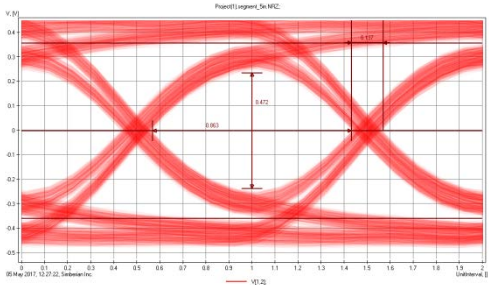
Overview

- Introduction
- Roughness Correction Coefficients (RCCs)
  - Unified 2-parameter form
  - Additive and multiplicative extensions
  - Commonly used RCCs in the unified form
- Inductive effect of roughness
- Practical examples
- Conclusion

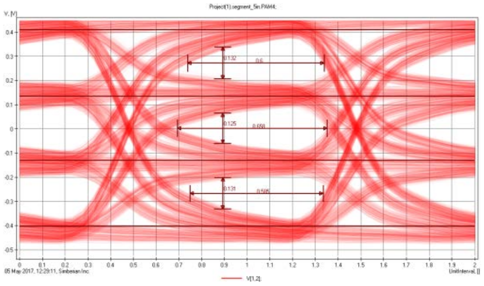
Printed Circuit Boards (PCBs)

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

100 Gbps – 6 mil, 5 inch strip



200 Gbps – 6 mil, 5 inch strip



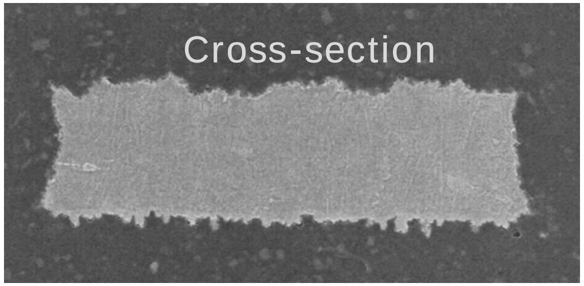
More in "Material World" tutorial and "Laminate Material Characterization" webinar…

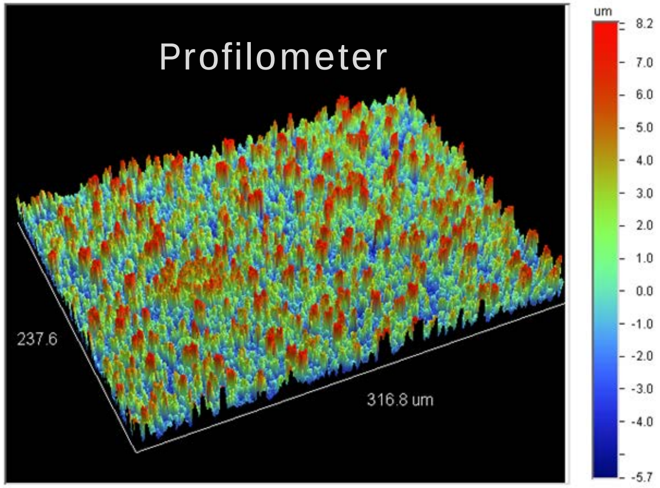
Rough copper bottleneck

- Copper made rough to stick to laminate dielectric and prevent the delamination
  - Rolled “smooth” copper roughened by copper foil manufacturers and by PCB manufacturers (oxide treatment)
  - Electrodeposited copper is rough on both side and may be further roughened by PCB manufacturer on the drum side
- Narrow rough copper traces is the major obstacle for increase of communication speed on PCBs
  - Low-loss homogeneous dielectrics are available, broadband models can be constructed from the specs data (Dk and LT at one or multiple frqs)
  - Practically nothing on copper foil datasheets can be used to build broadband models (Ra/Sa is not sufficient, all other numbers are irrelevant)
  - To have analysis to measurement correlation at frequencies above 3-5 GHz, copper roughness models must be identified

Roughness models

- Direct electromagnetic analysis is simply not possible or very approximate
- Differential Extrapolation Roughness Measurement (Koledintseva, Rakov,…)
- Effective Roughness Dielectric Layer (Koledintseva, Koul,…)
- Roughness Correction Coefficients (RCC): $K = P_{rough} \big/ P_{smooth}$
    - Hammerstad model (Hammerstad, Jensen)
    - Bushminskiy’s model (Bushminskiy, Yakuben,…)
    - Groiss model (Groiss, Bardi,…)
    - Stochastic models (Sanderson, Tsang,…)
    - Hemispherical model (Hall, Pytel,..)
    - Huray’s snowball model (Huray,…)
    - Modified Hammerstad (Shlepnev, Nwachukwu)
    - Causal Huray model (Bracken)





How to get all that models into software?

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

Unified 2-parameter form for six common roughness correction coefficients

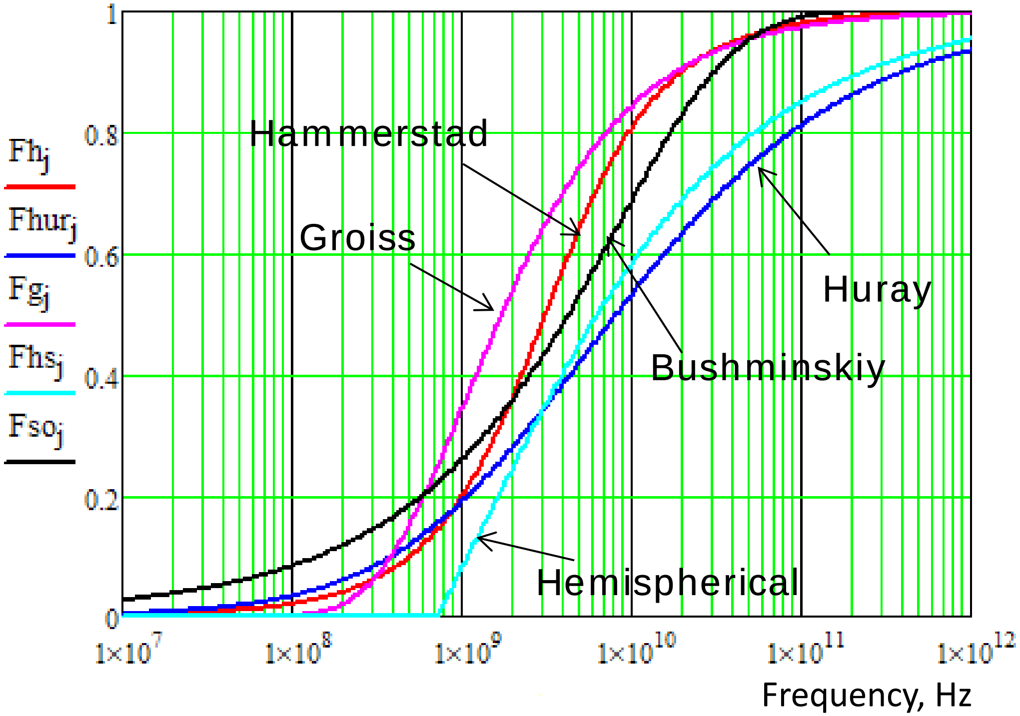
$$K_{ri} = 1 + \left(RF_i - 1\right) \cdot F\left(SR_i, \delta_s\right) \qquad \delta_s = \left(\pi \cdot f \cdot \mu \cdot \sigma\right)^{-1/2}$$ *"skin depth"*

RF>1 – Roughness Factor – maximal increase in loss due to roughness (common for all models);
SR – Surface Roughness parameter – defines roughness onset frequency, different for different RCCs;
$F\left(SR_i, \delta_s\right)$ - Roughness Transition Function (from 0 to 1), different for different RCCs;

$F_h\left(\Delta_i, \delta_s\right) = \frac{2}{\pi} \cdot \arctan\left[1.4\left(\frac{\Delta_i}{\delta_s}\right)^2\right]$	Hammerstad (*RF=2*) and Modified Hammerstad (*RF*)
$F_b\left(\Delta_i, \delta_s\right) = \tanh\left[\frac{\Delta_i}{1.8 \cdot \delta_s}\right]$	Bushminskiy aka Simbeor Original
$F_g\left(\Delta_i, \delta_s\right) = \exp\left[-\left(\frac{\delta_s}{2 \cdot \Delta_i}\right)^{1.6}\right]$	Groiss (*RF=2*) and Modified Groiss (*RF*)
$F_{hs}\left(r_i, \delta_s\right) = \frac{2}{\pi^2 r_i^2 \mu f \delta_s} \cdot \left\lvert \mathrm{Re}\left[\eta \frac{3\pi}{4k^2}\left(\alpha(1) + \beta(1)\right)\right]\right\rvert - \frac{1}{2}$	Hemispherical (diverges at high frq)
$F_{hur}\left(r_i, \delta_s\right) = \left(1 + \frac{\delta_s}{r_i} + \frac{\delta_s^2}{2r_i^2}\right)^{-1}$	Huray snowball (1-ball case or "cannonball")
$F_{hb}\left(r_i, \delta_s\right) = \left(1 + (1 - j)\frac{\delta_s}{2r_i}\right)^{-1}$	Causal Huray aka Huray-Bracken

Comparison of roughness transition functions

SR=1 um for all models, except Hemispherical
SR=2 um for Hemispherical

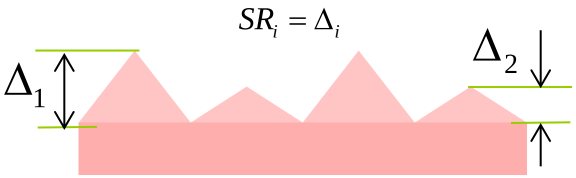


All are real – are the final models causal?

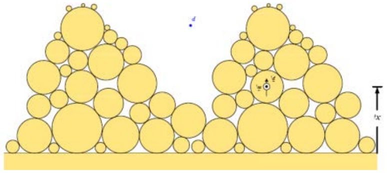
Additive and Multiplicative extensions

Additive – multiple bumps or balls at the same level

$$K_{ra} = 1 + \sum_i \left(RF_i - 1\right)\cdot F\left(SR_i, \delta_s\right)$$

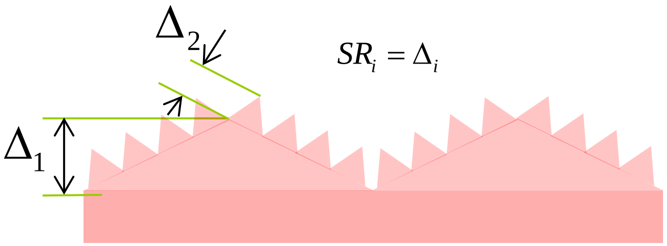


First Additive approach is Huray "multi-ball" model: P. G. Huray, O. Oluwafemi, J. Loyer, E. Bogatin and X. Ye, "Impact of Copper Surface Texture on Loss: A Model that Works," in *DesignCon 2010 Proceedings*, Santa Clara, CA, 2010.

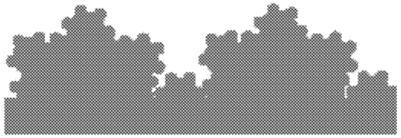


Multiplicative – fractal-type surface

$$K_{rm} = \prod_i \left[1 + \left(RF_i - 1\right)\cdot F\left(SR_i, \delta_s\right)\right]$$



First multiplicative approach is the extension of the Hemispherical model suggested in:
Y. Chu, Method for modeling conductor surface roughness, US Patent #8527246, 2013.



Multilevel Modified Hammerstad RCC

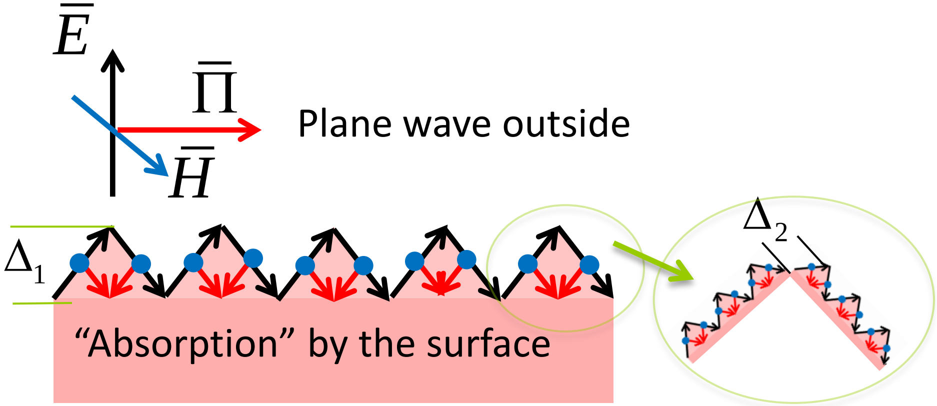
Multiplicative form:

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

Conductor skin-depth $\delta_s = \left(\pi \cdot f \cdot \mu \cdot \sigma \right)^{-1/2}$

Δ_i ~ root mean square peak-to-valley distance (SR for level *i*)

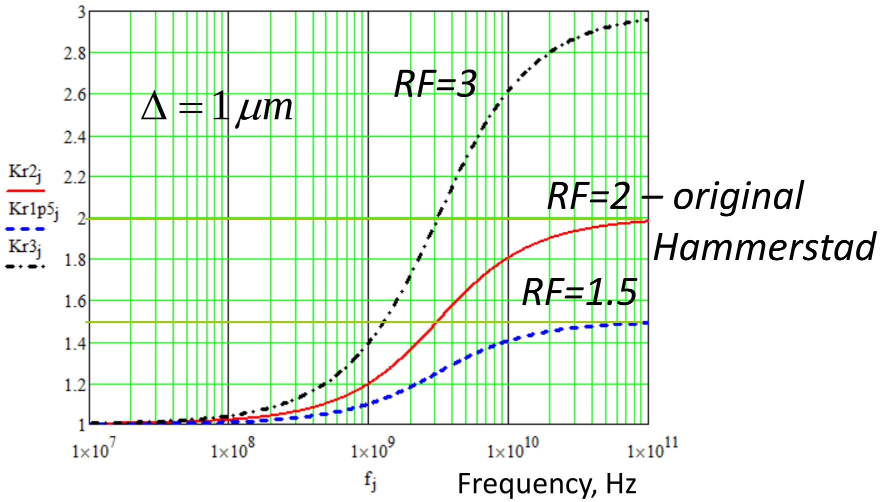
RFi - roughness factor, defines maximal growth of losses due to metal roughness (increase of surface at level *i*)



Plane wave outside

“Absorption” by the surface

Bumps are much smaller than wavelength!



1-level (i=1) model with RF=2 is proposed in E.O. Hammerstad, Ø. Jensen, “Accurate Models for Microstrip Computer Aided Design”, IEEE MTT-S Int. Microwave Symp. Dig., p. 407-409, May 1980.

1-level (i=1) modified model with RF is proposed 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

Multilevel Bushminskiy model

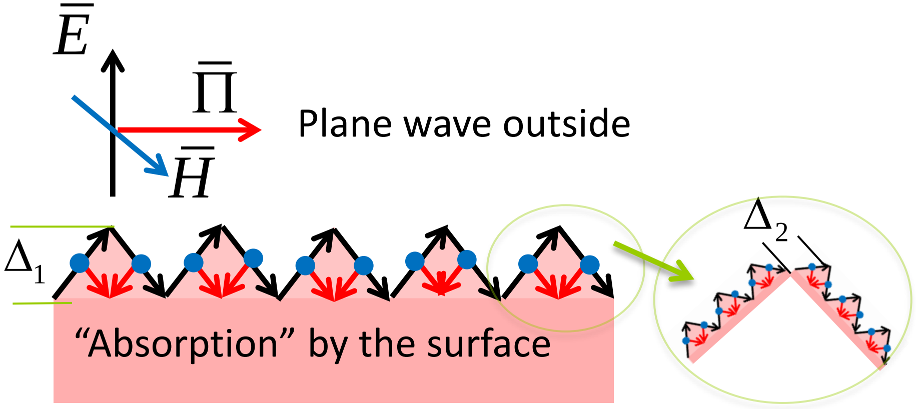
Multiplicative form:

$$K_{sr} = \prod_i \left[1 + \left(RF_i - 1 \right) \cdot \left(\tanh \left[\frac{\Delta_i}{1.8 \cdot \delta_s} \right] \right) \right]$$

Δ_i ~ root mean square peak-to-valley distance (SR for level *i*)

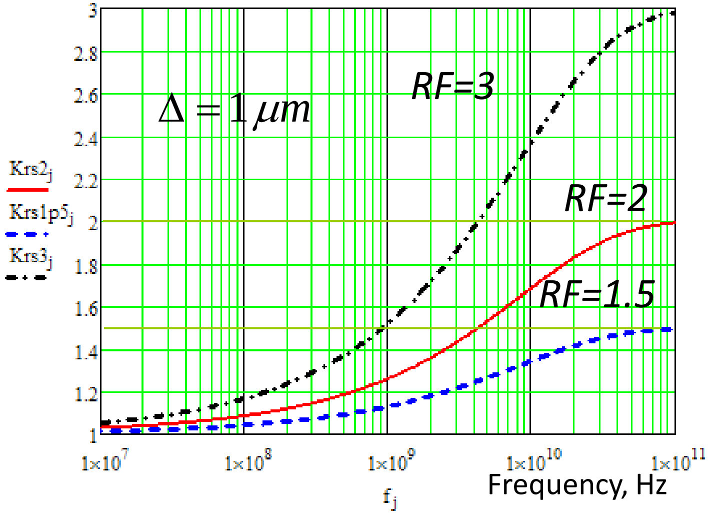
Conductor skin-depth $\delta_s = \left(\pi \cdot f \cdot \mu \cdot \sigma \right)^{-1/2}$

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



Plane wave outside

“Absorption” by the surface



Bumps are much smaller than wavelength!

1-level model (i=1) is published in Russian at: Бушминский И.П., Гудков А.Г., Якубень Л.Н. Потери в несимметричной микрополосковой линии. / Вопросы радиоэлектроники.- М.: Радиотехника.- 1982.-Вып. 2.- С. 73-87.

Multilevel Modified Groiss model

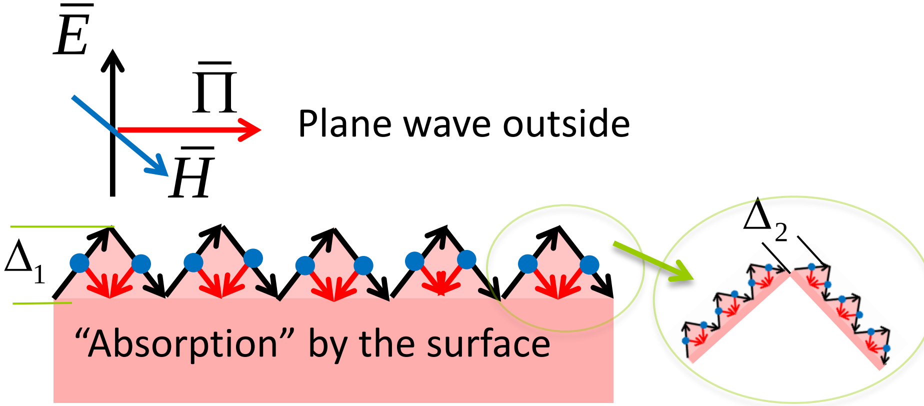
Multiplicative form:

$$K_{sr} = \prod_i \left[1 + \left(RF_i - 1\right)\cdot \left(\exp\left[-\left(\frac{\delta_s}{2\cdot\Delta_i} \right)^{1.6} \right] \right) \right]$$

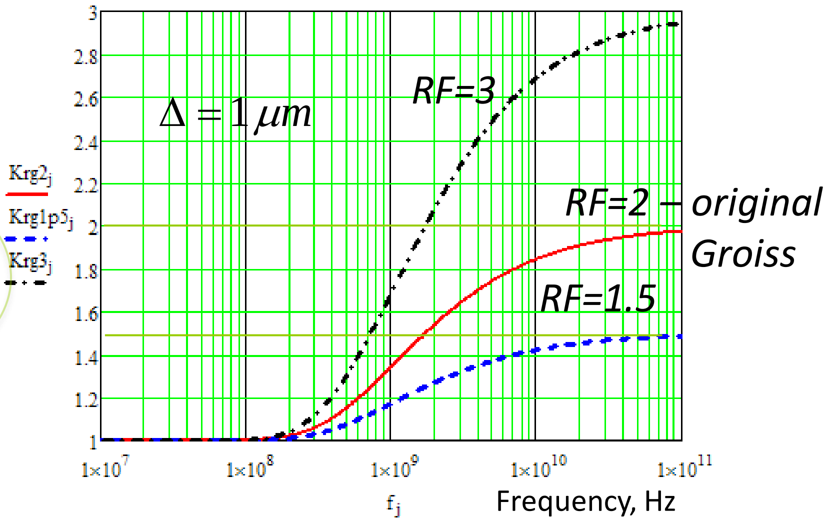
Conductor skin-depth $\delta_s = \left(\pi\cdot f\cdot\mu\cdot\sigma\right)^{-1/2}$

Δ_i ~ root mean square peak-to-valley distance (SR for level *i*)

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



Bumps are much smaller than wavelength!



1-level model (i=1) with RF=2 is proposed in: S. Groiss, I. Bardi, O. Biro, K. Preis and K.R. Richter, Parameters of Lossy Cavity Resonators Calculated by Finite Element Method, IEEE Transaction on Magnetics, Vol.32, No.3, 1996, p. 894-897.

1-level model with RF=2 is the Groiss model used in HFSS

Multilevel Hemispherical model

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

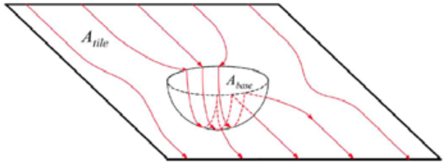


Fig. 13. Current streamlines of flowing over a single protrusion.

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

Unified multi-level form (multiplicative):

$$K_{sr} = \prod_i \left[1 + \left(RF_i - 1\right)\cdot\left(\frac{2}{\pi r_i^2 \mu\omega\delta_s}\cdot\left|\mathrm{Re}\left[\eta\frac{3\pi}{4k^2}\left(\alpha(1)+\beta(1)\right)\right]\right| - \frac{1}{2}\right)\right]$$

*RFi - roughness factor, defines maximal growth of losses due to spheres with radius ri at level i (**RFmax = 1+PI/2 – physical limit**);*
ri – sphere radius at level i (SRi parameter in Simbeor);

Roughness factor and Atile in the original equation:

$$RF_i = 1 + \frac{2\pi \cdot r_i^2}{Atile_i}$$

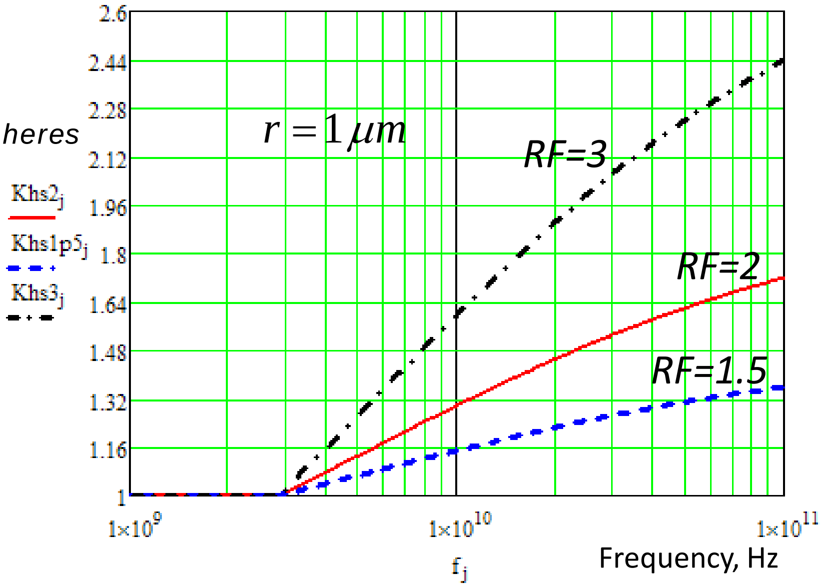
ri – shpere *i* radius;
Atile_i – tile area at level i;

Sphere radius to Rough and Bbase (ADS):

$$Rough_i = r_i \qquad Bbase_i = 2r_i$$

Roughness Factor (RF) and radius and Dpeaks (ADS):

$$RF_i = 1 + \frac{2\pi \cdot r_i^2}{Dpeaks_i^2} \qquad Dpeaks_i = r_i\sqrt{\frac{2\pi}{RF_i - 1}}$$

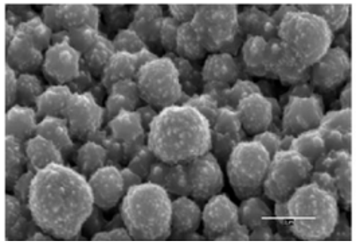


Multi-ball Huray snowball model

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

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

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



Additive model – no levels!

Amatte/Ahex can be accounted for by change of resistivity;
2-parameter addtive version of Huray Snowball model:

$$K_{sr} = 1 + \sum_i \left(\left(RF_i - 1\right) \cdot \left(1 + \frac{\delta_s}{r_i} + \frac{\delta_s^2}{2r_i^2}\right)^{-1} \right) \qquad \delta_s = \left(\pi \cdot f \cdot \mu \cdot \sigma\right)^{-1/2}$$

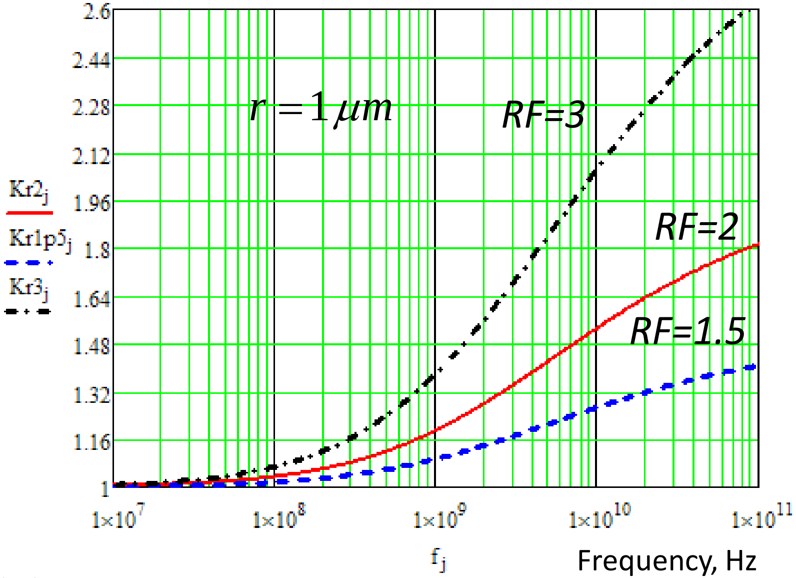
RFi - roughness factor, defines maximal growth of losses due to all balls with radius ri;
ri – ball radius (SRi parameter in Simbeor);

Roughness factor and the original equation:

$$\frac{N_i}{A_{hex}} = \frac{RF_i - 1}{6\pi \cdot r_i^2}$$

$$RF_i = 1 + \frac{3}{2}\frac{N_i \cdot 4\pi \cdot r_i^2}{A_{hex}}$$

ri – ball *i* radius;
Ni – number of balls with radius *ri*;



Roughness Factor (RF) and Hall-Huray Surface Ratio (sr):

$$RF_i = 1 + \frac{3}{2} \cdot sr_i; \qquad sr_i = \frac{2}{3} \cdot \left(RF_i - 1\right)$$

sri – Hall-Huray Surface Ratio in HFSS;

Use of roughness correction coefficients in simulations

- Adjust t-line attenuation in propagation constant:

$$\Gamma(f) = K_r(f)\cdot\alpha(f) + i\beta(f)$$

- Adjust conductor internal impedance (static t-line models):

$$Z(f) = K_r(f)\cdot Z_s(f) + i2\pi f\cdot L(\infty)$$

$$Z_s(f) = (1-i)\cdot R_{sn}\cdot\sqrt{f}\cdot\cot\left((1-i)\cdot\frac{R_{sn}}{R_{DC}}\sqrt{f}\right)$$

$$Z_s(f) = R_{sn}\cdot\sqrt{f}\cdot(1+i)$$

- Adjust Surface Impedance or Schukin-Leontovich BC:

$$Z(f) = \frac{K_r(f)}{\sigma\cdot\delta_s}(1+i)$$

$$\delta_s = (\pi\cdot f\cdot\mu\cdot\sigma)^{-1/2}$$ *“skin depth”*

- Adjust differential conductor impedance operator (*Zcs*):

$$Z''_{cs} = K_{sr}^{1/2}\cdot Z_{cs}\cdot K_{sr}^{1/2}$$ at high frequencies converges to diagonal $$Z(f) = \frac{K_r(f)}{\sigma\cdot\delta_s}(1+i)$$

Ksr is the diagonal matrix with RCC for each area of the conductor surface

Real *Kr* increases the real and imaginary parts of impedance keeping Wheeler’s rule
Only Huray-Bracken model has complex *Kr* and increases the imaginary part more – it is causal, but breaks the Wheeler’s rule

Causal Huray-Bracken model

J. E. Bracken, A Causal Huray Model for Surface Roughness, DesignCon 2012

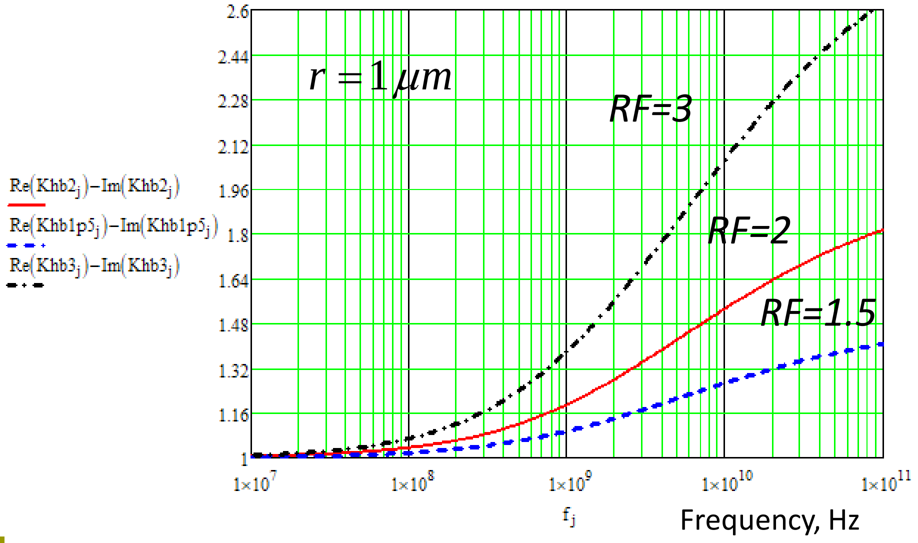
$$K_{sr}=1+\sum_k\left((RF_k-1)\cdot\left(1+(1-i)\frac{\delta_s}{2r_i}\right)^{-1}\right)\qquad \delta_s=(\pi\cdot f\cdot\mu\cdot\sigma)^{-1/2}\qquad Z_{rough}=\frac{K_{sr}}{\sigma\cdot\delta_s}\cdot(1+i)$$

Makes SIBC causal!

RFi - roughness factor, defines maximal growth of losses due to all balls with radius ri;
ri – ball radius (SRi parameter in Simbeor);

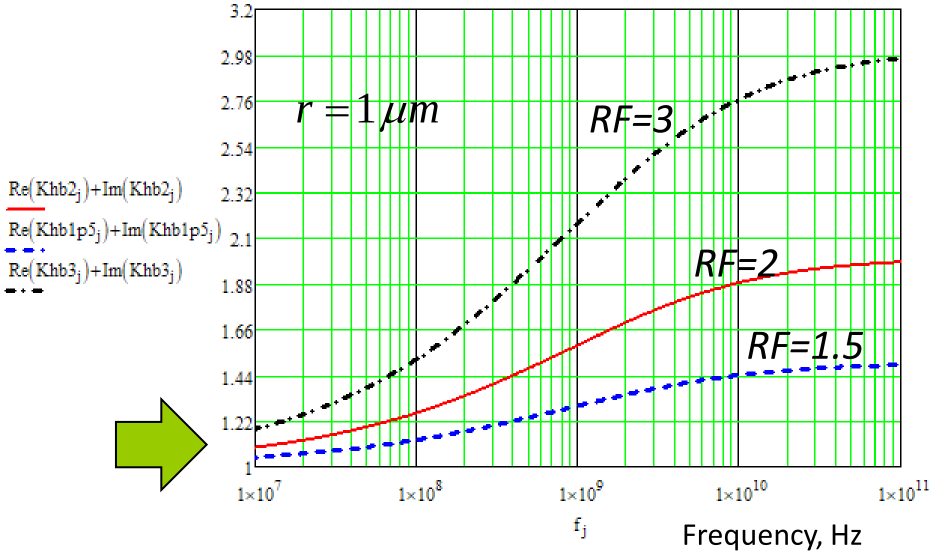
Conductor losses (same as in Huray model)

$$\mathrm{Re}(Z_{rough})=\underbrace{\left[\mathrm{Re}(K_{sr})-\mathrm{Im}(K_{sr})\right]}\cdot\frac{1}{\sigma\cdot\delta_s}$$



Additional conductor inductance

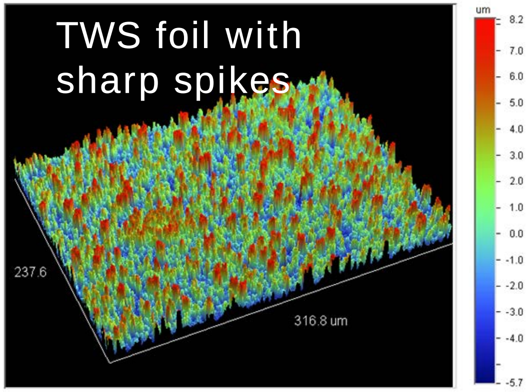
$$\mathrm{Im}(Z_{rough})=\underbrace{\left[\mathrm{Re}(K_{sr})+\mathrm{Im}(K_{sr})\right]}\cdot\frac{1}{\sigma\cdot\delta_s}$$



The effect of roughness

CAPACITIVE?

A. Deutsch, et al, Accuracy of Dielectric Constant Measurement Using the Full-Sheet-Resonance Technique IPC-T650 2.5.5.6, , *EPEPS 2002* p. 311-314
A. Albina at al., Impact of the surface roughness on the electrical capacitance, Microelectron. J. 37 (2006) 752-758.
Y. Shlepnev, C. Nwachukwu, Roughness characterization for interconnect analysis, IEEE Symp. on EMC 2011, p. 518-523.


TWS foil with sharp spikes

OR INDUCTIVE?

A. F. Horn ; J. W. Reynolds ; J. C Rautio Conductor profile effects on the propagation constant of microstrip transmission lines – *In Proc. of IEEE MTT-S International Microwave Symp., 2010, p. 868-871.*

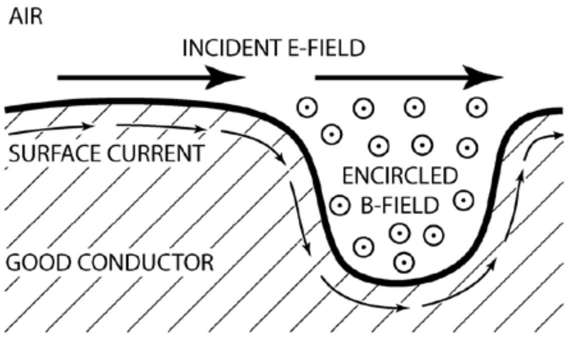
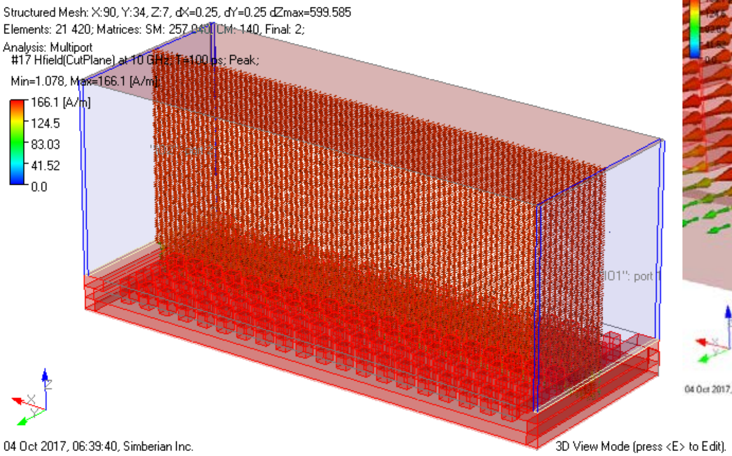


Fig. 7. Magnetic field encircled by the surface current flowing on a rough conductor and excited by the incident electric field results in substantial surface inductance, above and beyond that generated by the smooth surface skin effect.

Let's fact check it with the electromagnetic analysis...

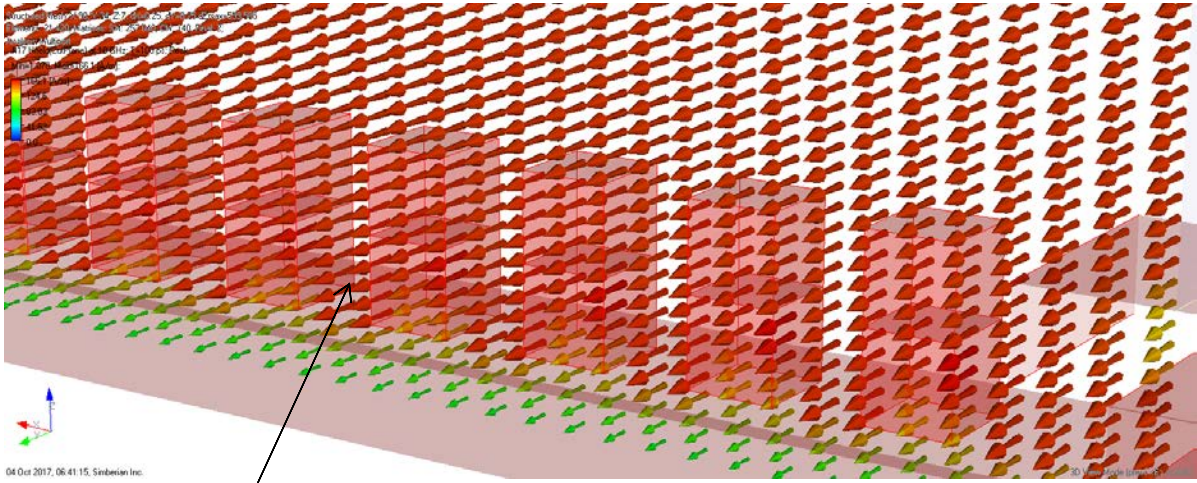
Roughness model with posts in PPW

Parallel-plate waveguide with one ideal conductor and another with 1 um posts (0.5 by 0.5 um) at 0.5 um distance

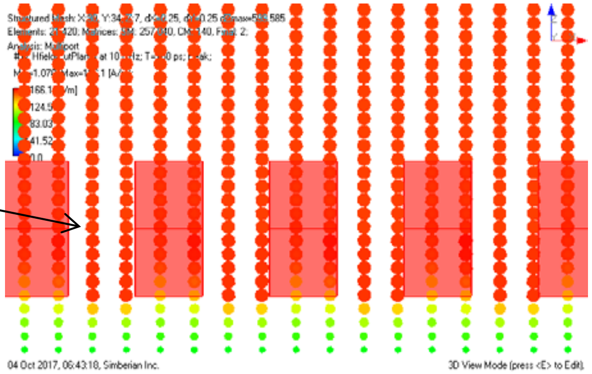


Structured Mesh: X:90, Y:34, Z:7, dX=0.25, dY=0.25 dZmax=599.585
Elements: 21 420; Matrices: SM: 257 040, CM: 140, Final: 2;
Analysis: Multiport
#17 Hfield(CutPlane) at 10 GHz; T=100 ps; Peak;
Min=1.078, Max=166.1 [A/m];

Cut plane along the PPW through the posts
Magnetic field intensity [A/m]
Peak values at 10 GHz



Uniform H inside and between the posts

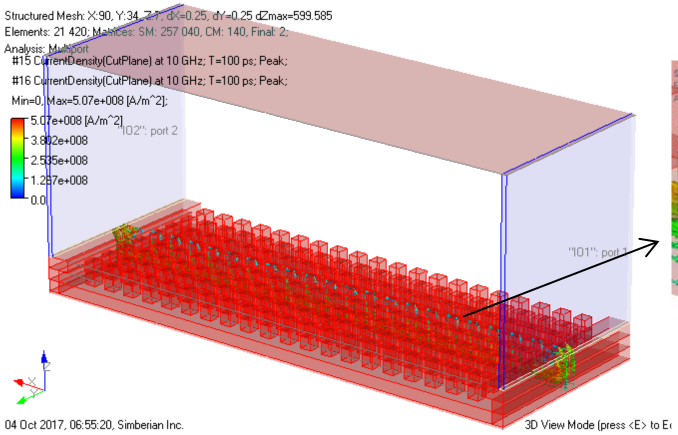


Computed with Simbeor THz

Roughness model with posts in PPW

Parallel-plate waveguide with one ideal conductor and another with 1 um posts (0.5 by 0.5 um) at 0.5 um distance

Cut planes along the PPW through the posts and between the posts
Current flow density [A/m^2]
Peak values at 10 GHz



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Structured Mesh: X:90, Y:34, Z:7, dX=0.25, dY=0.25 dZmax=599.585
Elements: 21 420; Matrices: SM: 257 040, CM: 140, Final: 2;
Analysis: Multiport
  #15 CurrentDensity(CutPlane) at 10 GHz; T=100 ps; Peak;
  #16 CurrentDensity(CutPlane) at 10 GHz; T=100 ps; Peak;
  Min=0, Max=5.07e+008 [A/m^2];
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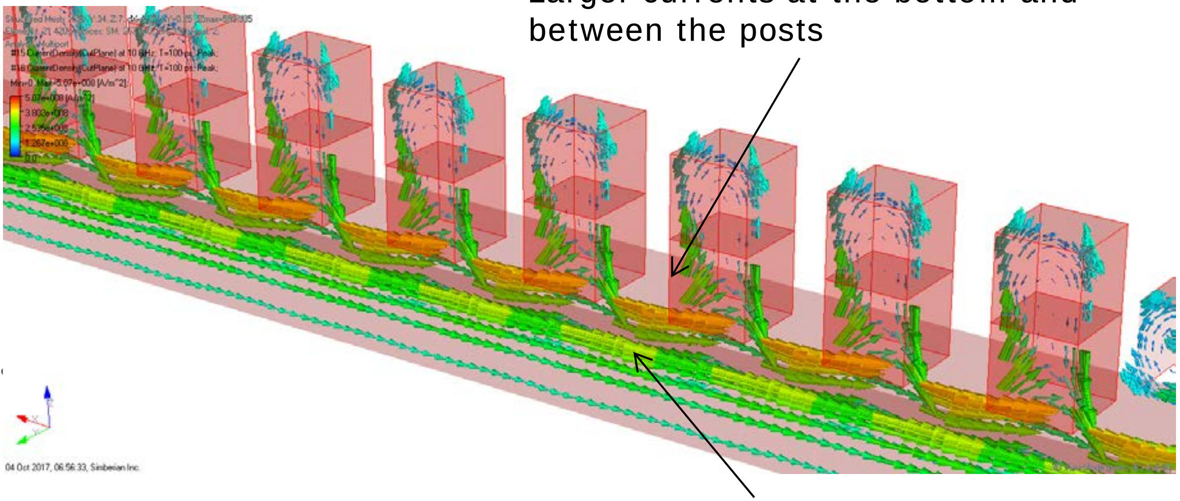


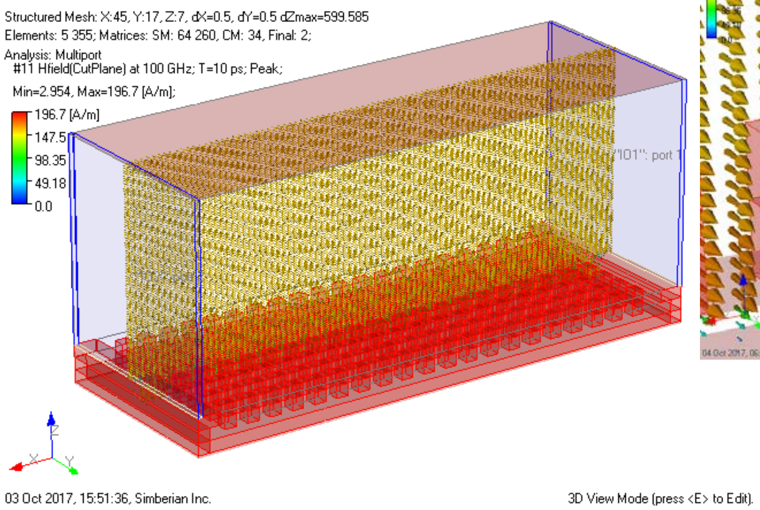
Larger currents at the bottom and between the posts

Smaller currents in the “valleys”

Computed with Simbeor THz

Roughness model with posts in PPW

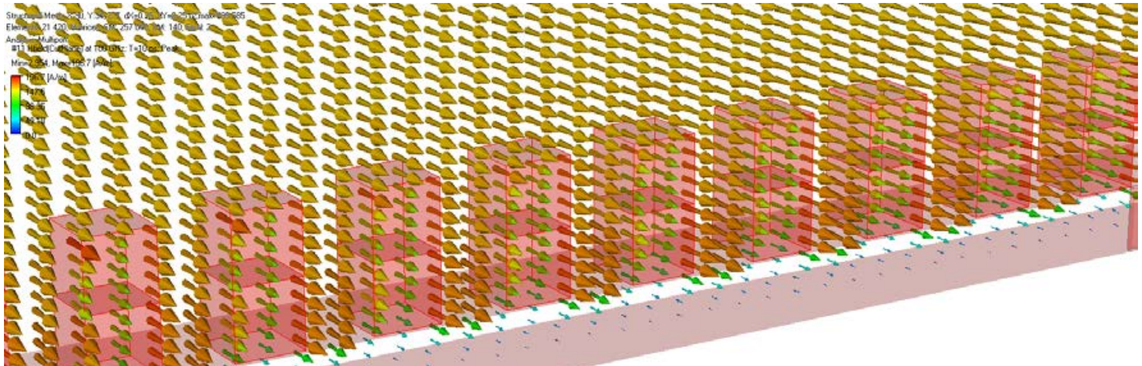
Parallel-plate waveguide with one ideal conductor and another with 1 um posts (0.5 by 0.5 um) at 0.5 um distance

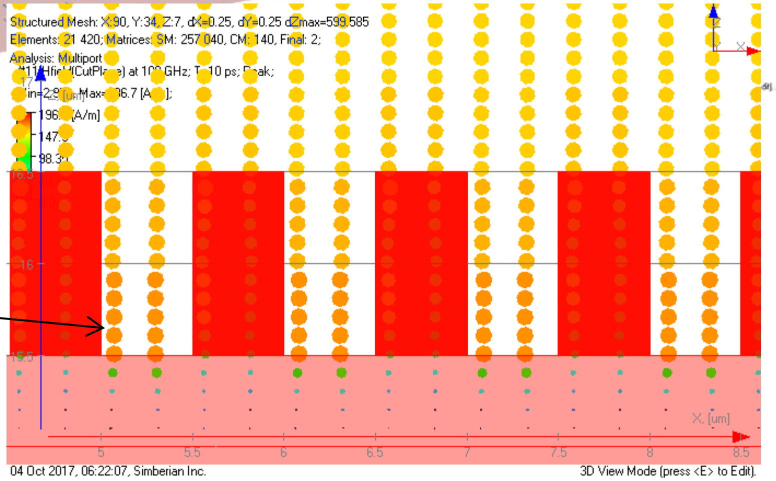


Structured Mesh: X:45, Y:17, Z:7, dX=0.5, dY=0.5 dZmax=599.585
Elements: 5 355; Matrices: SM: 64 260, CM: 34, Final: 2;
Analysis: Multiport
#11 Hfield(CutPlane) at 100 GHz; T=10 ps; Peak;
Min=2.954, Max=196.7 [A/m];

03 Oct 2017, 15:51:36, Simberian Inc.
3D View Mode (press <E> to Edit).

Cut plane along the PPW through the posts
Magnetic field intensity [A/m]
Peak values at 100 GHz





Structured Mesh: X:90, Y:34, Z:7, dX=0.25, dY=0.25 dZmax=599.585
Elements: 21 420; Matrices: SM: 257 040, CM: 140, Final: 2;
Analysis: Multiport

04 Oct 2017, 06:22:07, Simberian Inc.
3D View Mode (press <E> to Edit).

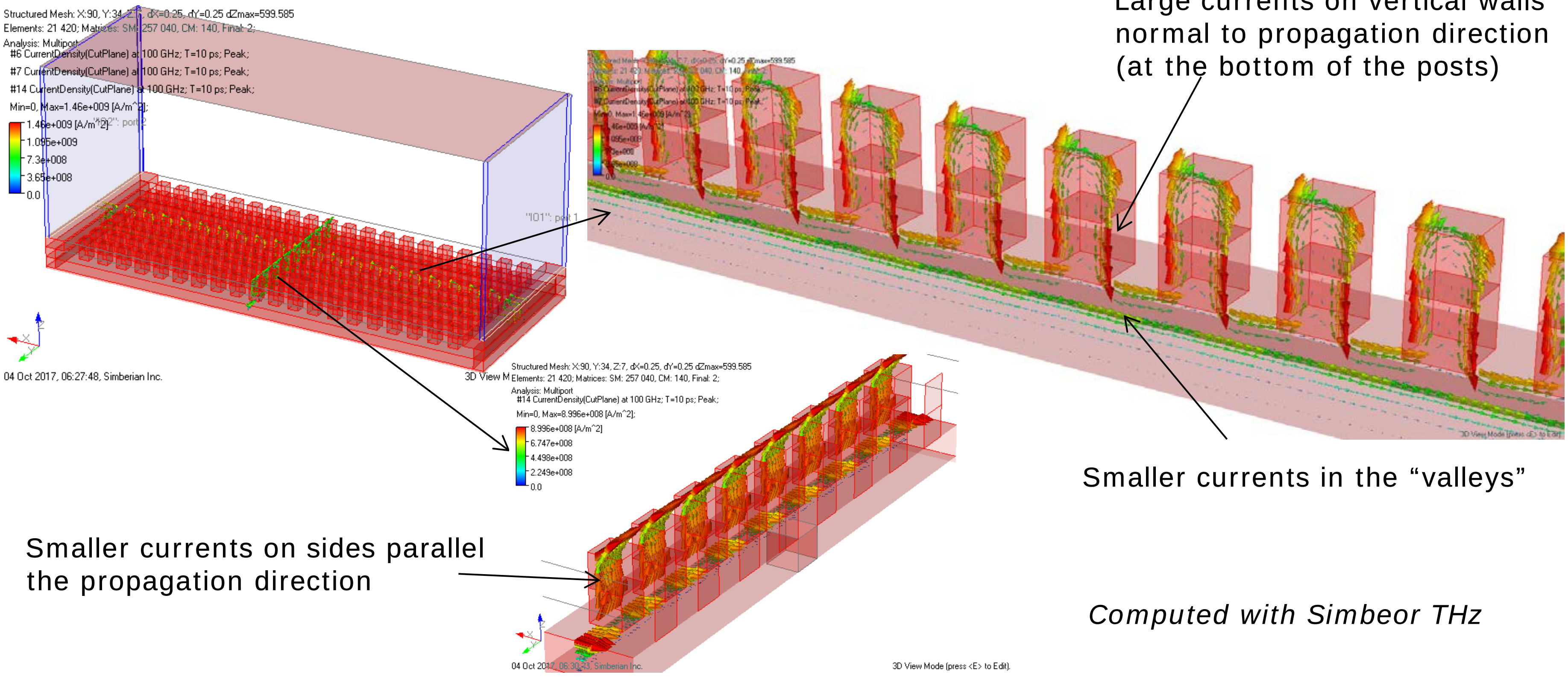
Larger H between the posts
Smaller H inside the posts

Computed with Simbeor THz

Roughness model with posts in PPW

Parallel-plate waveguide with one ideal conductor and another with 1 um posts (0.5 by 0.5 um) at 0.5 um distance

Cut planes along the PPW through the posts and between the posts
Current flow density [A/m^2]
Peak values at 100 GHz



Structured Mesh: X:90, Y:34, Z:7, dX=0.25, dY=0.25 dZmax=599.585
Elements: 21 420; Matrices: SM: 257 040, CM: 140, Final: 2;
Analysis: Multiport
#6 CurrentDensity(CutPlane) at 100 GHz; T=10 ps; Peak;
#7 CurrentDensity(CutPlane) at 100 GHz; T=10 ps; Peak;
#14 CurrentDensity(CutPlane) at 100 GHz; T=10 ps; Peak;
Min=0, Max=1.46e+009 [A/m^2];

Structured Mesh: X:90, Y:34, Z:7, dX=0.25, dY=0.25 dZmax=599.585
Elements: 21 420; Matrices: SM: 257 040, CM: 140, Final: 2;
Analysis: Multiport
#14 CurrentDensity(CutPlane) at 100 GHz; T=10 ps; Peak;
Min=0, Max=8.996e+008 [A/m^2];

Large currents on vertical walls normal to propagation direction (at the bottom of the posts)

Smaller currents in the "valleys"

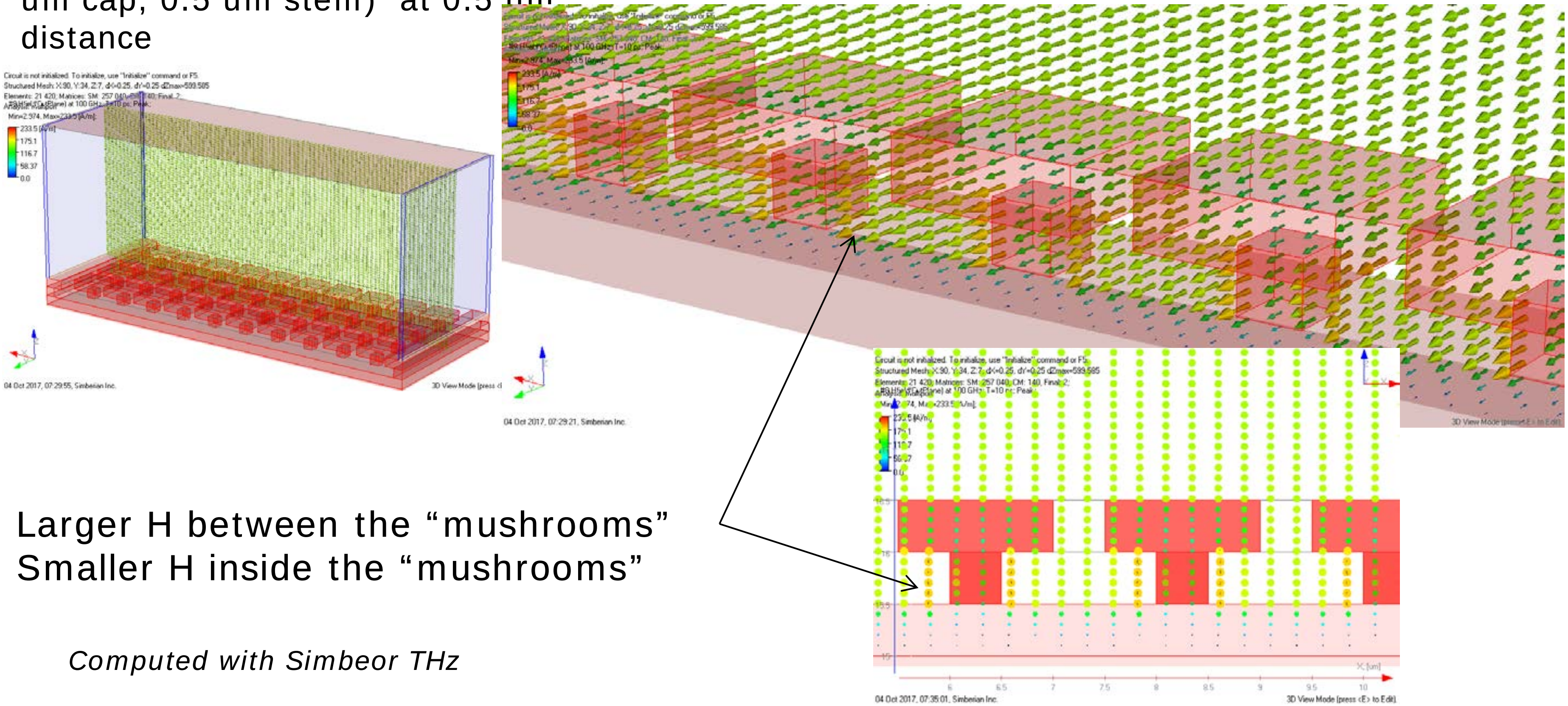
Smaller currents on sides parallel the propagation direction

Computed with Simbeor THz

Roughness model with “mushrooms” in PPW

Parallel-plate waveguide with one ideal conductor and another with 1 um “mushrooms” (1.5 by 1.5 um cap, 0.5 um stem) at 0.5 um distance

Cut plane along the PPW through the posts
Magnetic field intensity [A/m]
Peak values at 100 GHz

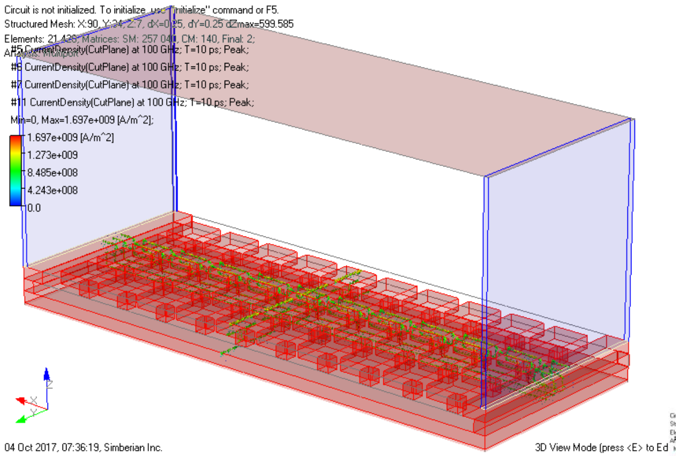


Larger H between the “mushrooms”
Smaller H inside the “mushrooms”

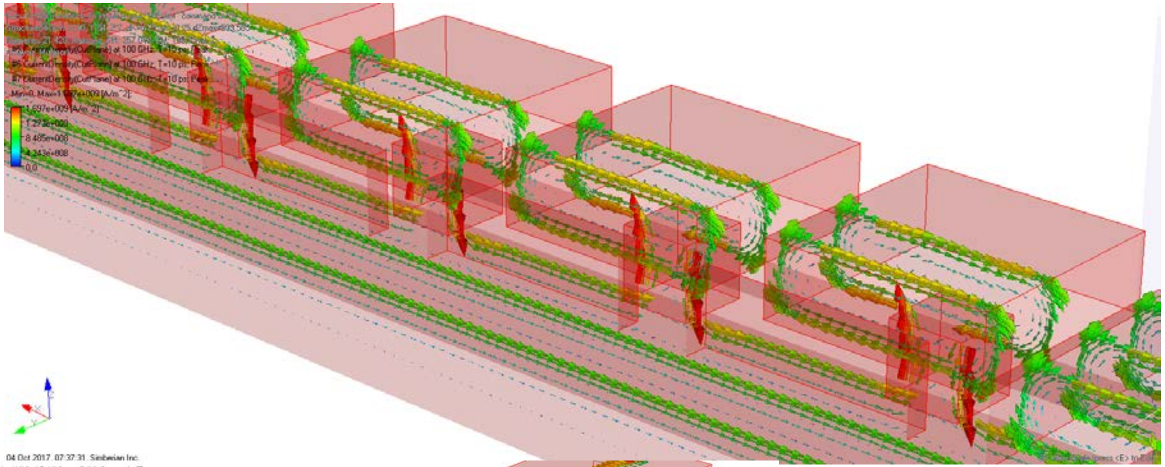
Computed with Simbeor THz

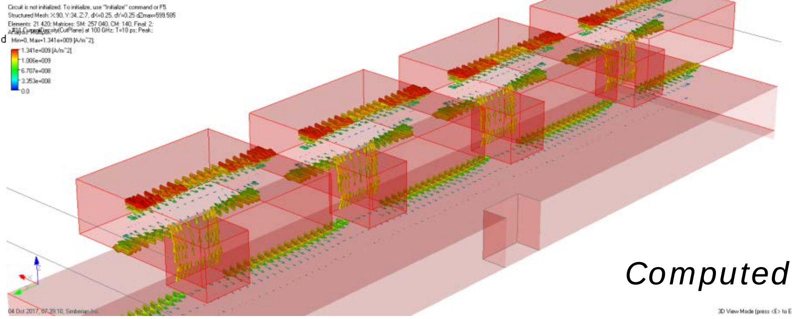
Roughness model with “mushrooms” in PPW

Parallel-plate waveguide with one ideal conductor and another with 1 um “mushrooms” (1.5 by 1.5 um cap, 0.5 um stem) at 0.5 um distance



3 cut planes along the PPW through the “mushrooms” and between
Current flow density [A/m^2]
Peak values at 100 GHz

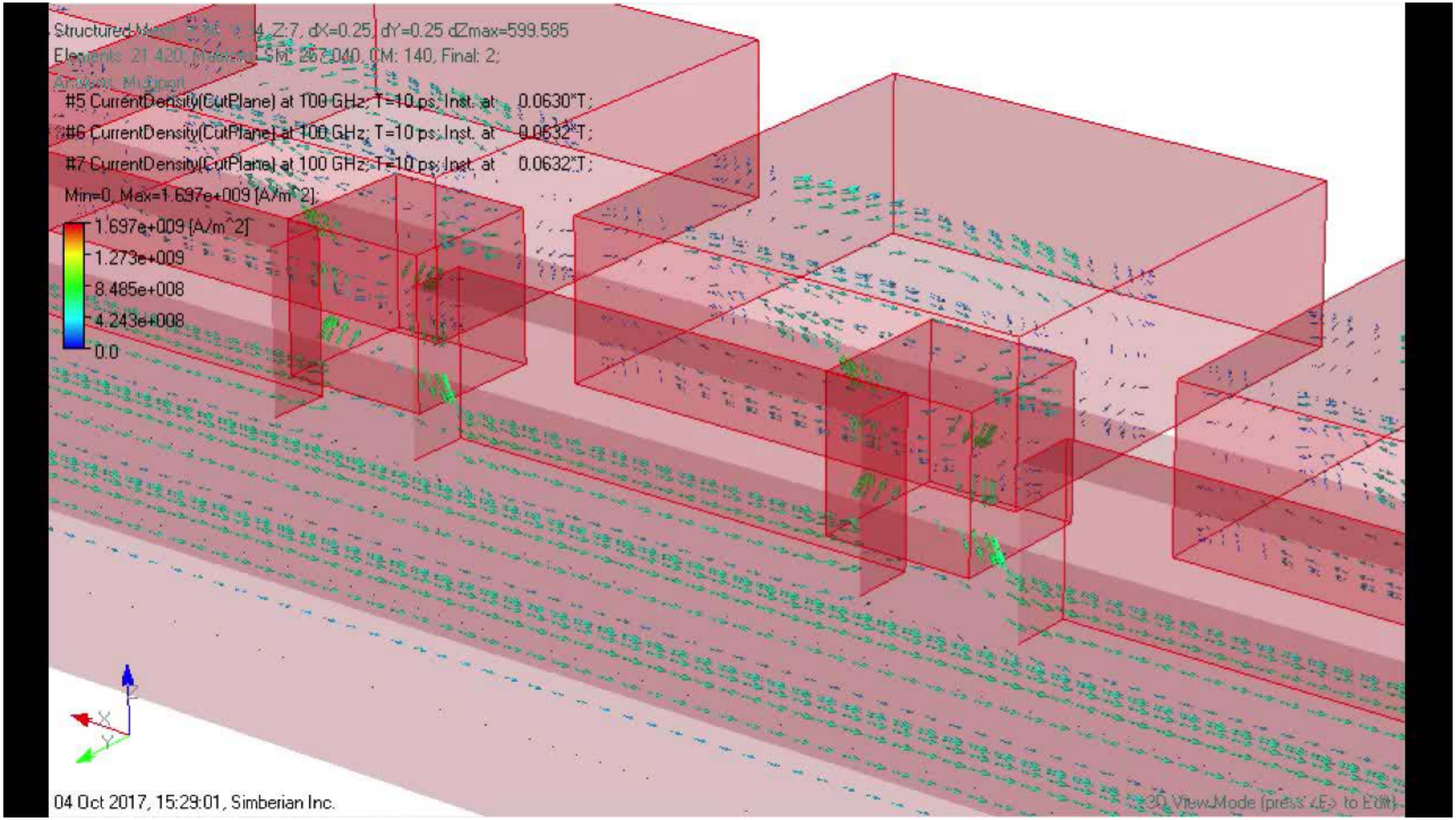




Currents are on both sides of “cap” in opposite directions

Computed with Simbeor THz

“Mushrooms” in PPW – current flow density at 3 cut planes (between, through cap and stem)

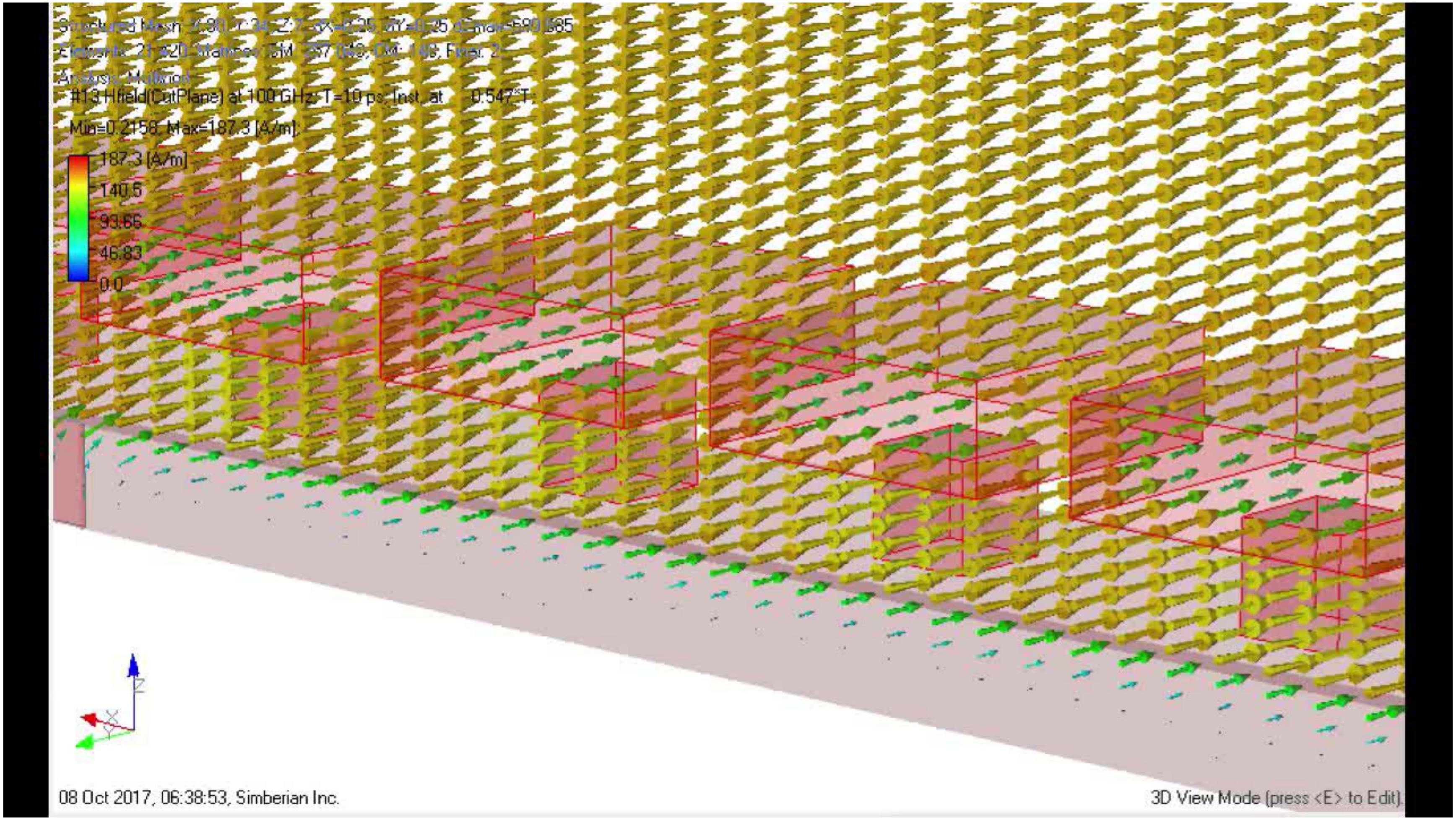


```
Structured Mesh: X:96, Y:34, Z:7, dX=0.25, dY=0.25 dZmax=599.585
Elements: 21 420, Matrix: SM: 267 040, CM: 140, Final: 2;
Analysis: Multiport
 #5 CurrentDensity(CutPlane) at 100 GHz; T=10 ps; Inst. at    0.0630*T;
 #6 CurrentDensity(CutPlane) at 100 GHz; T=10 ps; Inst. at    0.0632*T;
 #7 CurrentDensity(CutPlane) at 100 GHz; T=10 ps; Inst. at    0.0632*T;
 Min=0, Max=1.697e+009 [A/m^2];
```

04 Oct 2017, 15:29:01, Simberian Inc.

Animation at 100 GHz over one period

“Mushrooms” in PPW – magnetic field intensity in cut plane through cap (additional inductance)



#13 Hfield(CutPlane) at 100 GHz; T=10 ps; Inst. at 0.547*T;

Min=0.2158, Max=187.3 [A/m];

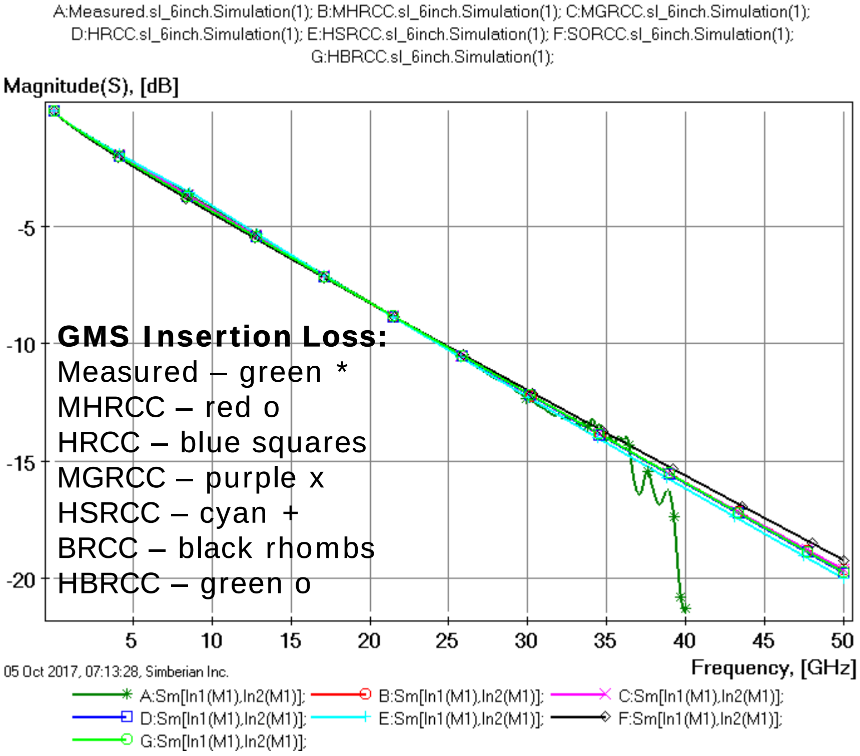
08 Oct 2017, 06:38:53, Simberian Inc.

3D View Mode (press <E> to Edit)

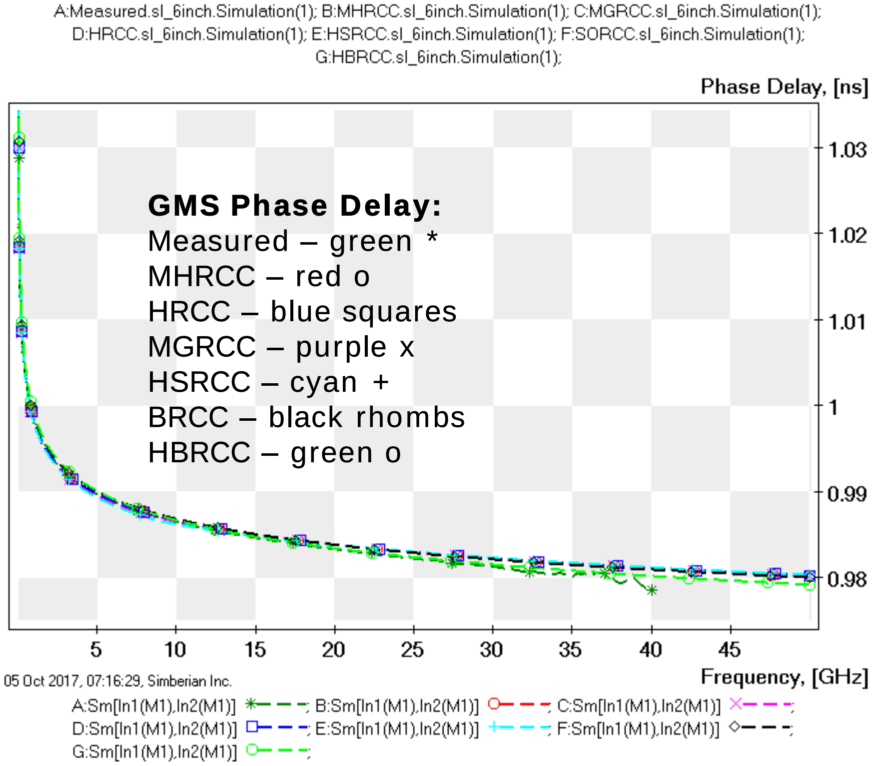
Animation at 100 GHz over one period

Roughness model identification with measurements

Identification with GMS-parameters for CMP-28 channel modeling platform from Wild River Technology – uses S-parameters of 2 line segments



GMS Insertion Loss:
Measured – green *
MHRCC – red o
HRCC – blue squares
MGRCC – purple x
HSRCC – cyan +
BRCC – black rhombs
HBRCC – green o



GMS Phase Delay:
Measured – green *
MHRCC – red o
HRCC – blue squares
MGRCC – purple x
HSRCC – cyan +
BRCC – black rhombs
HBRCC – green o

Details of the method: Y. Shlepnev, Broadband material model identification with GMS-parameters, *in Proc. of 2015 IEEE 24th Conference on EPEPS*, October 25-28, 2015, San Jose, CA.

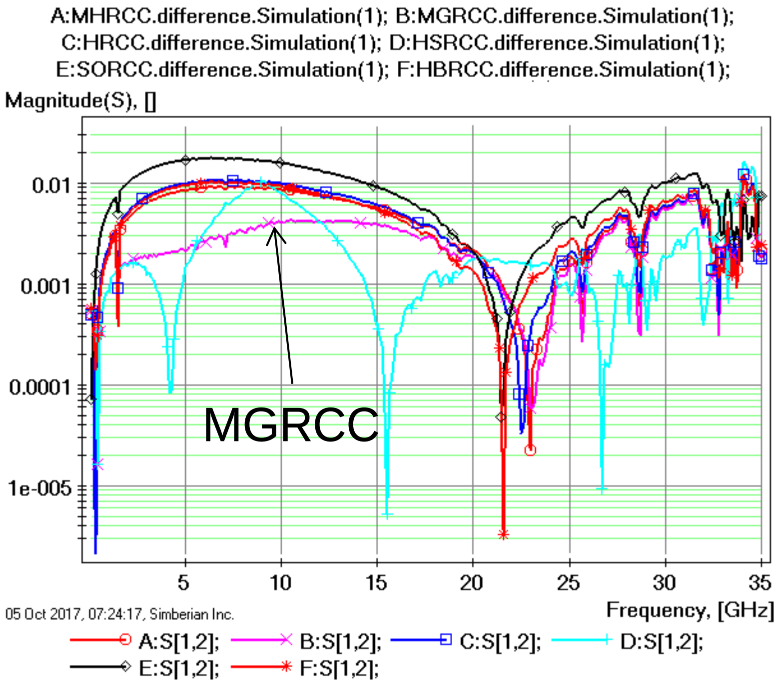
Difference in GMS magnitude and phase delay: measured vs. identified

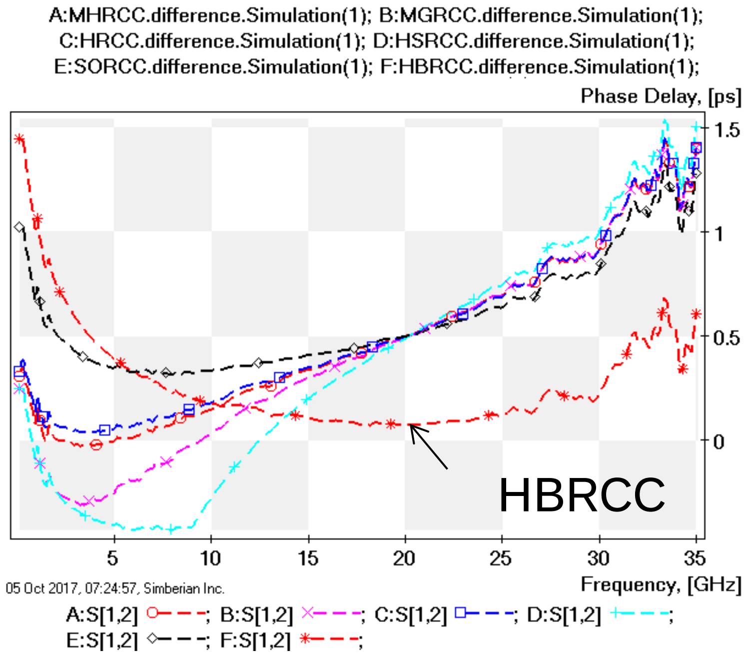
Modified Hammerstad (MHRCC, red o): SR=0.313 um, RF=2.595;
Huray (HRCC, blue squares): SR=0.123 um, RF=7.846;
Modifed Groiss (MGRCC, purple x): SR=0.216 um, RF=2.759;
Hemispherical (HSRCC, cyan +): SR=0.563 um, RF=3.969;
Bushminskiy (BRCC, black rhombs): SR=0.362 um, RF=2.405;

Dielectric model is Wideband Debye:
Dk=3.811, LT=0.00111 @ 1 GHz

Huray-Bracken (HBRCC, red *): SR=0.123 um, RF=7.846;

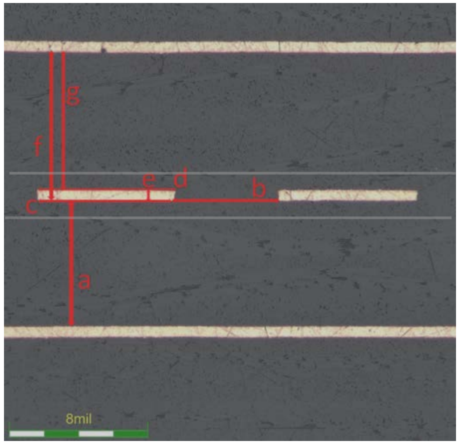
Dk=3.787, LT=0.00111 @ 1 GHz



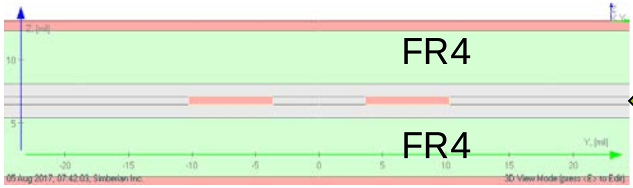


Higher inductance and lower Dk increase impedance. No way to validate – CMP-28 was not cross-sectioned!

Practical example with cross-sectioning



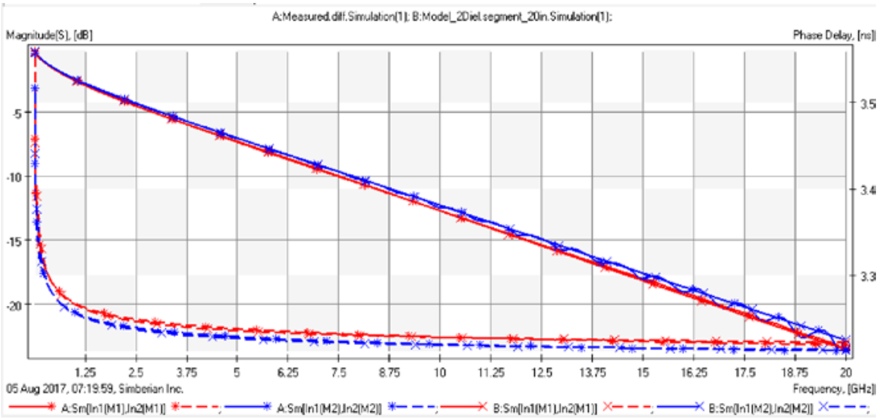
Differential strip with FEXT, HVLP copper



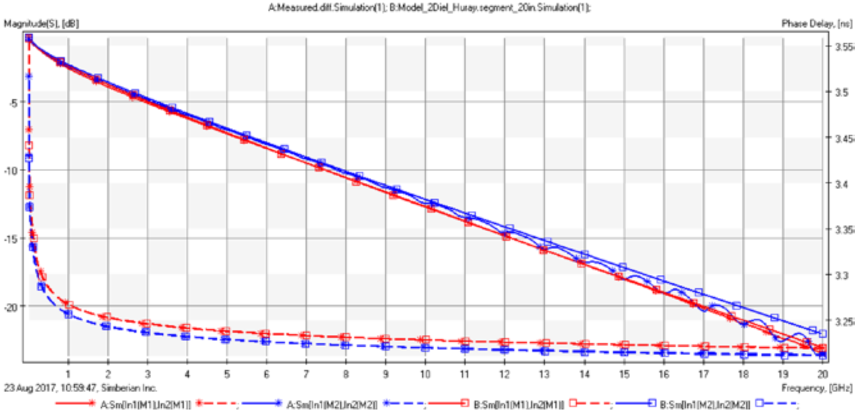
mostly resin

Details in App Note #2017_03 at www.simberian.com

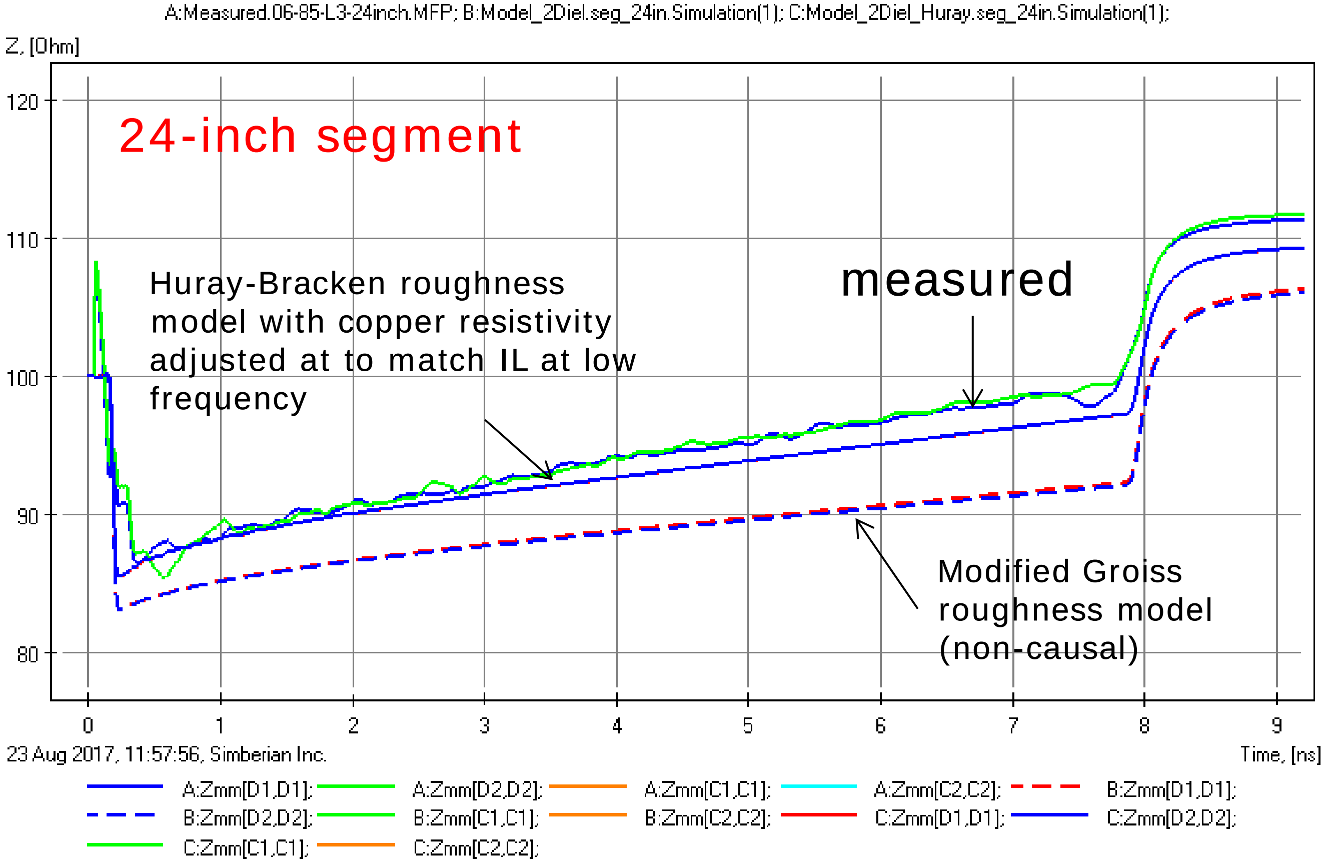
FR4: Dk=3.54, LT=0.0058 @ 1 GHz;
Resin: Dk=3.76, LT=0.0058 @ 1 GHz;
Roughness: Modified Groiss SR=0.19 um, RF=2.75



FR4: Dk=3.465, LT=0.002 @ 1 GHz;
Resin Dk=3.63, LT=0.002 @ 1 GHz;
Roughness: Huray-Bracken SR=0.2 um, RF=7.75



Validation with TDR



24-inch segment

Huray-Bracken roughness model with copper resistivity adjusted at to match IL at low frequency

measured

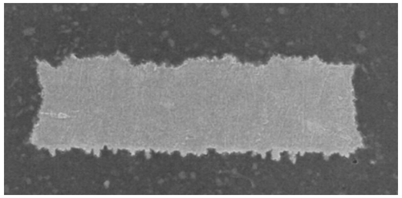
Modified Groiss roughness model (non-causal)

Conclusion

- Unified 2-parameter form for most of the roughness correction coefficients with additive and multiplicative extensions is proposed

$$K_{ri} = 1 + \left(RF_i - 1\right) \cdot F\left(SR_i, \delta_s\right)$$

- Some observations on the roughness
  - All mentioned roughness correction coefficients are “heuristic”
  - We definitely know that the roughness increases the losses – no doubts about it and all RCCs predict it
  - Drawing flat boundary changes both capacitance and inductance of the model – may be interpreted as capacitance or inductance of rough surface



  - Some surfaces may increase the inductance above predicted by the Wheeler’s rule and beyond the boundary positioning – accounted in Huray-Bracken RCC
  - Some surfaces may increase the capacitance beyond the boundary positioning – cannot be accounted by RCCs