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

Secondary Copper Plate  Barrier Layer Treatment  Anti Tarnish

Stain proof layer
Anti-tarnish layer
Drum foil
Dendrite plating
Protective barrier
Stain proof layer
Oxide 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

Test structures – 4 and 8 inch line segment with transitions to probe pads
TWS&1080 cross-sections

1080CORE    TWS    L3
1080PPEG

1080PPEG    TWS    TOP

19146 L3

4.15 mil

0.775 mil

4.3 mil

3.9 mil

3.9 mil

3.15 mil

8.7 mil

2.05 mil

8.975 mil

3.9 mil

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LP3 & 2116 cross-sections
Initial data from specifications

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

<table>
<thead>
<tr>
<th>Prepreg Designation</th>
<th>Resin Content (%)</th>
<th>Thickness (in.)</th>
<th>Thickness (mm)</th>
<th>Dk @ 2, 5 and 10 GHz</th>
<th>Df @ 2, 5 and 10 GHz</th>
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<tbody>
<tr>
<td>106</td>
<td>80</td>
<td>0.0030</td>
<td>0.075</td>
<td>2.80</td>
<td>0.0028</td>
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<td>1057</td>
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<td>0.0038</td>
<td>0.085</td>
<td>2.80</td>
<td>0.0028</td>
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<td>1090</td>
<td>72</td>
<td>0.0040</td>
<td>0.100</td>
<td>3.00</td>
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<td>1096</td>
<td>72</td>
<td>0.0047</td>
<td>0.118</td>
<td>3.00</td>
<td>0.0030</td>
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<tr>
<td>3313</td>
<td>60</td>
<td>0.0047</td>
<td>0.118</td>
<td>3.25</td>
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<td>2116</td>
<td>50</td>
<td>0.0058</td>
<td>0.145</td>
<td>3.30</td>
<td>0.0034</td>
</tr>
</tbody>
</table>

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


Hammerstad’s correction coefficient

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

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
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):

\[
GMSm = \begin{bmatrix}
0 & T_{11} \\
T_{11} & 0
\end{bmatrix} 
\]

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


Differential impedance operator of one Trefftz element:

\[
\begin{align*}
\delta_s &= \sqrt{\frac{2}{2\pi \cdot f \cdot \mu \cdot \sigma}} \\
\Gamma &= (1 + i) \frac{1}{\delta_s} \\
Z_m &= \frac{\Gamma}{\sigma}
\end{align*}
\]

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 (*)

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

<table>
<thead>
<tr>
<th>NxM</th>
<th>100 KHz</th>
<th>10 MHz</th>
<th>100 MHz</th>
<th>1 GHz</th>
</tr>
</thead>
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<tr>
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<td>1.34206195</td>
<td>3.31296611</td>
<td>10.0971387</td>
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<tr>
<td>16x2</td>
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<td>32x4</td>
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<tr>
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<tr>
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<tr>
<td>Ref. [2]: 172x16</td>
<td>1.2110346</td>
<td>3.127071</td>
<td>9.9028058</td>
<td>4.848</td>
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</tbody>
</table>


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

<table>
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<tr>
<th>NxM</th>
<th>100 KHz</th>
<th>10 MHz</th>
<th>100 MHz</th>
<th>1 GHz</th>
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<tr>
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<td>Ref. [2]: 172x16</td>
<td>0.5943148</td>
<td>3.1686575</td>
<td>9.9028058</td>
<td>4.0287</td>
</tr>
</tbody>
</table>

Wheeler’s [1] | 0.5943148 | 3.1686575 | 9.9028058 |

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

Exact DC resistance is 1.2725805 Ohm/m
Even 1 element produces acceptable accuracy!

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:

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

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

\( \Delta \) - 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 $\Delta=1$ um
Red lines – modified Hammerstad-Jensen model
Blue lines – model used in Simbeor software (less then 10% difference)
Huge difference in insertion loss (IL) and in Group Delay both in microstrip and strip-line configurations.
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


- The effect is actually capacitive because of group delay increases and the observed impedance decreases

![Graph showing TDR measurements](image1)

Computed TDR of 4 inch line with adjusted Dk (no launches)

![Graph showing measured TDR](image2)

Measured TDR of Strip in L3, TWS & 1080

weave effect
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
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
Dielectric constants are adjusted 3.3 -> 3.36 for 2116 prepreg, 3.3 -> 3.25 for 2116 core.

Roughness parameters from profilometer: $R_q=0.68 \, \mu m$, $RF=1.3$ (25% for shiny).

Insertion loss is considerably smaller than measured!
Dielectric constants are adjusted 3 -> 3.15 for 1080 prepreg, 3-> 3.35 for 1080 core

- Roughness parameters: $R_q=0.35$ um, $RF=2.8$ for all surfaces
- Both insertion loss and group delay now match well!

Stars – measured and fitted, Circles - modeled

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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!
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 μm, RF=7 for all surfaces
- Acceptable match for insertion loss and group delay (not perfect for strip)
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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Appendix: Backup slides

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

- Electrolyte preparation
  - Dissolve copper wire
  - Foil Sheets
  - Foil Rolls

- Electro-deposition
  - Cutting
  - Trimming

- Surface treatment
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

Interconnect or plane thickness in micrometers vs. Frequency in GHz

Ratio of r.m.s. surface roughness to skin depth 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


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

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

\[
L(\omega) = L_{\text{ref}} + \frac{R(\omega)}{\omega}
\]

\[
C(\omega) = C_{\text{ref}} \cdot \varepsilon_r(\omega) / \varepsilon_{\text{ref}}
\]

\[
R(\omega) = R_{\text{ref}} \cdot \sqrt{\omega / \omega_{\text{ref}}} \cdot K_{sr}
\]

\[
G(\omega) = G_{\text{ref}} \cdot [\varepsilon_r(\omega) / \varepsilon_{\text{ref}}] (\omega / \omega_{\text{ref}}) \cdot [\tan \delta(\omega) / \tan \delta_{\text{ref}}]
\]

Good agreement in insertion loss and pulse delay for rough copper
“Snowball” model


“Snowballs”

Huray’s correction coefficient

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

Good agreement in insertion loss only
Hemispherical model


Hemispherical approximation

“Hemispherical” correction coefficient

\[
K_{\delta} = \left[ \Re \left( \eta \frac{3\pi}{4k^2} (\alpha(1) + \beta(1)) \right) \right] + \frac{\mu_0\omega\delta}{4} \left( A_{\text{tile}} - A_{\text{base}} \right)
\]

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 μm, then Hammerstad’s formula (3) has been shown to adequately approximate the surface roughness losses.”
Small perturbation method


Sundstroem’s correction coefficient

\[ \alpha_c = \frac{\beta_0 \eta_0}{4 p Z_o} \left[ \delta + \frac{1}{\delta} \sum_{n=1}^{\infty} H_n^2 \left( 1 - \sqrt{\frac{1}{2} \left( \sqrt{n^4 s^4 \delta^4 + 4} - n^2 s^2 \delta^2 \right)} \right) \right] \]

Figure 6.
Trace dimensions and surface roughness of the trace
Stochastic approach


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

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

(38)

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

Difficult to measure, profilometer does not provide enough resolution
Experimental separation of losses


Differential extrapolation and redistribution method (DERM)

\[
\alpha_{T}^{STD} = K_{1}^{STD} \sqrt{\omega} + K_{2}^{STD} \omega + K_{3}^{STD} \omega^2;
\]

\[
\alpha_{T}^{VLP} = K_{1}^{VLP} \sqrt{\omega} + K_{2}^{VLP} \omega + K_{3}^{VLP} \omega^2;
\]

\[
\alpha_{T}^{HVL} = K_{1}^{HVL} \sqrt{\omega} + K_{2}^{HVL} \omega + K_{3}^{HVL} \omega^2.
\]

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

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Equivalent boundary conditions


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 $\varepsilon_{\text{eff}}$ and permeability $\mu_{\text{eff}}$. 
Surface as a periodic structure


Rough surface as 2D and 3D periodic structures

Lukic’-Filipovic correction coefficient:

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

(3)
Direct electromagnetic analysis


Brute force approach – not practical

![Diagram](image)

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


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


Roughness increases not only attenuation, but also effective dielectric constant or $K_{\text{eff}}$ (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?

Composed 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)

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

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!