Copper Roughness and how to account for it

Martyn Gaudion– October 2017 (Rev 1)

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Acknowledgments

Alan Staniforth

Bert Simonovich
"All models are wrong but some are useful"
George E. P. Box
Introducing Polar Instruments

Welcome to a presentation that will cover the following topics:

1. Overview and significance of copper roughness
2. Methods for calculating insertion loss with roughness
Overview of Copper Roughness

Current Distribution Through a Conductor

DC current is uniform through cross-sectional area of conductor

AC current above ~10MHz flows mainly along “skin” of the conductor

[1] Simonovich 2015, pg 5
Overview of Copper Roughness

Skin Depth Vs Frequency

\[ \delta = \sqrt{\frac{1}{\pi f \mu_0 \sigma}} \]

\( \mu_0 = \) Permeability of free space in H/m
\( \sigma = \) Conductivity in S/m.

AC current above \( \sim 10\text{MHz} \) flows mainly along “skin” of the conductor

Overview of Copper Roughness

Copper is Roughened for Various Reasons

No such thing as a perfectly smooth PCB conductor surface

Roughness is always applied to promote adhesion to the dielectric material

[2] Simonovich 2015, Slide 17
Overview of Copper Roughness

Copper Foil Manufacturing Processes

Rolled

Electro-deposited (ED)

SmOOTher

LSower Cost

[2] Simonovich 2015, Slide 18
Overview of Copper Roughness

Rolled Copper Foil Fabrication Process

Copper bar fed through a series of progressively smaller rollers to achieve final thickness

Roller smoothness determines final smoothness of foil

Overview of Copper Roughness

Electrodeposited Copper Foil Fabrication Process

Drum speed controls foil thickness

Matte side always rougher than drum side

Overview of Copper Roughness

Common Roughness Profiles

IPC Standard Profile
No min/max spec

IPC Very Low Profile (VLP)
< 5.2 μm max

Ultra Low Profile (ULP) Class
- Other names: HVLP, VSP
- No IPC spec
- Typically < 2 μm max

[2] Simonovich 2015, Slide 21
Overview of Copper Roughness

Electro-deposited Copper Foil Nodulation Treatment

Overview of Copper Roughness

Profilometers Used to Measure Surface Roughness

- Provides 2D Scan Profile
- Faster
- More reliable
- More accurate

Methods for Calculating Insertion Loss with Roughness

- Smooth Conductor
- Morgan-Hammerstad
- Groisse Method
- Huray “Snowball” Method
Methods for Calculating Insertion Loss with Roughness

Garbage In = Garbage Out
Which is correct?
Measured or modelled?
Methods for Calculating Insertion Loss with Roughness

Loss Calculations

Total Loss = Insertion Loss of Dielectric +

Surface Roughness Coefficient X Insertion Loss of Conductor

\[ IL_{total}(f) = IL_{dielectric}(f) + K_{SR}(f) \cdot IL_{conductor}(f) \]
Methods for Calculating Insertion Loss with Roughness

Morgan-Hammerstad

Based on scratches on conductor surfaces

[3] Bogatin et al., Pg. 5
Methods for Calculating Insertion Loss with Roughness

Morgan-Hammerstad

• Based on scratches on conductor surfaces
• First developed in 1949. Republished in 1975 by Hammerstad
• Saturates for rough conductor at low frequencies to a value of 2

\[
\frac{\alpha_{\text{rough}}}{\alpha_{\text{smooth}}} = 1 + \left(\frac{2}{\pi}\right) \arctan \left[ 1.4 \left(\frac{\Delta}{\delta}\right)^2 \right]
\]
Methods for Calculating Insertion Loss with Roughness

Groisse

Also Saturates as the Ksr approaches 2.

Depending on Conductor roughness, predictions can go to higher frequencies than Hammerstad

Groisse Equation:

\[
\frac{P_{\text{rough}}}{P_{\text{smooth}}} = 1 + \exp\left(-\left[\frac{\delta}{2\Delta}\right]^{1.6}\right)
\]
Methods for Calculating Insertion Loss with Roughness

Huray

- The surface can be modelled using a pyramid of metal spheres called “snowballs”
Methods for Calculating Insertion Loss with Roughness

Huray

• The theory starts with a single snowball between conductors with an electromagnetic wave incident on it.
• The wave is both reflected (scattered) and absorbed

[4] Huray, Paul G
Methods for Calculating Insertion Loss with Roughness

Huray

- In the pyramid of snowballs, multiple scattering and absorption occurs. However, it is found that absorption dominates over scattering at the frequencies of interest.

![Graph showing absorption and scattered cross-sections](image)

Methods for Calculating Insertion Loss with Roughness

Huray

• Equation

\[
\frac{P_{\text{rough}}}{P_{\text{smooth}}} = \frac{A_{\text{smooth}}}{A_{\text{rough}}} + 6 \sum_{i=1}^{j} \left[ \left( \frac{N_i \pi a_i^2}{A_{\text{smooth}}} \right) \left( 1 + \frac{\delta}{a_i} + \frac{\delta^2}{2a_i^2} \right)^{-1} \right]
\]

\( P \)  is the power lost
\( A \)  is the area
\( N \)  is the number of snowballs in area \( A \)
\( j \)  is the distribution of snowballs
\( \delta \)  is the skin depth

[4] Huray, Paul G
Methods for Calculating Insertion Loss with Roughness

Huray

• In order to simplify the formula for practical use simulations, using different ball radii have been conducted.
Methods for Calculating Insertion Loss with Roughness

Huray

• Simplification of the formula for a single effective ball radius

\[
\frac{P_{\text{rough}}}{P_{\text{smooth}}} = \frac{A_{\text{rough}}}{A_{\text{smooth}}} + \left(\frac{3}{2}\right)(SR) \left( \frac{1}{1 + \frac{\delta}{a} + \frac{1}{2} \left(\frac{\delta}{a}\right)^2} \right)
\]

SR is the Hall-Huray Surface Ratio \(\frac{4\pi Na^2}{A_{\text{smooth}}}\)

\(a\) is the effective radius of all snowballs

\(N\) is the number of snowballs in area \(A\)

[4] Huray, Paul G
Methods for Calculating Insertion Loss with Roughness

Comparisons with Si9000e
Methods for Calculating Insertion Loss with Roughness

Practically How Do I do this?
References


"Si9000e insertion loss solver"
Copper Roughness and Si9000e

Graph

Surface Microstrip 1B

Frequency Distribution

Logarithmic
Linear

Result Presentation

Length of Line

(R)/n
/m

Extended Substrate Data

Constant Er/TanD
Causally Extrapolate Er/TanD
Multiple Er/TanD

Surface Roughness Compensation

Smooth
Hammered
Grosse
Husay

Measurement Data

No Data Imported

S-Parameter Configuration

Frequency Steps
200
Source and Load Impedance (Ohm)
Source:
Load:

Graph Settings

Display Series

All Losses

Loss Budget (dB)
0.0000

Picked Data Point Information

Maximize
Print
Export
Copper Roughness and Si9000e

Surface Microstrip 1B

www.polarinstruments.com

Images courtesy of Circuit foil Luxembourg
European Institute for the PCB Community

Linking PCB design and fabrication professionals with OEMs and suppliers through technical networking events and conferences.

eipc.org
The Printed Circuit Designer's Guide to™
Secrets of High-Speed PCBs

by: Martyn Gaudion, Polar Instruments

If you're a PCB designer or design engineer, chances are you're probably dealing with high-speed PCBs and their attendant issues. This book, Secrets of High-Speed PCBs: Specifying, Modelling, and Measuring, Part 1, is a must-read, not just for designers, but for anyone involved with, or confused by, high-speed PCBs: purchasing agents, salespeople, marketing professionals, recent graduates, etc.

This micro eBook is a compilation of columns written by Martyn Gaudion, CEO of Polar Instruments, for The Printed Circuit Design Magazine over several years. Martyn examines complex signal integrity challenges, modelling and measurement issues, transmission line theory, the effects of glass weave on signal integrity, and much more.
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