UNDERSTANDING SKIN EFFECT AND DIELECTRIC LOSS MATERIAL EFFECTS ON DIGITAL INTERCONNECTS

An Innovative and Fundamental Perspective

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Introductory Questions

- How do you choose PWB or cable materials to fit your specific serial digital application?
- What is the best trace width to achieve a given performance?
- Is the choice of PWB materials driven by cost, performance or anecdotal discussions with the your buddy in the next cube over?
- Can you make your legacy design go faster without spending much in the way of engineering development except for new semiconductors?
- How does the Nyquist frequency enter into material choices and design parameters for serial interconnects?

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Summary

- This presentation summarizes the tradeoffs between PCB copper and dielectric material properties which are relevant to the design of 10 and 25 Gbps digital channels.
- First principles of transmission line theory is used to derive a unique and important frequency parameter: the crossover frequency where skin effect losses = dielectric losses. This frequency point is the boundary where losses increase as the square root of frequency vs dielectric losses where the losses are directly proportional to frequency.
- In the case of low loss PWB and cable dielectric materials, it will be shown that skin effects can extend beyond the bit rate as determined by the Nyquist frequency of the digital signal.

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Background Theory

The crossover between skin effects and dielectric loss was derived by Sayre and Sayre & Chen starting with the low loss equivalent per unit length circuit element definition of insertion loss:

$$Insertion\ Loss_{dB} = 4.343 \cdot \left[G_d \cdot f \cdot Z_o + \frac{R_{dc} + R_s \cdot \sqrt{f}}{Z_o} \right] * L$$

Where: $f = operating\ frequency,\ [Hertz]$

$G_d = shunt\ dielectric\ conductance = 2 \cdot \pi \cdot C \cdot tan(\delta),$ [siemens/frequency]

$C = capacitance\ of\ the\ transmission\ line\ per\ unit\ length,$ [Farads/m]

$\tan(\delta) = the\ loss\ tangent\ of\ the\ dielectric; also\ called\ Df\ in\ PCB\ specifications$

$Z_o = the\ characteristic\ impedance\ of\ the\ transmission\ line$

$R_{dc} = the\ dc\ resistance\ of\ the\ transmission\ line$ [ohms]

$R_s = \sqrt{\frac{\pi \cdot \mu}{\sigma}} / Perimeter\ of\ conductor$ [ohms/sqrt(f)]

$\mu = magnetic\ permeability\ (for\ nonmagnetic\ materials) = 4 \cdot \pi \cdot 10^{-7}$

$\epsilon = dielectic\ permittivity = \varepsilon_o \cdot \varepsilon_r = 8.854 \cdot 10^{-12} \cdot \varepsilon_r; also\ called\ Dk\ in\ PCB\ specfications$

$\sigma = conductor\ conductivity = 5.8 \cdot 10^7\ for\ smooth\ copper, higher\ for\ rough\ copper.$

L= *interconnect length*

“First Principles in 10 Gbps and 25 Gbps Channel Design”, Dr. Edward P. Sayre, Presentation at the Ethernet Technology Summit, San Jose, CA June, 2012

“Limits of FR-4” by Drs., Edward P. Sayre and Jinhua Chen, North East Sytems Associates, Inc., Notes for Signal Integrity Seminar “Signal Integrity "Right by Design" For high performance DDR and DDR2 Memories and Multi-Gigabit Designs", Day 2, 2004

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Skin Effect to Dielectric Crossover Frequency

The frequency f_e where the skin effect losses equal the dielectric losses can be shown to be given by:

$$f_e \approx \left[\frac{R_S}{G_d} \cdot \frac{1}{Z_o^2}\right]^2$$

- For frequencies $f \leq f_e$ Insertion Losses are dominated by $\frac{1}{\sqrt{f}}$ skin effect behavior and
- For $f \geq f_e$, Insertion Losses are dominated by $\frac{1}{f}$ dielectric losses.

In general, the higher f_e, the lower will be the Insertion Loss.

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Single Ended and Differential Impedance

- All serial data interconnects are specified as constant differential impedance.
  - PCIe specifies 85 ohms differential impedance
  - Ethernet, OIF, Serial Rapid IO, Infiniband, SATA/SAS all specify 100 ohms differential impedance
- These specifications do not specify the actual design in terms of trace thickness and trace width, PWB, connector or cable materials.
- This analysis will assume that all calculations are conducted for either 100 ohms differential or 50 ohms single ended, +/- 10%.
- The analysis will consider constant impedance trace width designs between 3mils [76µm] through 10mils [254µm].

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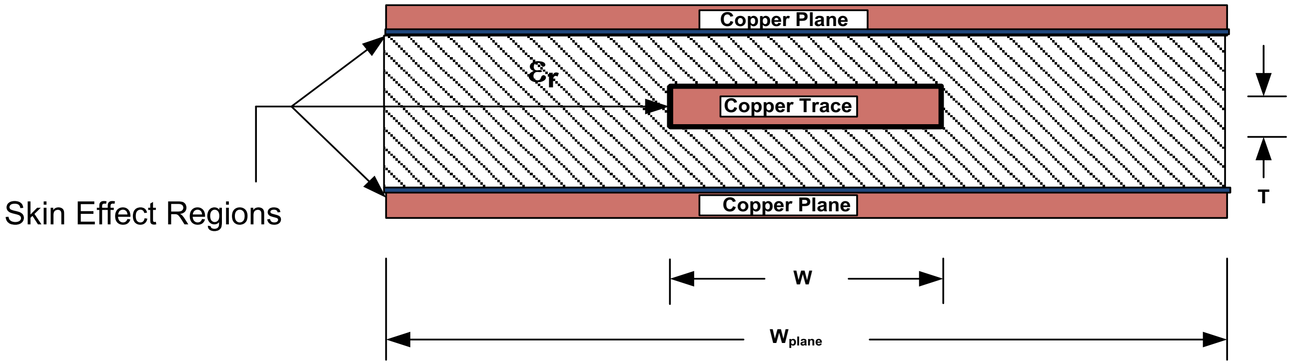
Useful PWB Approximations



The skin effect parameter R_s can be approximated by:

$$R_s \cong \frac{1}{\sigma \cdot \Delta \cdot (2 \cdot [W+T])} + \frac{1}{\sigma \cdot \Delta \cdot (\alpha \cdot W)}$$

where: $\alpha \cong (1.4 - 1.6)$ depending on the Stripline design

The dielectric conductance G_d in units of Siemens per meter is directly related to the transmission line unit capacitance C between the trace and surrounding planar conductors.

$$G_d = shunt\ dielectric\ conductance = 2 \cdot \pi \cdot C \cdot tan(\delta)$$

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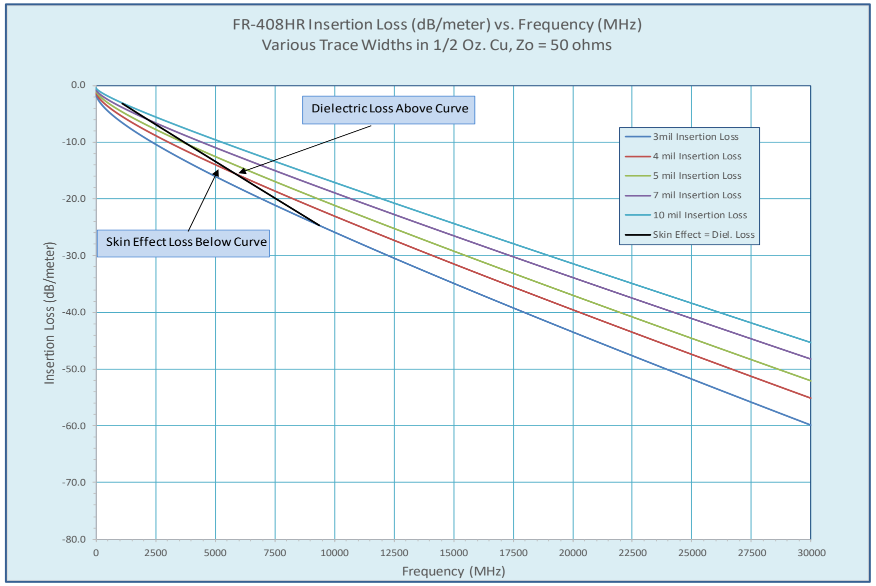
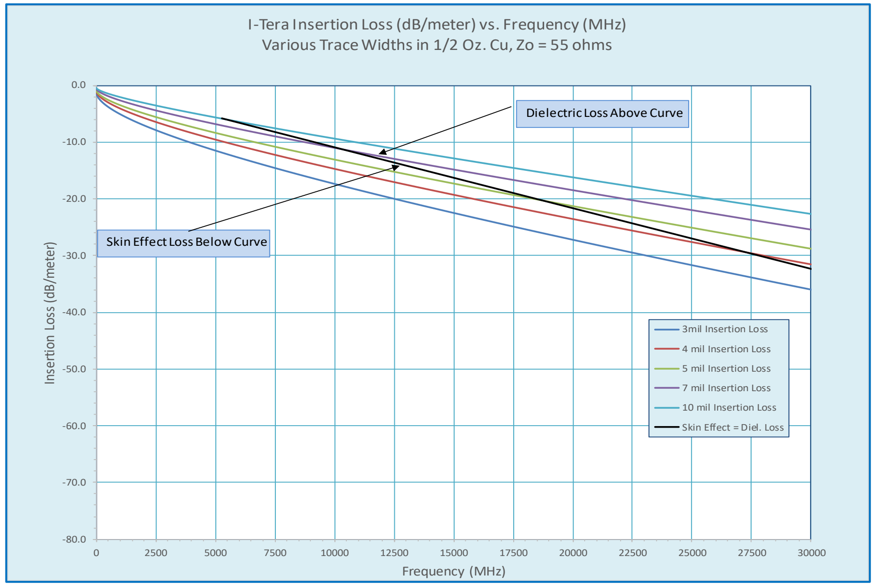
PWB Design Example 1: FR-408 vs. I-Tera Design

Material Name	FR-408HR	I-Tera
Dk (Dielectric Constant)	3.67	3.45
Df (Loss Tangent)	7.20E-03	3.10E-03
Transmission Line Impedance Zo	50	50

PCB Dielectric Material Properties



Insertion Loss – FR-408 Design



Insertion Loss – I-Tera Design

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Example 2: Maintain the PCB trace geometry and stackup designs; just reduce the loss tangent

- It is shown in this example, that it is possiblt to scale designs by using a reduced loss tangent.
- The example shows that maintaining the dielectric constant Dk while decreasing the dielectric loss tangent, Df, allows the data rate to rise with a minimum of extra design cost.

$$\frac{f_{e_2}}{f_{e_1}} = \frac{[tan(\delta_1)]^2}{[tan(\delta_2)]^2}$$

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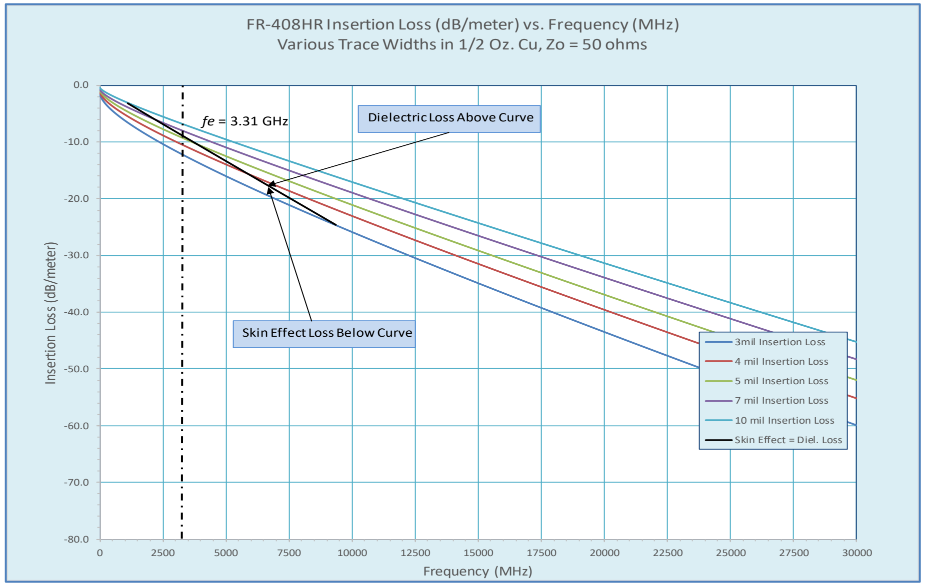
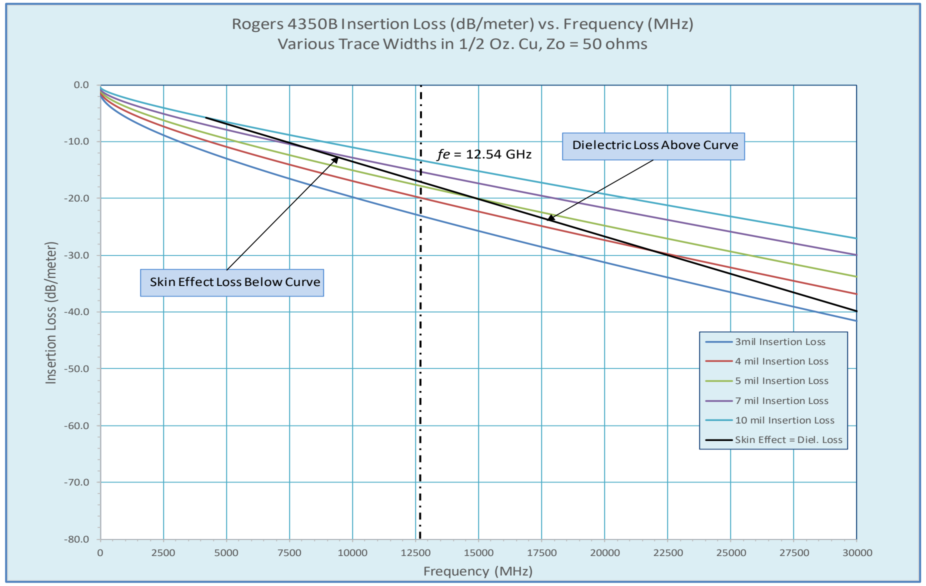
Changing the Loss Tangent, Physical Design the Same

Material Name	FR-408HR	Rogers 4350B
Dk (Dielectric Constant)	3.67	3.67
Df (Loss Tangent)	7.20E-03	3.70E-03
Trace Width	5.5 mil	5.5 mil
Transmission Line Impedance Zo	50	50

Published PCB Properties



Isola FR-408 Design



Rogers 4350B Design

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Experimental Determination of *fe*

- The transmission equation is a quadratic in the square root of frequency.

$$IL(f) = 4.343 \cdot [G_d \cdot Z_o \cdot f + \frac{R_s}{Z_o} \cdot \sqrt{f} + \frac{R_{DC}}{Z_o}]$$

- The crossover frequency characterization of a low loss Twin-ax cable 100Ω differential assembly (the DUT) is desired.
- The fitted quadratic for the measured insertion Loss 2.5-meter twin-ax data fitted LMS fit is given by:

$$IL_{dB} = 4.0e^{-10} \cdot f + 1.999e^{-3} \cdot \sqrt{f} + 0.49$$

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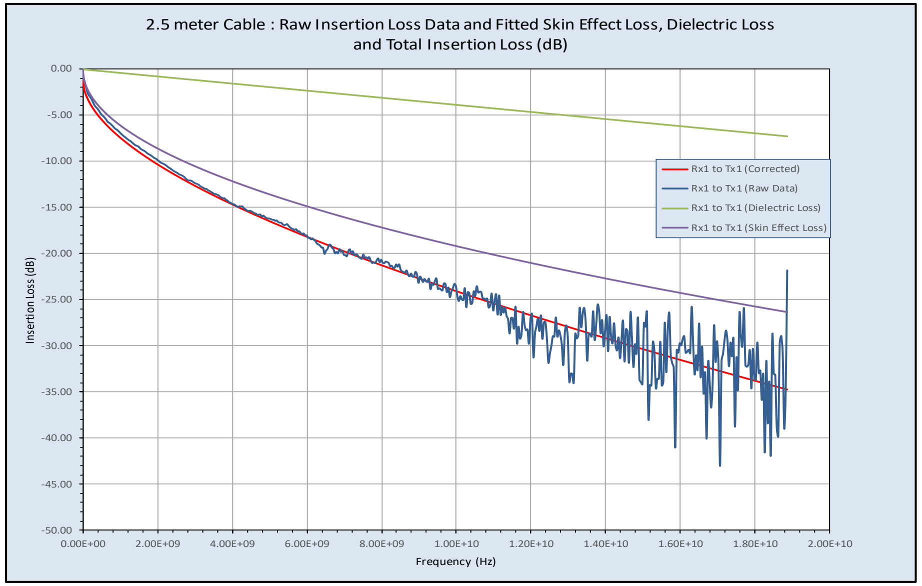
Measured and Fitted 2.5 meter Twin-ax Insertion Loss



Measured and Fitted 2.5 meter Twin-ax Insertion Loss

- Using the equation for *fe* to determine the skin effect to dielectric loss crossover frequency, we find:

$$f_e = 24.98e^3 \ \ GHz$$

- As expected for low-loss cable, the total loss is well characterized only by the skin effect losses.

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Take-Aways

1. The methodology presented herein is suitable for both PWB interconnects as well as cable assemblies. The curve fitting methodology is consistent with other methods developed for Ethernet and OIF serial communication data stream evaluation.
2. The most important takeaway is that when the Nyquist Frequency ≤ *fe* satisfies this inequality, the interconnect losses are largely governed by the skin effect losses of the interconnect. The Nyquist frequency f_N is ≤ half of the sampling rate of a discrete signal being processed through a system.
3. The availability of low loss materials where *fe* is ≥ 10 Gbps, means that lower loss designs can be cost effectively designed by the proper choice of loss tangent PWB materials.
4. The skin effect losses are a strong function of the trace width. Increasing the PWB trace width is the only practical means to lower skin effect losses. Increases in copper weight, except for the narrowest traces are second order effects.
5. The crossover frequency *fe* increases as the inverse square of the loss tangents. Halving the loss tangent moves the skin effect to dielectric loss crossover frequency up by a factor of four (4).
6. When the dielectric constant Dk, and Transmission Line Impedances are equal, moving to a lower loss tangent will result in reduced total losses with little or no change in the physical design beyond new semiconductors.
7. The crossover frequency *fe* is mildly affected by the changes in the Transmission Line Impedance but the total losses are not. As the example shows, reducing Line Impedance 55 ohms to 46 ohms, the crossover frequency of 2,910 MHz is increased to 4,162 MHz, but the total loss was largely unaffected.

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