Successful Design of OC-48/2.5Gbps Interconnects

Limits of FR-4 in High-Speed Designs

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The FR-4 Problem in Gigabit Design

- FR-4 is the most common PCB Fabrication material and the most cost effective.
- Fabricators know how to laminate and etch a wide variety of conductor patterns and conditions.
- A well known material with UL and other approvals.
- Question of the Hour!!!!

How far can Gigabit signals be run on 100 Ω impedance differential etch and at what speeds?
Total RF Transmission Line Loss

\[
\frac{\text{Attenuation}}{\text{Per Unit Length}} (dB) = 4.35 \left[ G_d \times f \times Z_0 + \frac{R_{dc} + R_s \sqrt{f}}{Z_0} \right]
\]

Where:
- \( G_d \) = shunt dielectric conductance \([\Omega \text{ Hz}]^{-1}\)
- \( R_s \) = skin effect series loss \([\Omega(\text{Hz})^{-1/2}]\)
Frequency Where Skin Effect Losses Equal Dielectric Losses

\[ f_e = \left( \frac{R_s}{G_d} \cdot \frac{1}{Z_0^2} \right)^2 \]

Where:
- \( R_s \) = Skin Effect Resistance [\( \Omega(\text{Hz})^{-1/2} \)]
- \( G_d \) = Dielectric Shunt Conductance [\( \Omega \text{ Hz}^{-1} \)]
- \( Z_0 \) = Transmission Line Impedance [\( \Omega \)]
Typical Values for FR-4 & Common Line Parameters

- Line Width - 8 mil
- Line thickness - 1 oz Cu (1.4 mils)
- Differential Impedance $Z_o = 100 \Omega$
- FR-4 Dielectric Constant $= 4.5$
- FR-4 Loss Tangent $= 0.021$ (assumed constant)

- Skin Loss = Dielectric Loss at $f_e = 205$ MHz
RF Total Loss vs. Normalized Frequency

![Graph showing RF Total Loss vs. Normalized Frequency](image-url)
100 Ω Differential PCB
percentage peak to peak loss as the function of data rate, PCB lengths from 10” to 50” with 8 mil line width

![Graph showing the percentage peak to peak loss for different PCB lengths and data rates.](image-url)
100 Ω Differential PCB
percentage peak to peak loss as the function of PCB length with 8 mil line width
100 Ω Differential PCB

percentage peak to peak loss as the function of data rate, PCB lengths from 10” to 50” with 6 mil line width
100 \ Ohm Differential PCB
percentage peak to peak loss as the function of PCB length with 6 mil line width
100 Ω Differential PCB
percentage peak to peak loss as the function of data rate, PCB lengths from 10” to 50” with 4 mil line width
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100 Ω Differential PCB
percentage peak to peak loss as the function of PCB length with 4 mil line width

High Performance Engineering & Design

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100 Ω Differential PCB

percentage peak to peak loss as the function of data rate
30" traces with 4, 6 and 8 mil line width
Simulated 2.5 Gbps Eye Pattern

skin effect + dielectric loss (FR-4 loss tangent 0.021) for 40” trace
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Simulated 2.5 Gbps Eye Pattern

- skin effect + dielectric loss for 40” trace with two backplane connectors
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Measured 2.5 Gbps Eye Pattern

skin effect + dielectric loss for 40” trace with two backplane connectors
Differential 1.25 Gbps Eye Pattern
23” trace including two backplane connectors
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Poor Fabrication Results
Differential TDR vs. Risetime

Skin Effect Region
Highly Resistive Lossy Etch
SMA Connector

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1.25 Gbps Eye Pattern
properly etched differential pair
1.25 Gbps Eye Pattern
over-etched differential pair
FR-4 PCB Limits - Summary

- **Eye Diagram Response**
  - Deterministic Jitter and Risetime Losses are well known and due to dielectric and conductor skin effect losses.
  - Eye diagram mask violations in amplitude or bit time jitter lead to unacceptable Bit Error Rates.

- **Fabrication Quality of PCB traces strongly affects eye response.**
  - $100 \, \Omega$ impedance line losses not strongly affected by line size.

- **Semiconductor pulse fidelity and receiver determining factors**
  - Receiver threshold region < (15 - 20%) of swing OK.
  - Risetimes < (15 - 20)% of bit width reduces mask violations.

- **FR-4 max. line length depends on devices, bit rate, reflections and losses**
  - As a practical matter, jitter more forcefully impacted by bandwidth limits due to losses.
  - Connector reflections shorten maximum length.

- **Maximum usable clock rate** $F_{\text{clk}} \sim (7 - 10) \times f_e$ at reasonable PCB lengths of 0.5 meter to 1.25 meter.