Lesson AGCD-03-01 Download the pdf slides here

Course AGCD: Advanced Gigabit Channel Design

With Eric Bogatin,
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Adjunct Professor, University of Colorado, Boulder, ECEE

- AGCD-03-01: recorded live, Dec 1, 2013
  - Download a pdf copy of the slides by clicking on the link on this page

Lesson AGCD-03-10 How lossy lines collapse the eye vertically

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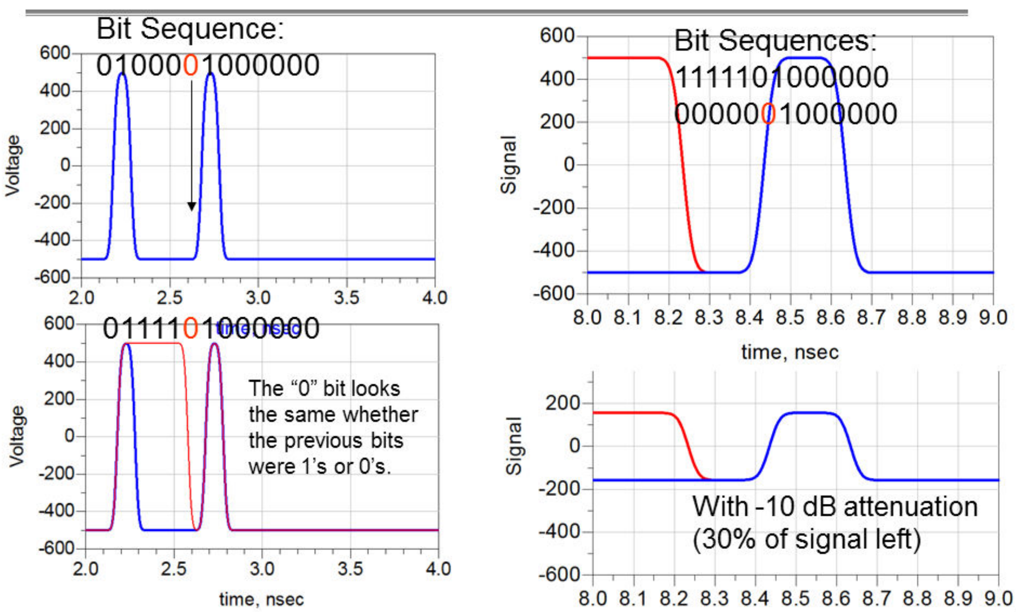
- AGCD-03-10: recorded live, Dec 1, 2013
  - Why short rise time signals have no ISI
  - How to think of the origin of Inter Symbol Interference
  - Rise time degradation when passing through real interconnects
  - How increased rise time creates vertical collapse of the eye

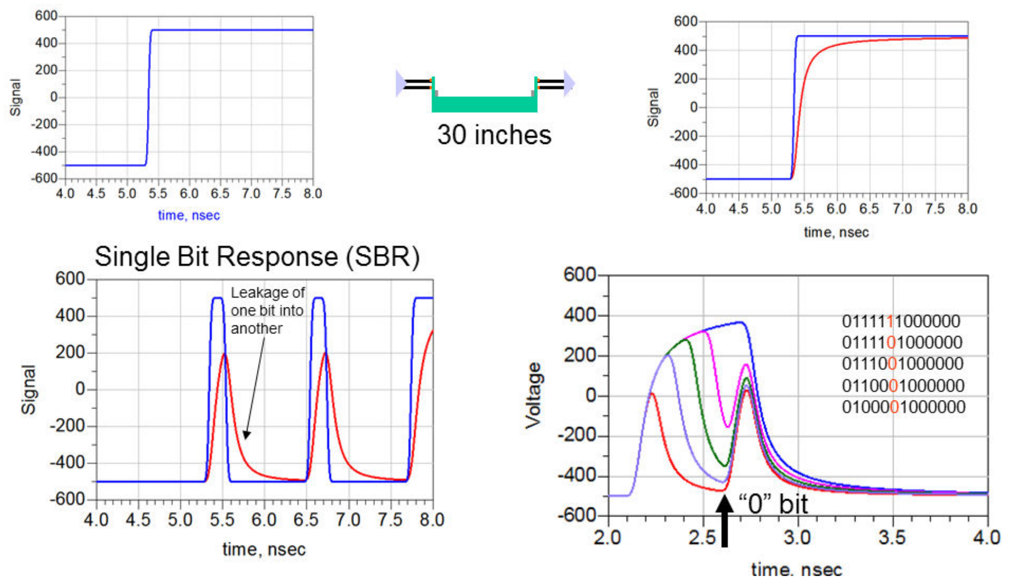
AGCD: A 2-Day Workshop

- **Day 1**
  - ✓ AGCD 1 Opening eyes
  - ✓ AGCD 2 Differential pairs and routing
  - ✓ Lunch
  - ✓ **AGCD 3 Lossy Lines and ISI**
  - ✓ AGCD 4 Channel to channel cross talk
- Day 2
  - ✓ AGCD 5 Mode conversion
  - ✓ AGCD 6 Discontinuities
  - ✓ Lunch
  - ✓ AGCD 7 Transparent Via Design
  - ✓ AGCD 8 Practical consideration

Short Rise Time Bits Have NO ISI



Enter the Real World: Rise Time Degradation Causes ISI



Lesson AGCD-03-20 ISI and data dependent jitter

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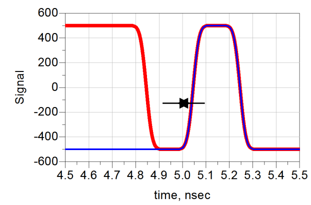
- AGCD-03-20: recorded live, Dec 1, 2013
  - How increased rise time signals create jitter
  - ISI and deterministic jitter
  - Describing the losses in a transmission line in terms of the attenuation per length
  - Quick review of the dB as related to insertion loss and attenuation

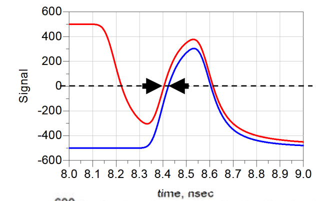
ISI Causes "Data Dependent" Jitter (Deterministic Jitter)

- SBR for extreme bit patterns,
  - 11111010000000
  - 00000010000000
  - 5 Gbps, RT = 50 psec
- Switching threshold time for the "1" bit is different when previous bits were all 0 or all 1
- The more rise time degradation, the more deterministic jitter

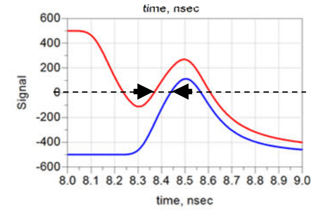
No interconnect



20 inch interconnect:

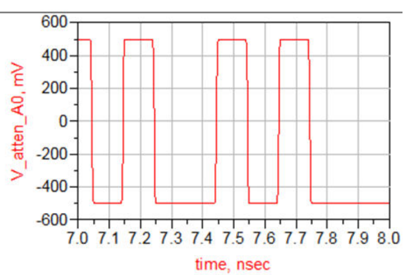


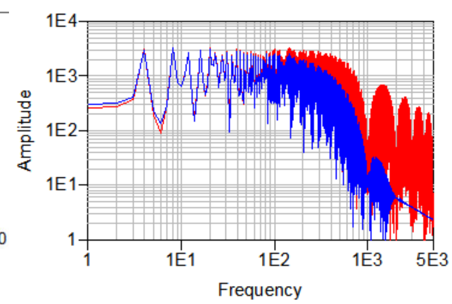
40 inch interconnect:

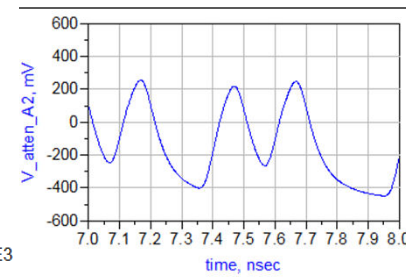


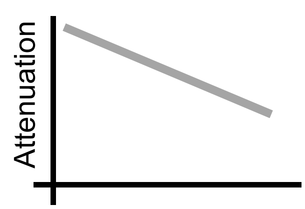
What causes the rise time degradation?

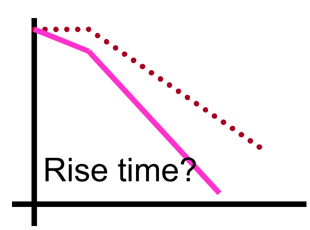
Frequency Dependent Loss = Rise Time Degradation



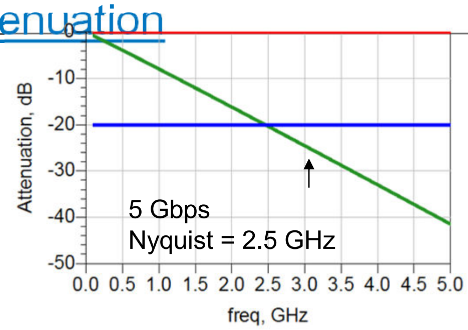


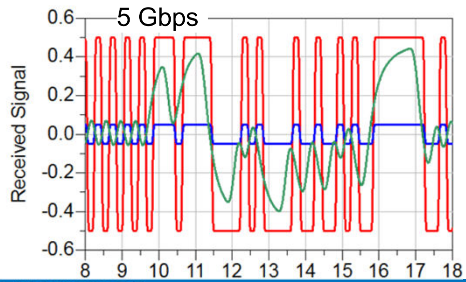


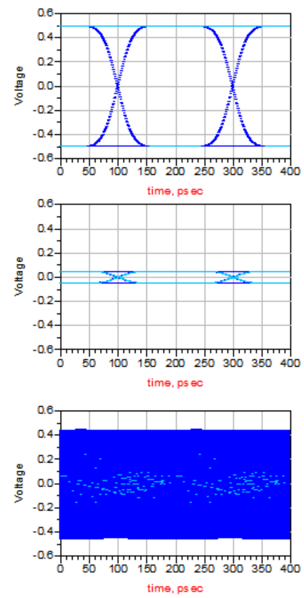




It's not just Attenuation @ Nyquist, it's Frequency Dependent Attenuation







No attenuation: Perfect eye

-20 dB

Constant attenuation: Collapsed, but NO jitter- Can be recovered with some gain at RX

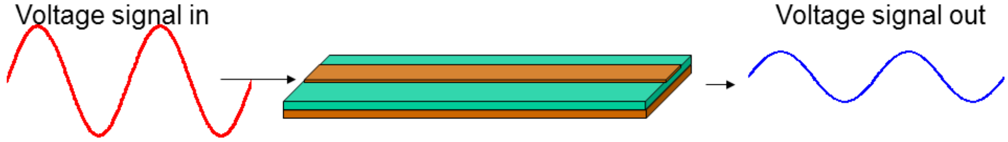
-20 dB Frequency dependent

Frequency dependent attenuation: Completely collapsed eye with too much jitter

Attenuation in the Frequency Domain

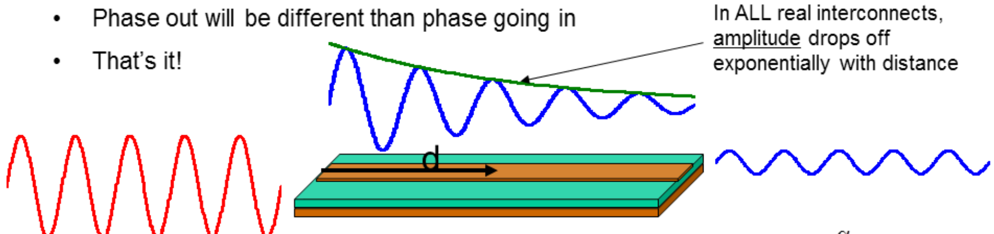
Voltage signal in

Voltage signal out



- NEVER any distortion of a sine wave: sine wave goes in, sine wave comes out
- Frequency coming out ALWAYS = frequency going in
- Amplitude coming out ALWAYS < amplitude going in
- Phase out will be different than phase going in
- That's it!

In ALL real interconnects, amplitude drops off exponentially with distance



$$V_{out}(d) = V_{in} e^{-\alpha_{nepers/len} d} = V_{in} 10^{-\frac{\alpha_{dB/len}}{20} d}$$

Quick Review of the dB

0 dB = 1

$$\frac{V_{output}}{V_{input}} = 10^{\frac{A_{dB}}{20}}$$

$$A_{dB} = 20 \text{ x } \log\left(\frac{V_{output}}{V_{input}}\right) \text{dB}$$

Ratio of amplitudes	value in dB
100%	0 dB
90%	-1 dB
80%	-2 dB
70%	-3 dB
50%	-6 dB
30%	-10 dB
10%	-20 dB
5%	-26 dB
3%	-30 dB
1%	-40 dB

-20 dB is:

$$\frac{V_{output}}{V_{input}} = 10^{\frac{-20}{20}} = 0.1 = 10\%$$

-40 dB is:

$$\frac{V_{output}}{V_{input}} = 10^{\frac{-40}{20}} = 0.01 = 1\%$$

-10 dB is:

$$\frac{V_{output}}{V_{input}} = 10^{\frac{-10}{20}} = \frac{1}{\sqrt{10}} \sim 30\%$$

Lesson AGCD-03-30 How much attenuation is too much?

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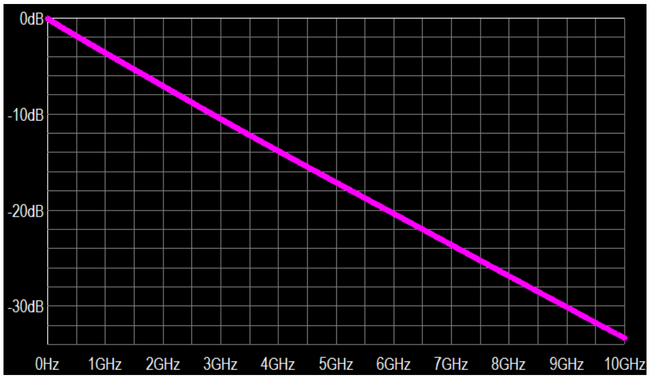
- AGCD-03-30: recorded live, Dec 1, 2013
  - The attenuation in real interconnects
  - The connection between frequency dependent attenuation and rise time
  - Data rate, attenuation and collapse of the eye
  - The maximum data rate and allowed attenuation for an acceptable eye

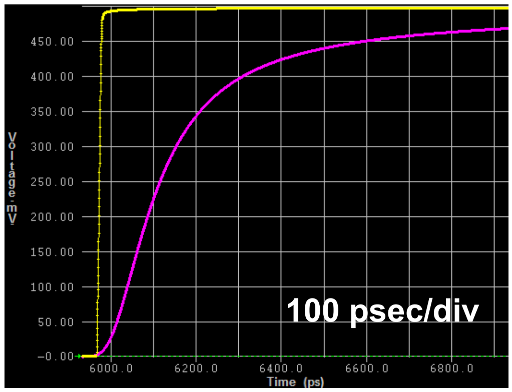
Frequency Domain and Time Domain Responses of the Channel

- What is the connection between attenuation at Nyquist and the eye diagram?

(36 inches, FR4, 4 mil wide line)
FOM ~ 34 dB/36 inch/10 GHz = ~ 0.1 dB/inch/GHz



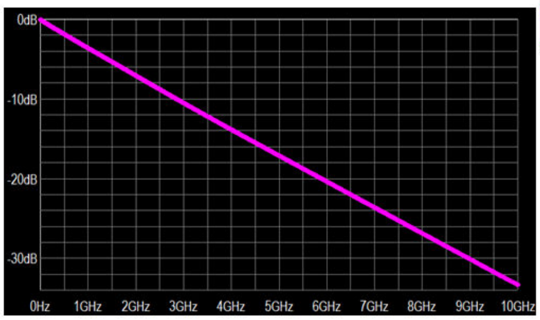
Step response



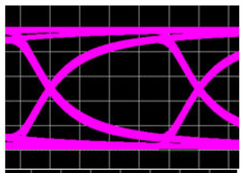
What will the eye look like if the UI is 1 nsec, 0.5 nsec, 0.1 nsec?

Attenuation at Nyquist and Eye Diagram

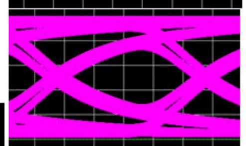
- What is the connection between attenuation at Nyquist and the eye diagram?
- Define xx dB-Bandwidth as the highest frequency at which the attenuation is less than xx dB
- What BW is required for eye opening?



Atten @Nyquist:

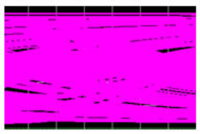


2 Gbps -4 dB
(little impact from losses)



4 Gbps -8 dB
(highest data rate without equalization)

7 Gbps -12 dB
(eye barely open)



9 Gbps -16 dB
(eye completely closed- can be opened with CTLE)

Lesson AGCD-03-40 Equalization and limits to attenuation

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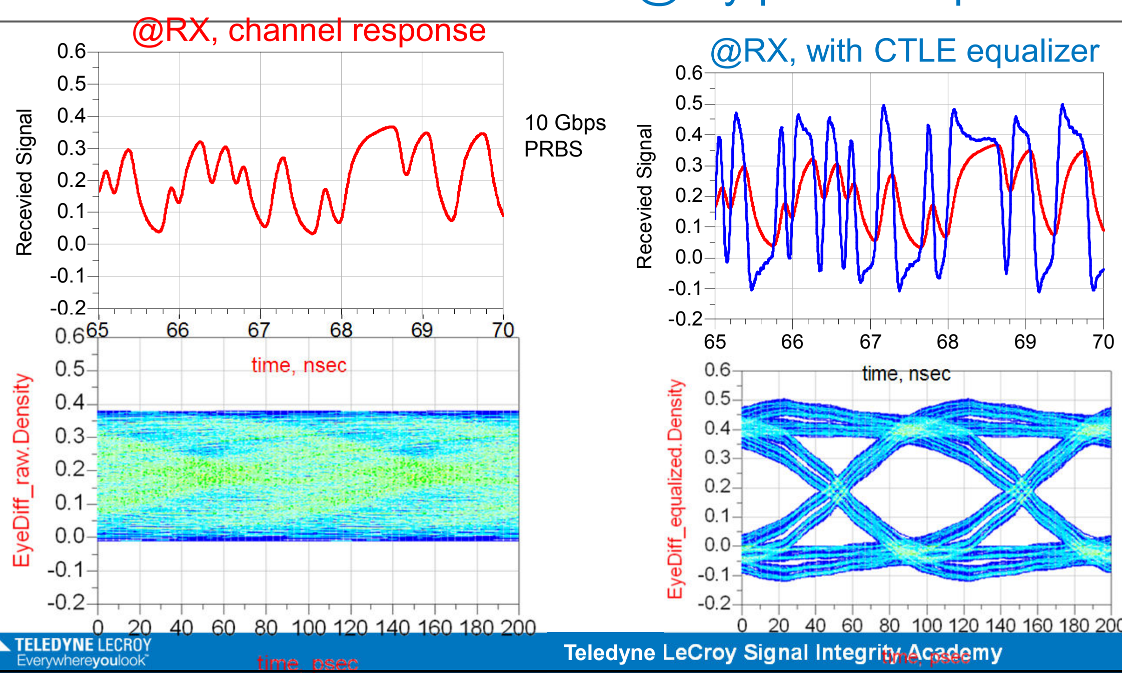
- AGCD-03-40: recorded live, Dec 1, 2013
  - When the attenuation closes the eye
  - Using CTLE equalization to open a closed eye
  - 10Gbase spec for maximum attenuation at the Nyquist
  - Estimating a channel's maximum data rate from the insertion loss curve

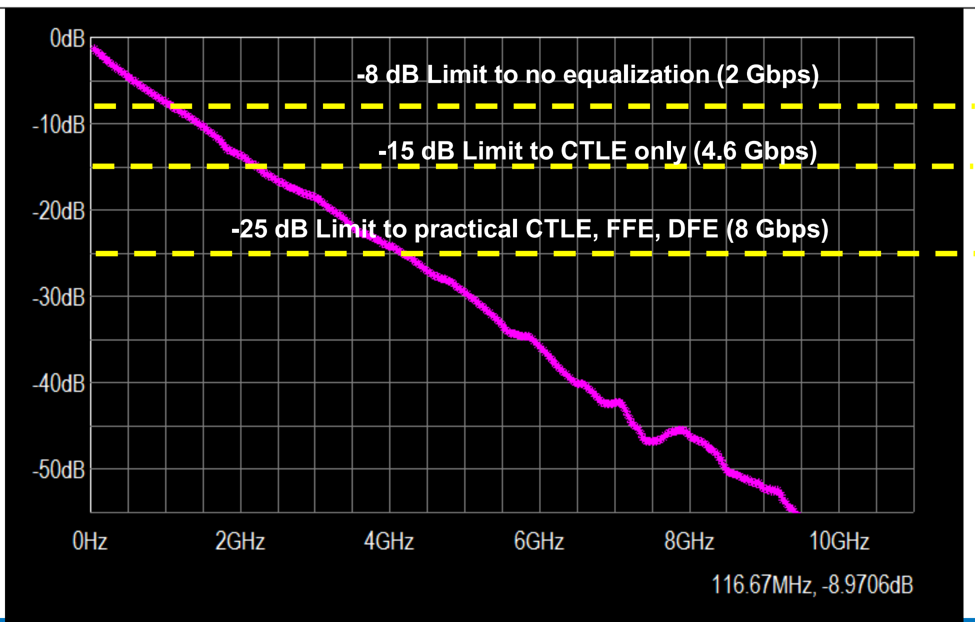
How to Use a Channel with -15 dB @ Nyquist? : Equalization



What if Attenuation @ Nyquist is > |-8| dB?

- Bit error ratio (BER) maybe too high
- Must use equalization to recover data:
  - CTLE: continuous time linear equalizer
  - FFE: feed forward equalization
  - DFE: decision feedback equalization
- Just CTLE may give acceptable eye when |S21| < |-15| dB
- Very good equalization may give acceptable eye when |S21| < |-25| dB

Example: Typical 40 inch Backplane



Lesson AGCD-03-50 Engineering a lower attenuation

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- AGCD-03-50: recorded live, Dec 1, 2013
  - Four ways of reducing the attenuation in a channel
  - Estimating attenuation from conductor and dielectric losses
  - Important figure of merit for dielectric loss
  - Typical values of attenuation in dB/in/GHz for common laminates

How do we Engineer Interconnects to Have Insertion loss below ~ -25 dB?

- Shortest interconnects practical
- Minimize conductor loss
  - Engineer widest line width balanced with required interconnect density
    - Loose coupling
    - Lowest impedance practical
    - Lowest Dk practical
    - Thickest dielectric layers practical
    - Conductor thickness > ½ oz. copper not much impact
  - Use smoother copper
- Minimize dielectric loss (no design features affect dielectric loss)
  - Lowest dissipation factor laminate practical
  - Use lower loss laminate on selected layers for lowest cost
- Keep surface traces (microstrip) short
  - Humidity sensitivity
  - Higher loss from surface treatment, rougher copper
  - Possible high far end cross talk

Estimating Attenuation (a first order approximation)

$$\text{atten}[\text{dB/in}] = 4.34 \text{ x} \left(\frac{R_{len}[\text{Ohms/in}]}{Z_0[\text{Ohms}]} + G_L[\text{Siemens/in}] \text{ x } Z_0[\text{Ohms}] \right)$$

Conductor loss **Dielectric loss**

$$G_L = 2\pi f \text{ x } C_0 \text{ x } Dk \text{ x } Df = 2\pi f \text{ x } C_L \text{ x } Df \qquad Z_0 = \frac{\sqrt{Dk}}{c\, C_{Len}}$$

$$\text{atten}[\text{dB/in}] = -4.34 \text{ x} \left(2\pi f C_{Len} Df \text{ x } \frac{\sqrt{Dk}}{c C_{Len}} \right) = -\frac{4.34 \text{ x } 2\pi}{11.8 \,{}^{\text{inch}}\!/_{\text{n sec}}} \text{ x f x Df x } \sqrt{Dk}$$

$$= -2.3 \text{ x f x Df x } \sqrt{Dk}$$

Attenuation from dielectric loss:
- only depends on the materials, NOT design
- scales linearly with frequency
- is dominated by dissipation factor of material
- simple figure of merit (FOM): dB/in/GHz = 2.3 x Df x sqrt(Dk) = 0.1 dB/inch/GHz

For FR4:

Attenuation from Dielectric: Figure of Merit

$$\text{atten per length[dB / inch]} = 2.3 \text{ x f x Df x } \sqrt{Dk} \text{ dB / inch}$$

@ ~ 1 GHz

Material	Dk	Df	atten, dB/inch/GHz
Park Nelco N4000-6	4.3	0.02	0.1
Isola 370HR	4.4	0.016	0.077
GETEK	3.5-4.4	0.008- 0.01	0.046
N4000-13SI	3.4	0.01	0.042
Isola FR408HR	3.7	0.009	0.04
Park-Nelco N4000-13EP	3.6	0.008	0.035
Rogers RO4350	3.6	0.004	0.017
GoreSpeedBoard	2.6	0.004	0.015
Panasonic Megtron 6	3.7	0.002	0.009

Typical Vendors: Isola, Taconics, Rogers, Park-Nelco, Panasonic, Gore

Lesson AGCD-03-60 What are your laminate's properties?

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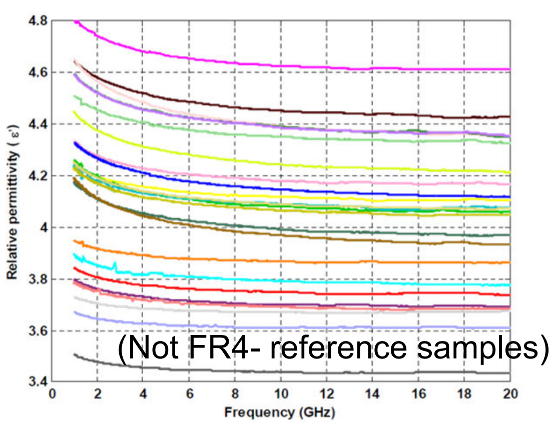
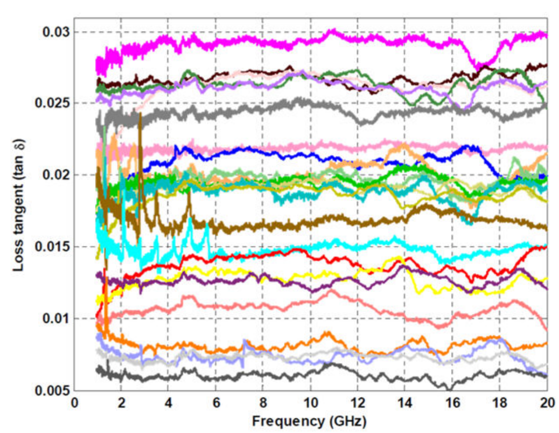
- AGCD-03-60: recorded live, Dec 1, 2013
  - Typical variation in the Dk and Df of "FR4"
  - Why what you ask for may not be what you get
  - The attenuation in microstrip compared with stripline
  - Humidity sensitivity to Df and dielectric losses

What is the Dk, Df of Your Laminate?

Measured Dk, Df of different "FR4" samples from 10 mil wide microstrips (different suppliers)

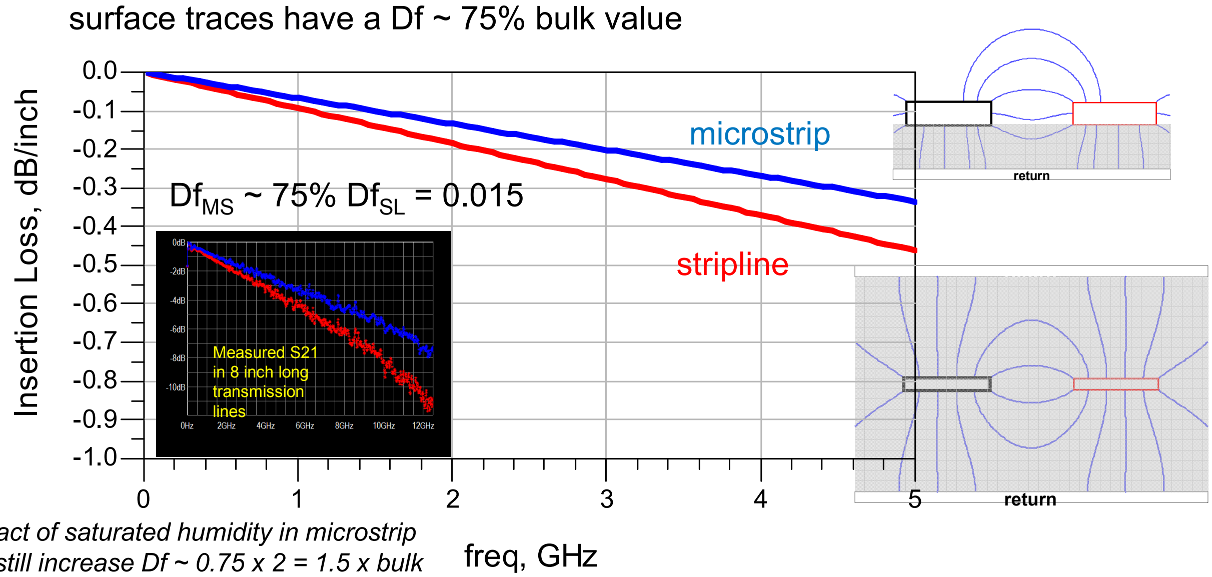




From: UMR Rolla MS&T, MS Thesis work of Abhilash Rajagopal, 2007

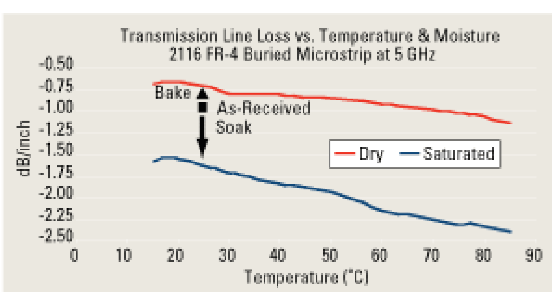
Depends also on temperature and humidity during measurement

Mixed Dielectric: Dielectric Loss Only, in Microstrip and Stripline



Impact of saturated humidity in microstrip can still increase Df ~ 0.75 x 2 = 1.5 x bulk material

Another 2nd Order Factor Influencing Attenuation from Dielectric: Temperature, Humidity Effects



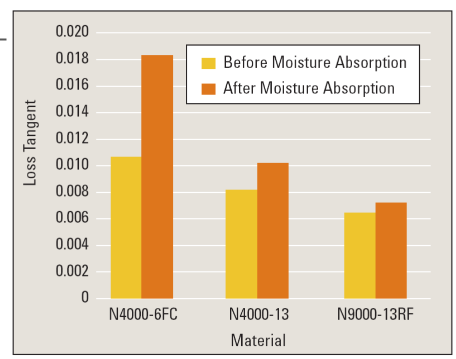


FIGURE 6. After moisture absorption, the N4000-6FC standard FR-4 has the biggest change in loss tangent.

From “Best Materials for 3-6 GHz Design”, Doug Leys, PCD&M, Nov 2004

1. Dry FR4, atten ~ -0.70 dB/inch @ 5 GHz (~ 0.14 dB/inch @ 1 GHz)
2. As received, atten ~ 1 dB/inch @ 5 GHz (~ 0.2 dB/inch @ 1 GHz)
3. Saturated humidity: S21 ~ 1.7 dB/in @ 5 GHz (~ 0.34 dB/inch @ 1 GHz)
4. Humidity can ~ double dissipation factor, temperature ~ 15%
5. Water pick up might account for variations in Df measurements
6. Water pick up ONLY affects microstrip surface traces, temperature, all traces
7. If loss is important, control humidity, temperature, keep surface traces short

Lesson AGCD-03-70 Attenuation from conductor loss

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- AGCD-03-70: recorded live, Dec 1, 2013
  - The origin of frequency dependent resistance
  - Estimating the conductor resistance
  - Estimating the attenuation from conductor resistance
  - Impact from surface roughness increasing resistance

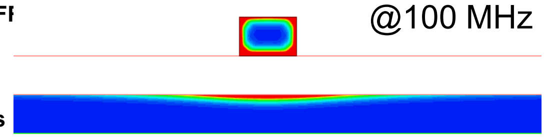
Skin Depth Limited Current Distributions: Smooth Copper

$$\delta = \sqrt{\frac{1}{\sigma\pi\mu_0\mu f}} = 2.1\mu\sqrt{\frac{1}{f}}$$ f in GHz

@ 1 GHz, skin depth = 2 u

Microstrip:
50 Ohm, FR
ε_r = 4.2
h = 38 μ
t = 3 mils
w = 5 mils

@100 MHz

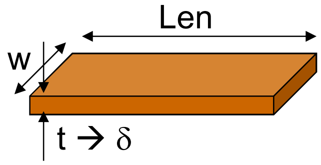


Ansoft SI 2D

- Properties of series resistance:
  - Above ~ 10 MHz, for 1 oz copper, current is skin depth limited
  - R will increase ~ sqrt(freq)
- All high end 2D field solvers will calculate the resistive and dielectric loss over frequency
  - Polar
  - Mentor Graphics HyperLynx
  - Agilent ADS
  - HFSS, CST, …

Estimating conductor loss:
1. Smooth copper
2. Skin depth
3. Return current loss
4. Roughness

Frequency Dependent Resistance



$$R = \rho \frac{Len}{t \times w} \rightarrow = \rho \frac{Len}{2 \times \delta \times w}$$

Assuming current is on both surfaces

At DC: For 1 oz copper
@ R_{sq} = 0.5 mOhms/sq
5 mil wide line = 200 squares
R_{DC} = 0.5 mOhms x 200 sq = 0.1 ohms/in

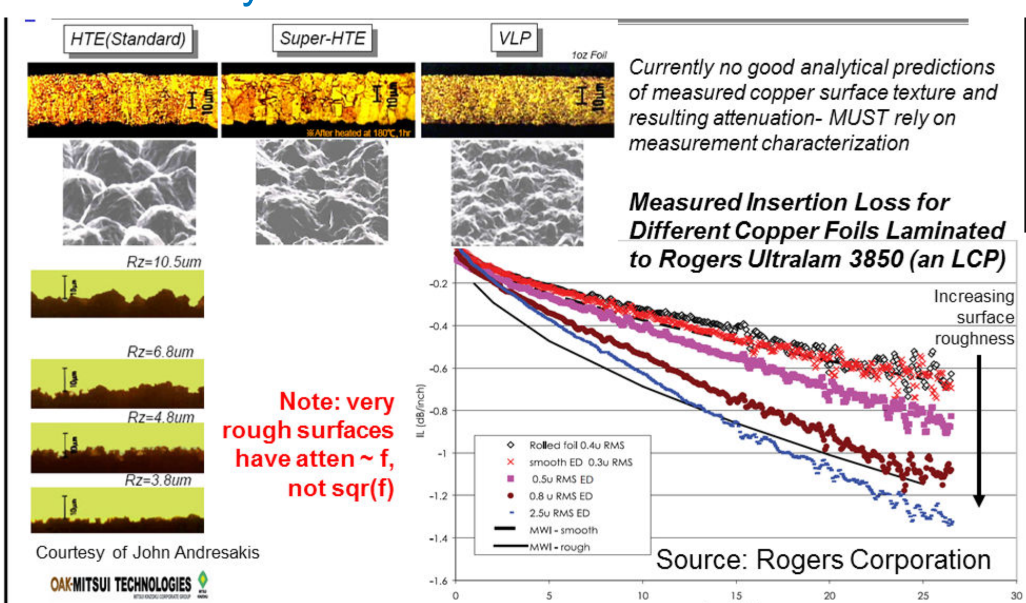
$$R_{Len} = \frac{R}{Len} = \frac{\rho}{2 \times \delta \times w} = \frac{1.8\times10^{-2}\,\Omega-\mu}{4.2\mu\sqrt{\frac{1}{f}} \times w} = \frac{4.3\Omega}{w}\sqrt{f}$$

R_{Len} in Ohms/inch
w in mils
f in GHz

Return current contributes ~ 20% additional series resistance

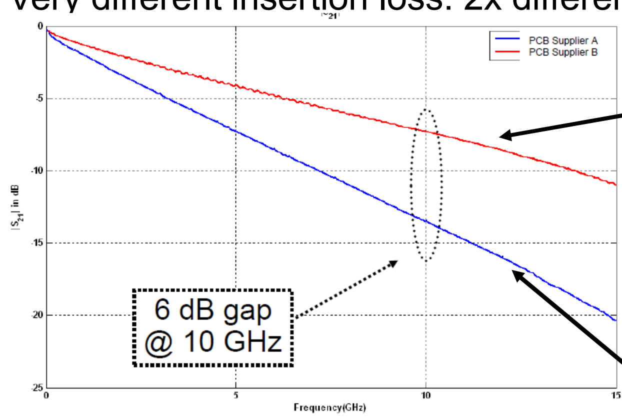
$$R_{Len}[Ohms/in] \sim \frac{5\,\Omega}{w[mils]}\sqrt{f[GHz]}$$

Impact from Copper Surface Roughness: Can increase attenuation by > 2x



A “Hidden Variable” to Real World Performance

- Identical boards from different suppliers
- Very different insertion loss: 2x difference- why?



example courtesy of Cisco

Attenuation from Conductor

Includes:
- skin depth in smooth copper
- current on both surfaces
- return current in plane

$$R_{Len}\left[Ohms/in\right] = \frac{5\Omega}{w\left[mils\right]}\sqrt{f\left[GHz\right]}$$

$$atten\left[dB/in\right] = 4.34 \text{ x } \frac{R_{len}\left[Ohms/in\right]}{Z_0\left[Ohms\right]} = \frac{22\left[Ohms/in\right]}{w\left[mils\right] \text{ x } Z_0\left[Ohms\right]}\sqrt{f\left[GHz\right]}$$

Z_0 is “single-ended impedance”

For differential pairs, R is 2x larger, Z_0 is 2x larger, attenuation is the same

Surface roughness can more than double series resistance
- *Very difficult to get accurate calculation of surface roughness impact*

For 50 Ω:

$$atten\left[dB/in\right] = \frac{44\left[Ohms/in\right]}{w\left[mils\right] \text{ x } Z_0\left[Ohms\right]}\sqrt{f\left[GHz\right]} \sim \frac{1}{w\left[mils\right]}\sqrt{f\left[GHz\right]}$$

Lesson AGCD-03-80 Attenuation in typical channels

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- AGCD-03-80: recorded live, Dec 1, 2013
  - Example of worst case channel: FR4 and narrow lines
  - Important figures of merit in FR4, lossy channels
  - Example of best case, low loss channel with Megtron 6
  - Comparing simple figures of merit estimates with measured channels

Typical Worst Case: FOM ~ 0.2 dB/inch/GHz Total Attenuation in FR4

$$\text{atten}[\text{dB/in}] = 4.34 \times \left(\frac{R_{len}[\text{Ohms/in}]}{Z_0[\text{Ohms}]} + G_L[\text{Siemens/in}] \times Z_0[\text{Ohms}] \right)$$

$$\text{atten}[\text{dB/in}] \sim \frac{1}{w[\text{mils}]} \sqrt{f[\text{GHz}]} + 2.3 \times f[\text{GHz}] \times \text{Df} \times \sqrt{\text{Dk}}$$

- skin depth
- current on both surfaces
- resistance of return path
- 2x surface roughness
- for 50 Ohm single-ended, 100 Ohm diff

Example: @ 1 GHz, (2 Gbps) w = 5 mil, Dk = 4.3, Df = 0.02

$$\text{atten}[\text{dB/in}] \sim \frac{1}{5}\sqrt{1} + 2.3 \times 1 \times 0.02 \times \sqrt{4.3} =$$

Figure of Merit ~ 0.3 dB/in/GHz

$$0.2\text{dB/in} + 0.1\text{dB/in} = 0.3\text{dB/in}$$

Example: @ 4 GHz, (8 Gbps) w = 5 mil, Dk = 4.3, Df = 0.02

$$\text{atten}[\text{dB/in}] \sim \frac{1}{5}\sqrt{4} + 2.3 \times 4 \times 0.02 \times \sqrt{4.3} =$$

Figure of Merit ~ 0.22 dB/in/GHz

$$0.4\text{dB/in} + 0.5\text{dB/in} = 0.9\text{dB/in}$$

Typical Best Case: FOM ~ 0.1 dB/inch/GHz Total Attenuation in Megtron6

$$\text{atten}[\text{dB/in}] = 4.34 \text{ x } \left(\frac{R_{len}[\text{Ohms/in}]}{Z_0[\text{Ohms}]} + G_L[\text{Siemens/in}] \text{ x } Z_0[\text{Ohms}] \right)$$

$$\text{atten}[\text{dB/in}] \sim \frac{1}{w[\text{mils}]}\sqrt{f[\text{GHz}]} + 2.3 \text{ x } f[\text{GHz}] \text{ x Df x } \sqrt{\text{Dk}}$$

- skin depth
- current on both surfaces
- resistance of return path
- 2x surface roughness
- for 50 Ohm single-ended, 100 Ohm diff

Example: @ 1 GHz, (2 Gbps) w = 7 mil, Dk = 3.7, Df = 0.002

$$\text{atten}[\text{dB/in}] \sim \frac{1}{7}\sqrt{1} + 2.3 \text{ x } 1 \text{ x } 0.002 \text{ x } \sqrt{3.7} =$$

Figure of Merit ~ 0.15 dB/in/GHz

$$0.14\text{dB/in} + 0.009\text{dB/in} = 0.15\text{dB/in}$$

Example: @ 4 GHz, (8 Gbps) w = 7 mil, Dk = 3.7, Df = 0.002

$$\text{atten}[\text{dB/in}] \sim \frac{1}{7}\sqrt{4} + 2.3 \text{ x } 4 \text{ x } 0.002 \text{ x } \sqrt{3.7} =$$

Figure of Merit ~ 0.08 dB/in/GHz

Very expensive material wasted by conductor loss

$$\boxed{0.28\text{dB/in}} + \boxed{0.035\text{dB/in}} = 0.32\text{dB/in}$$

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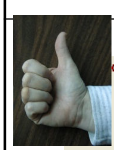
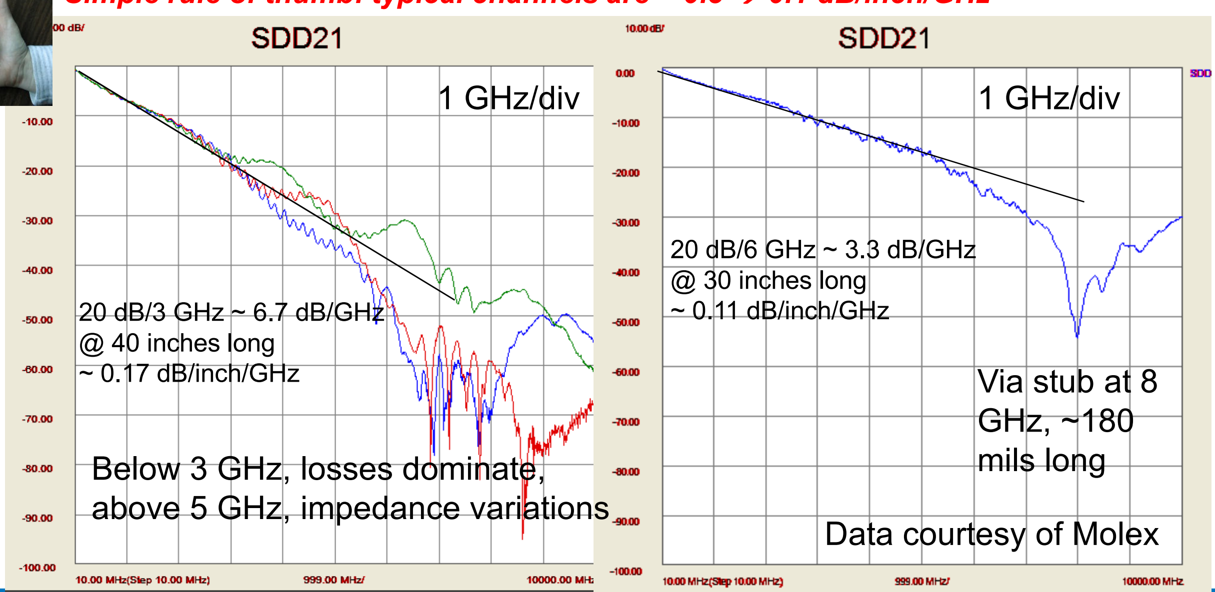
Attenuation and SDD21: Measured Backplane Channels

Simple rule of thumb: typical channels are ~ 0.3 → 0.1 dB/inch/GHz





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Summary of Bandwidth Terms

If ISI is affected ONLY by losses (doing EVERYTHING else right) best cases:

~ 2 x (-4 dB BW) is the highest data rate at which the eye will not be strongly affected by loss

~ 2 x (-8 dB BW) is the highest data rate at which you may not need any equalization

~ 2 x (-15 dB BW) is the highest data rate at which CTLE equalization may recover acceptable eye

~ 2 x (-25 dB BW) is the highest data rate at which reasonable CTLE, FFE, DFE equalization might recover acceptable eye

Examples

- In a low loss channel, how far can you go at 10 Gbps using best equalization?
  - -25 dB = -0.1 dB/inch/GHz x Len x 5 GHz= 0.5 dB/inch x Len
  - Len = 50 inches
- In a lossy channel, how far can you go with no equalization at 10 Gbps?
  - -10 dB = -0.2 dB/inch/GHz x Len x 5 GHz = 1 dB/inch x Len
  - Len = 10 inches

How do we Engineer Interconnects to Have S21 loss below ~ -25 dB?

- Shortest interconnects practical
- Minimize conductor loss
  - Engineer widest line width balanced with required interconnect density
    - Loose coupling
    - Lowest impedance practical
    - Lowest Dk practical
    - Thickest dielectric layers practical
    - Conductor thickness > ½ oz. copper not much impact
  - Use smooth copper
- Minimize dielectric loss (no design features affect dielectric loss)
  - Lowest dissipation factor laminate practical
  - Use lower loss laminate on selected layers for lowest cost
- Keep surface traces (microstrip) short
  - Humidity sensitivity
  - Higher loss from surface treatment, rougher copper
  - Possible high far end cross talk